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*Monitoring Completed Navigation Projects (MCNP) Program*

## **Use of Dolos Armor Units to Repair Hurricane Sandy-Damaged Great Lakes Harbor Breakwaters**

Michael C. Mohr, Gerlyn J. Hinds, Weston P. Cross,  
Shanon A. Chader, and Jeffrey A. Melby

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# **Use of Dolos Armor Units to Repair Hurricane Sandy-Damaged Great Lakes Harbor Breakwaters**

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## Abstract

After traveling up the eastern U.S. coastline, Hurricane Sandy made landfall on 29 October 2012 near Atlantic City, NJ, with winds of 80 mph. The backside of the storm moved inland, bringing high winds and rain far into the nation's interior. No longer a hurricane, but termed Superstorm Sandy, the winds were generally from the north over the Great Lakes, extending as far west as Lake Michigan, causing extensive damage to several federal harbor structures especially in the Lower Great Lakes, including Cleveland East Breakwater on Lake Erie and Oswego Detached Breakwater on Lake Ontario. Concrete dolos armor units were selected to repair damage on these two structures. During 2015, 6,919 6.5-ton unreinforced dolosse were placed, and an additional 11,340 dolosse were placed in 2016 on the Cleveland East Breakwater. During 2015, 973 16-ton steel-reinforced dolosse were placed on the Oswego Detached Breakwater. The dolos design process, creation of the forms, strength testing, and placement are described and documented. Knowledge gained from this initial placement and from future periodic monitoring will correlate dolos movement with environmental forces. This information will be used for reliability analysis of coastal structures in determining remaining useful life for asset-management funding prioritizations.

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## Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the USACE Monitoring Completed Navigation Projects (MCNP) Program, under Work Unit “Reliability Analysis of Coastal Structures.”

This study was executed by the Technical Services Division (CELRB-TD), Design Branch (CELRB-TD-D), Coastal and Geotechnical Engineering Section (CELRB-TD-DC), of the USACE Buffalo District (CELRB); and by the Harbors, Entrances, and Structures Branch (CEERD-HN-H), Navigation Division (CEERD-HN) of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). During conduct of this study, Mr. Thomas Switala was Chief, CELRB-TD; Mr. Todd Kufel was Chief, CELRB-TD-D; Mr. Michael Mohr was Chief, CELRB-TD-DC; Mr. James Gutshall was Chief, CEERD-HN-H; and Dr. Jacqueline Pettway was Chief, CEERD-HN. Dr. Jeffrey A. Melby was the principal investigator of the “Reliability Analysis of Coastal Structures” work unit of the USACE MCNP Program being executed by ERDC CHL. Mr. Jeffrey A. McKee, Chief, HQUSACE Navigation Branch, was the Navigation Business Line Manager. Mr. W. Jeff Lillycrop, ERDC CHL, was the ERDC Technical Director for Civil Works and Navigation Research, Development, and Technology Transfer portfolio. Dr. Lyndell Z. Hales was the MCNP Program Manager.

At the time of publication of this report, Mr. Charles E. Wiggins was the Acting Chief of CEERD-HN, Mr. Jeffrey R. Eckstein was the Acting Director of ERDC CHL, and Dr. Jacqueline Pettway was the Acting Deputy Director of ERDC CHL.

COL Bryan S. Green was the Commander of ERDC, and Dr. David W. Pittman was the Director of ERDC.

## Unit Conversion Factors

Multiply	By	To Obtain
acres	0.404686	hectares
cubic yards	0.7646	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785401	liters
inches	2.54	centimeters
knots	0.5144444	meters per second
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
ounces (mass)	28.3495	kilograms
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.453592	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters
tons (2,000 pounds, mass)	907.1847	kilograms

# 1 Introduction

## Background

Hurricane Sandy originated as a tropical wave in the eastern Caribbean on 19 October 2012. It quickly developed into a tropical depression, and within 6 hours (hr), transitioned into a tropical storm that began to slowly travel westward. Tropical Storm Sandy was upgraded to a hurricane on 24 October 2012 when its maximum sustained winds reached 74 miles per hour (mph). Sandy made landfall in Jamaica on 24 October 2012. As it swept across the Bahamas, Sandy gained strength to become a Category 1 hurricane before turning north toward the U.S. coastline.

Hurricane Sandy slowly traveled northward along the eastern U.S. coastline before turning westward and making landfall in the United States on 29 October 2012, striking near Atlantic City, NJ, with winds of 80 mph. At one point, Sandy's hurricane-force winds extended up to 175 miles from its center, and tropical storm-force winds (39 mph) reached out as far as 485 miles.

As Hurricane Sandy traveled northward along the U.S. coastline, the backside counterclockwise rotation of the storm moved farther inland, bringing high winds and rain far into the nation's interior. No longer called a hurricane, Sandy was now termed a *superstorm*, with winds generally from the north over the Great Lakes, extending as far west as Lake Michigan, causing severe extensive damage to several harbor structures especially in the Lower Great Lakes.

Cleveland Harbor East Breakwater on Lake Erie, and Oswego Detached Breakwater on Lake Ontario, were severely damaged on the lake sides by wave and water level effects resulting from Sandy. It was subsequently determined that the Cleveland Harbor East Breakwater would be rehabilitated by using 6.5-ton dolosse<sup>1</sup>, and the Oswego Detached Breakwater would be repaired by using 16-ton dolosse.

While the destruction wrought by Sandy was overwhelming, the repair of the damage suffered by these two U.S. Army Corps of Engineers (USACE)

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<sup>1</sup> dolos (singular), dolosse (plural)

coastal structures provided an opportunity for obtaining high-fidelity data and knowledge regarding design, construction, and placement of those dolosse. These data will be invaluable for use by the “Reliability Analysis of Coastal Structures” work unit of the USACE Monitoring Completed Navigation Projects (MCNP) Program in asset-management decision-making regarding the appropriate time and sequence for expending federal funds to rehabilitate USACE infrastructure. Potentially, future periodic re-surveying can be conducted to gain information about remaining future life of the protection provided by the dolosse as settling and displacement occur during future storms and Great Lakes ice conditions.

This U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), technical report describes the design methodology, construction, and experience of rehabilitating two harbor breakwaters located on Lakes Erie (Cleveland Harbor East Breakwater, Ohio) and Lake Ontario (Oswego Detached Breakwater, New York) using 6.5-ton and 16-ton dolos, respectively.

## Project locations

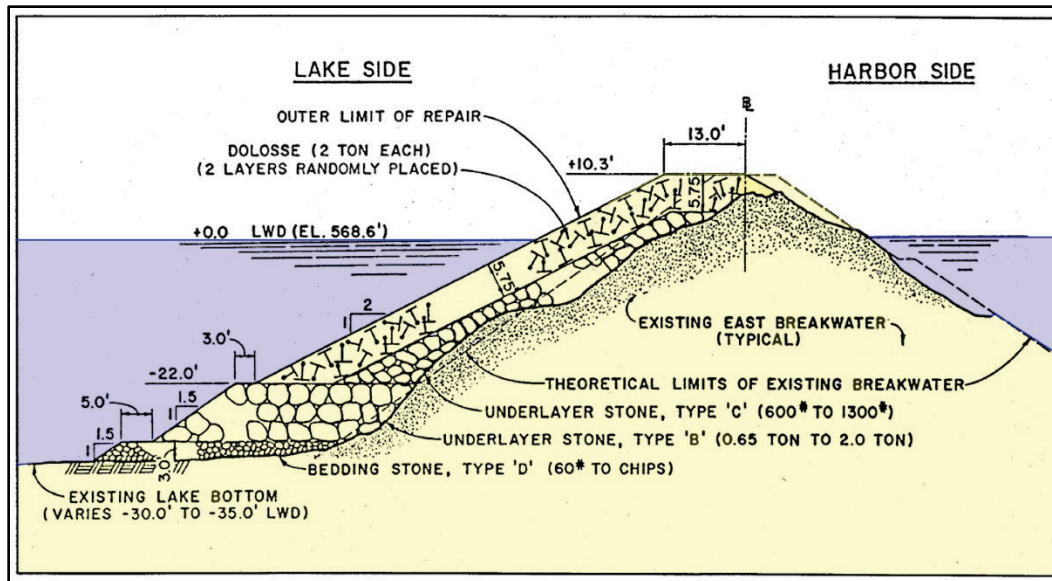
Cleveland Harbor is located at the city of Cleveland, OH, along the south shore of Lake Erie, at the mouth of the Cuyahoga River, 176 miles westerly from Buffalo, NY. Oswego Harbor is located at the city of Oswego, NY, along the southeast shore of Lake Ontario, 57 miles westerly from Rochester, NY (Figure 1-1).

Figure 1-1. Project location map.





Figure 1-3. Cleveland East Breakwater section with 2-ton dolosse, 1979.



### Oswego Harbor, New York

Oswego Harbor provides for an outer harbor, approximately 280 acres in area, formed by a system of breakwaters comprising an outer west breakwater 4,515 feet (ft) long connected with the shore, a west arrowhead breakwater 2,700 ft long, an east arrowhead breakwater approximately 2,200 ft long, and a detached breakwater 850 ft long at the harbor entrance. It was the latter structure that received damage from Hurricane Sandy.

The detached breakwater is a laid-up cut stone structure built in 1958–1960. The cap is composed of cast-in-place concrete blocks 10 ft long × 8 ft wide. Light blocks, 8 ft × 8 ft × 4 ft, were cast in place at both ends to support U.S. Coast Guard light towers. The blocks do not rely fully for support by the surrounding stone; rather, they are each supported by four steel H-piles that were driven into the lake bed. The cast-in-place concrete cap extended another 12 ft from these blocks. To make access to the breakwater crest and lights safer and easier, a concrete boat landing and stairs were also cast in place at the east end along the harbor side at the light block. The harbor map and typical detached breakwater cross section are presented in Figure 1-4 and Figure 1-5.

Figure 1-4. Oswego Harbor repair location map.

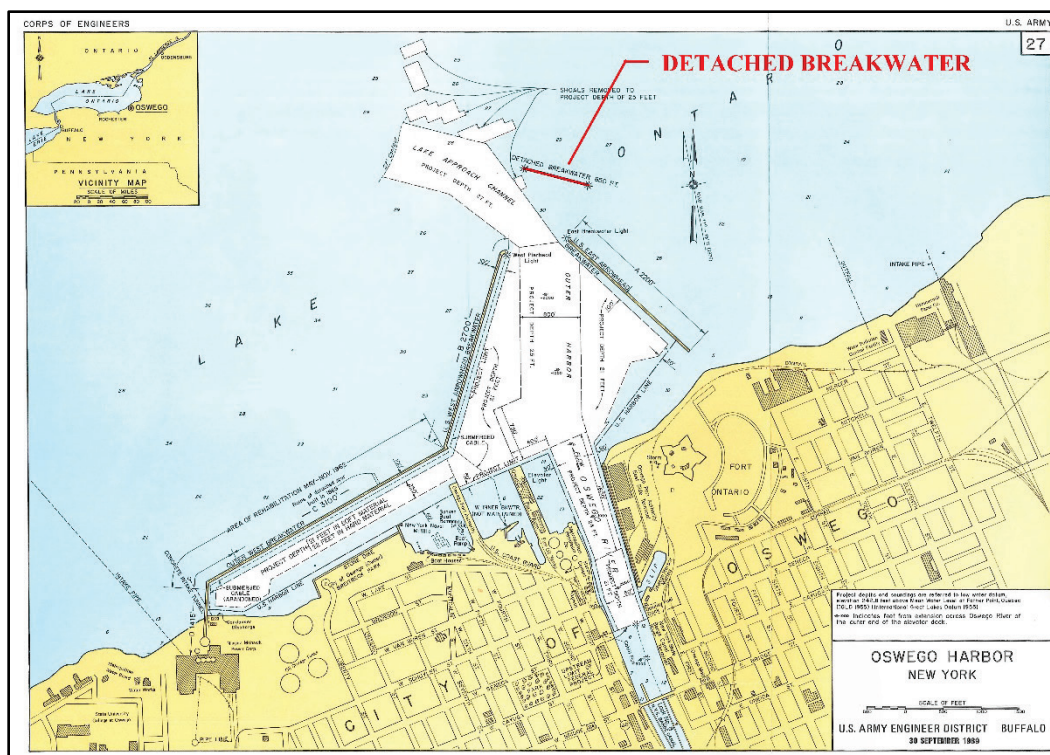
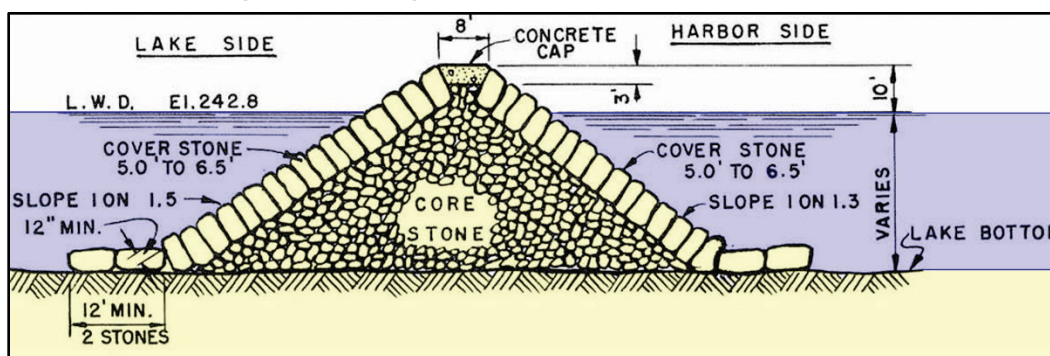


Figure 1-5. Oswego Detached Breakwater section, 1959.



## Objectives

The objectives of this ERDC CHL technical report are to present the design methodology, dolos construction, dolos placement, and lessons learned during the repair of two Great Lakes federal harbor breakwaters (Cleveland East Breakwater, Lake Erie; and Oswego Detached Breakwater, Lake Ontario). As the design methodology is fully discussed in the respective project Detailed Design Reports (USACE 2014b, 2014c, 2014d, 2014e), only pertinent information is extracted from those documents and presented herein. Interested readers are encouraged to peruse those documents for further details regarding the dolos design for these structures.

The precise location of each dolos placed on the Cleveland East Breakwater (6.5-ton units) and the Oswego Detached Breakwater (16-ton units) will be known from the Armor Unit Placement and Positioning System (AUPPS [USACE Buffalo District term]). Periodic surveys of these breakwater repairs should be conducted on a 3- to 5-year interval to provide data for predicting future dolos movement. This will develop a high-fidelity estimate of remaining useful life of the structures based on the probability of future storm events as deduced by the Coastal Hazards Rapid Prediction System, which stores a suite of storm scenarios that cover a range of statistical events. This time-dependent damage modeling approach being developed by the MCNP Work Unit “Reliability Analysis of Coastal Structures” allows for the assessment of structure performance throughout the structure lifetime for a wide range of forcing and design conditions, knowledge that is of particular interest for asset-management funding prioritization.

## **Approach**

This technical report is organized into five chapters. Chapter 1 “Introduction” presents background material leading to damages to the Cleveland East Breakwater and Oswego Detached Breakwater and describes the composition of these two structures. Chapter 2 “Dolos Design Methodology” reviews pertinent information from the Detailed Design Reports, including water levels and waves, dolos size and density, dolos strength, and typical sections and scale models of the structures. Chapter 3 “Dolos Construction Techniques” describes the minimum concrete requirements, fabrication of the dolos forms, and the dolos production. Chapter 4 “Dolos Placement Techniques” discusses the contractor AUPPS for the dolos placement, the contractor dolos placement equipment, and the contractor dolos placement rate. Chapter 5 “Summary” presents a brief review of the various necessary activities undertaken in producing and placing the dolos on the two structures, lessons learned, and future monitoring recommendations.

## 2 Dolos Design Methodology

### Water levels and waves

#### General

Standard design practice within the Great Lakes since the 1970s, and based upon practical experience, has been to use for the design conditions the greater of the combination of the 20-year wave and 10-year water level, or vice versa. Following this practice has resulted in reasonably sized structures that are resistant to wave and ice loadings. Lake level-frequency information within the Great Lakes has been developed (USACE 1993). Wave hindcast information at select locations for the Great Lakes is available from the ERDC CHL Wave Information Study (WIS) (USACE 2014a).

The 1 hr deepwater significant wave height information was developed for three class angles. The three angle classes are defined as viewed by an observer on shore:

- Class Angle 1: Mean wave approach angle greater than 30 degrees (deg) to the right of the normal from shore.
- Class Angle 2: Mean wave approach angle within 30 deg to either side of the normal from shore.
- Class Angle 3: Mean wave approach angle greater than 30 deg to the left of the normal from shore.

The WIS storm data set was used to develop partial duration frequency curves for the three wave angle classes. The corresponding wave period was determined by plotting wave periods with the wave heights and fitting a best fit curve in EXCEL™. Incident waves at the structures were calculated using CMS-Wave (Lin et. al. 2008) for the case of the 10-year wave and 20-year water level, and vice versa, as well as for the 2-year wave and 2-year water level.

#### Cleveland, OH

The U.S. National Oceanic and Atmospheric Administration (NOAA) maintains a water level gage at Cleveland Harbor, which has been in operation since 1904. Lake level-frequency information for Cleveland Harbor has been developed by the USACE, Detroit District (LRD),

(USACE 1993). The wave hindcast developed along the Lake Erie shore encompasses the years 1979–2012. This data set was used to determine the design parameters for the hindcast location (92070) shown in Figure 2-1. CMS-Wave was run for the water level and deepwater wave conditions presented in Table 2-1 and indicated that the largest incident wave along the repair reach was 14.2 ft.

Figure 2-1. WIS Hindcast Station 92070 location.



Table 2-1. Cleveland water levels and offshore waves.

Run	Water Level		Wave Characteristics				
	Low Water Datum, ft	Water Level Recurrence Interval	H <sub>mo</sub> , ft	T <sub>p</sub> , sec	Direction, deg, Clockwise from North	Wave Recurrence Interval, years	Wave Angle Class
1	4.5	2-year	7.3	6.9	360	2	1
2	4.5	2-year	10.3	7.1	330	2	2
3	4.5	2-year	11.5	7.4	300	2	3
4	5.8	10-year	12.1	8.7	360	20	1
5	5.8	10-year	14.8	8.1	330	20	2
6	5.8	10-year	14.6	8.2	300	20	3
7	6	20-year	11.5	8.5	360	10	1
8	6	20-year	14.1	8	330	10	2
9	6	20-year	14.4	8.2	300	10	3
10	0	Low Water	12.1	8.7	360	20	1
11	0	Low Water	14.8	8.1	330	20	2
12	0	Low Water	14.6	8.2	300	20	3

## Oswego, NY

NOAA maintains a water level gage at Oswego Harbor, New York. Lake level-frequency information for Oswego Harbor has been developed by USACE LRD (USACE 1993). The wave hindcast developed along the Lake Ontario shore encompasses the years 1979–2012. This data set was used to determine the design parameters, with the Hindcast Station (91042) shown in Figure 2-2. CMS-Wave was run for the water level and deepwater wave conditions presented in Table 2-2. Incident wave conditions at select locations (Figure 2-3) around the breakwater periphery are presented in Table 2-3 and indicated that the largest waves off the west head were 21 ft and decreased along the length to 14 ft at the eastern end. The large incident wave would result in prohibitively large armor, and with the attendant challenges of quarrying, transporting, and placing the armor, alternative armor types were investigated. Core-Loc™ or dolos concrete armor units were considered. Due to the compressed time frame associated with the availability of Hurricane Sandy funds and experience by ERDC, the use of Core-Loc was omitted as a hydraulic model study was deemed necessary to ensure their viability. Past U.S. Army Corps of Engineers, Buffalo District (LRB), experience with dolosse, and their use around the world, led LRB to choose dolosse as the preferred armor type at the west end.

Figure 2-2. WIS Hindcast Station 91042 location.



Table 2-2. Oswego water levels and offshore waves.

Run	Water Level		Wave Characteristics				
	Low Water Datum, ft	Water Level Recurrence Interval	H <sub>mo</sub> , ft	T <sub>p</sub> , sec	Direction, deg, Clockwise from North	Wave Recurrence Interval, years	Wave Angle Class
1	4.2	2-year	12.1	7.5	356	2	1
2	4.2	2-year	12.3	8.1	326	2	2
3	4.2	2-year	23.3	8.2	296	2	3
4	4.9	10-year	14.8	8.2	356	20	1
5	4.9	10-year	14.0	8.7	326	20	2
6	4.9	10-year	26.6	12.9	296	20	3
7	5.1	20-year	14.6	8.1	356	10	1
8	5.1	20-year	13.6	8.6	326	10	2
9	5.1	20-year	25.9	12.7	296	10	3
10	0	Low Water	14.8	8.2	356	20	1
11	0	Low Water	14.0	8.7	326	20	2
12	0	Low Water	26.6	12.9	296	20	3

Figure 2-3. Oswego Detached Breakwater CMS-Wave monitoring stations.

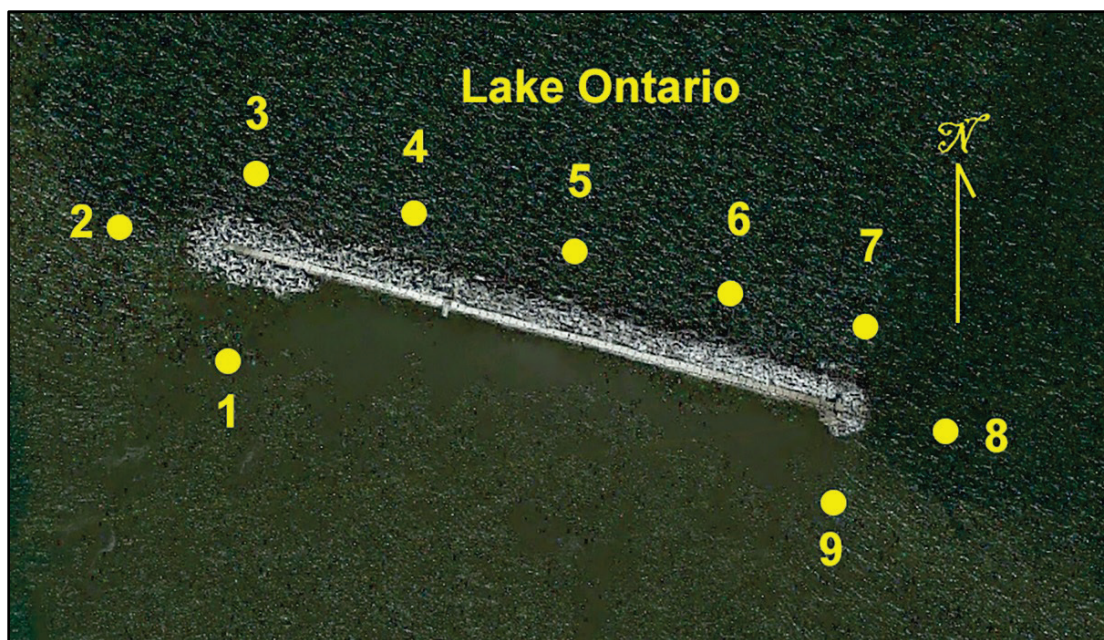


Table 2-3. Oswego Detached Breakwater incident waves.

Location	Point	H <sub>s</sub> , ft	T <sub>p</sub> , sec	Direction, deg, Clockwise from North	Low Water Datum, Water Level, ft	Case
West Head Lee	1	9.2	8.3	334	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
West Head Lee	1	12.2	8.3	309	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
West Head Lee	1	17.7	11.1	289	4.9	RUN 6 - 10-year water level, 20-year wave, class angle 3
West Head West	2	12	8.3	334	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
West Head West	2	13.1	8.3	316	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
West Head West	2	21	11.1	296	4.9	RUN 6 - 10-year water level, 20-year wave, class angle 3
West Head Lakeside	3	13.9	8.3	344	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
West Head Lakeside	3	11.5	8.3	313	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
West Head Lakeside	3	20.2	11.1	293	4.9	RUN 6 - 10-year water level, 20-year wave, class angle 3
Lakeside, 2+00	4	14.8	8.3	349	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
Lakeside, 2+00	4	11.5	8.3	322	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2

Location	Point	H <sub>s</sub> , ft	T <sub>p</sub> , sec	Direction, deg, Clockwise from North	Low Water Datum, Water Level, ft	Case
Lakeside, 2+00	4	16.9	11.1	306	5.1	RUN 6 - 10-year water level, 20-year wave, class angle 3
Lakeside, 4+00	5	15.1	8.3	352	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
Lakeside, 4+00	5	11.8	8.3	326	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
Lakeside, 4+00	5	15.4	11.1	312	5.1	RUN 6 - 10-year water level, 20-year wave, class angle 3
Lakeside, 6+00	6	14.7	8.3	356	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
Lakeside, 6+00	6	12.2	8.3	329	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
Lakeside, 6+00	6	15.1	11.1	314	5.1	RUN 6 - 10-year water level, 20-year wave, class angle 3
East Head Lakeside	7	13.6	8.3	357	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
East Head Lakeside	7	11.6	8.3	332	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
East Head Lakeside	7	13.9	11.1	319	5.1	RUN 6 - 10-year water level, 20-year wave, class angle 3
East Head East	8	11.9	8.3	360	4.9	RUN 4 - 10-year water level, 20-year wave, class angle 1
East Head East	8	9.6	8.3	338	4.9	RUN 5 - 10-year water level, 20-year wave, class angle 2
East Head East	8	10.6	11.1	324	5.1	RUN 6 - 10-year water level, 20-year wave, class angle 3
East Head Lee	9	6.4	8.3	10	4.9	RUN 7 - 20-year water level, 10-year wave, class angle 1
East Head Lee	9	5.8	8.3	337	5.1	RUN 8 - 20-year water level, 10-year wave, class angle 2
East Head Lee	9	7.6	11.1	303	5.1	RUN 9 - 20-year water level, 10-year wave, class angle 3

## Dolos size and density

### Dolos weight

The required individual weight for the dolos was determined using Hudson (1958)<sup>1</sup>:

$$W = \frac{W_r H^3}{K_D (S_r - 1)^3 \cot \theta}$$

where:

- W = weight of armor unit in primary cover layer
- $W_r$  = unit weight of armor
- H = design wave height
- $K_D$  = stability coefficient
- $S_r$  = specific gravity of the armor unit
- $\cot \theta$  = structure inverse slope.

Selection of the appropriate  $K_D$  value is crucial to successfully sizing the dolos. Through consultation with coastal structure specialists at ERDC<sup>2</sup>, a  $K_D$  value of 8 was selected. This value is based upon experience with structures around the world. With incident wave heights of 14.2 and 21.0 ft, unit weights of 140 pounds per cubic foot (lb/ft<sup>3</sup>) (no reinforcement) and 150 lb/ft<sup>3</sup> (with steel reinforcement), the required individual dolos weights were determined as 6.5 tons and 16.0 tons for the Cleveland and Oswego repairs, respectively.

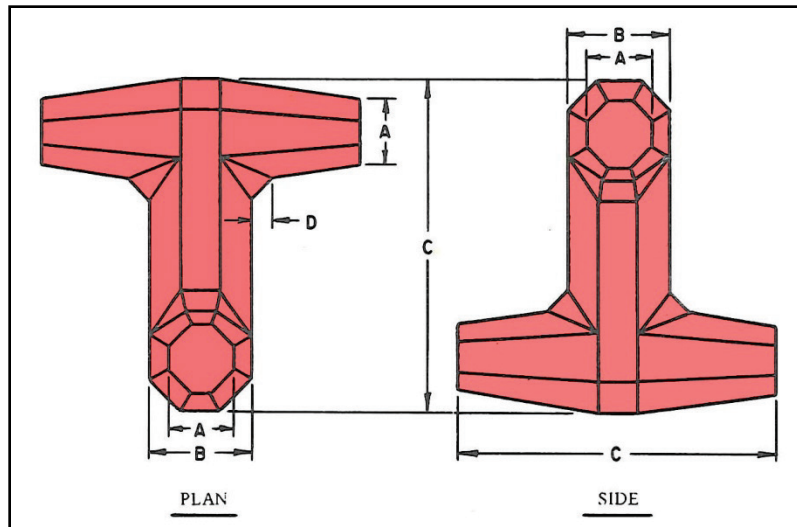
### Dolos geometry

The geometric dimensions of the dolos have been normalized by the primary or characteristic length, C, as shown in Figure 2-4 (USACE 1984, 2011).

<sup>1</sup> During the Oswego dolos design, Carver and Heimbaugh (1989) and Burcharth and Liu (1992) were also used and suggested weights of 16.1 and 13.6 tons, respectively. (USACE 2014c).

<sup>2</sup> Jeffrey Melby (ERDC-CHL-MS) to Michael Mohr (CELRB-TD-DC), Subject: Dolos, personal communication, 18 March 2014.

Figure 2-4. Non-dimensional schematic of typical dolos.



where:

$$A = 0.20C$$

$$B = 0.32C$$

$$C = \text{overall dimension}$$

$$D = 0.057C$$

$$E = 0.364C.$$

The volume,  $V$ , of an individual dolos can be expressed in terms of the characteristic length as

$$V = 0.16C^3$$

The layer thickness,  $R$ , is

$$R = 1.020C$$

The number of dolosse per unit area,  $N_r$ , is

$$N_r = 0.83V^{-\frac{2}{3}}$$

Table 2-4 presents the adopted dolos parameters in feet (ft), square feet (ft<sup>2</sup>), and cubic feet (ft<sup>3</sup>).

Table 2-4. Cleveland and Oswego dolos parameters (Figure 2-4).

Variable	Cleveland 6.5-ton Dolos	Oswego 16-ton Dolos
Dolos dimension, A	1.67 ft	2.2 ft
Dolos dimension, B	2.67 ft	3.52 ft
Dolos dimension, C	8.33 ft	11.0 ft
Dolos dimension, D	0.47 ft	0.6270 ft
Dolos dimension, E	3.03 ft	4.00 ft
Layer thickness, R	8.5 ft	11.22 ft
Volume, V	92.5 ft <sup>3</sup>	212.96 ft <sup>3</sup>
Number units per area, N <sub>r</sub>	40.6/1,000 ft <sup>2</sup>	23.274/1,000 ft <sup>2</sup>

## Dolos strength

Unreinforced concrete has a brittle failure mode. The maximum flexural tensile stress that the dolosse can be expected to experience during handling and placement was established using USACE (2011), Figure VI-5-44 (Figure 2-5), and resulted in a recommended value of 368 pounds per square inch (lb/in.<sup>2</sup>) (2.54 megapascals [MPa]) and 537 lb/in.<sup>2</sup> (3.70 MPa) for the Cleveland and Oswego dolosse, respectively. The minimum precast compressive strengths,  $f_c$ , are 5,000 lb/in.<sup>2</sup> and 10,000 lb/in.<sup>2</sup> for Cleveland and Oswego, respectively. It would be prohibitively expensive or impractical to specify sufficient concrete tensile strength with the corresponding compressive strength to prevent breakage of the Oswego dolosse, and hence steel reinforcement was used. The analysis for the Oswego reinforcing steel may be found in USACE (2014d) and considered load cases of lifting by straps at the end of two flukes, in the center of the shaft, at the end of one fluke and around one end of the shaft. It was determined that a single point lift at an end of the fluke was not acceptable and hence not allowed as the reinforcement was unlikely to provide adequate strength for this load condition. The addition of the steel reinforcement resulted in a unit weight of 150.1 lb/ft<sup>3</sup>, consistent with the initial design assumption. Figure 2-6 presents a view of the 16-ton dolos with reinforcing steel.

Figure 2-5. Dolos weight versus maximum flexural tensile stress.

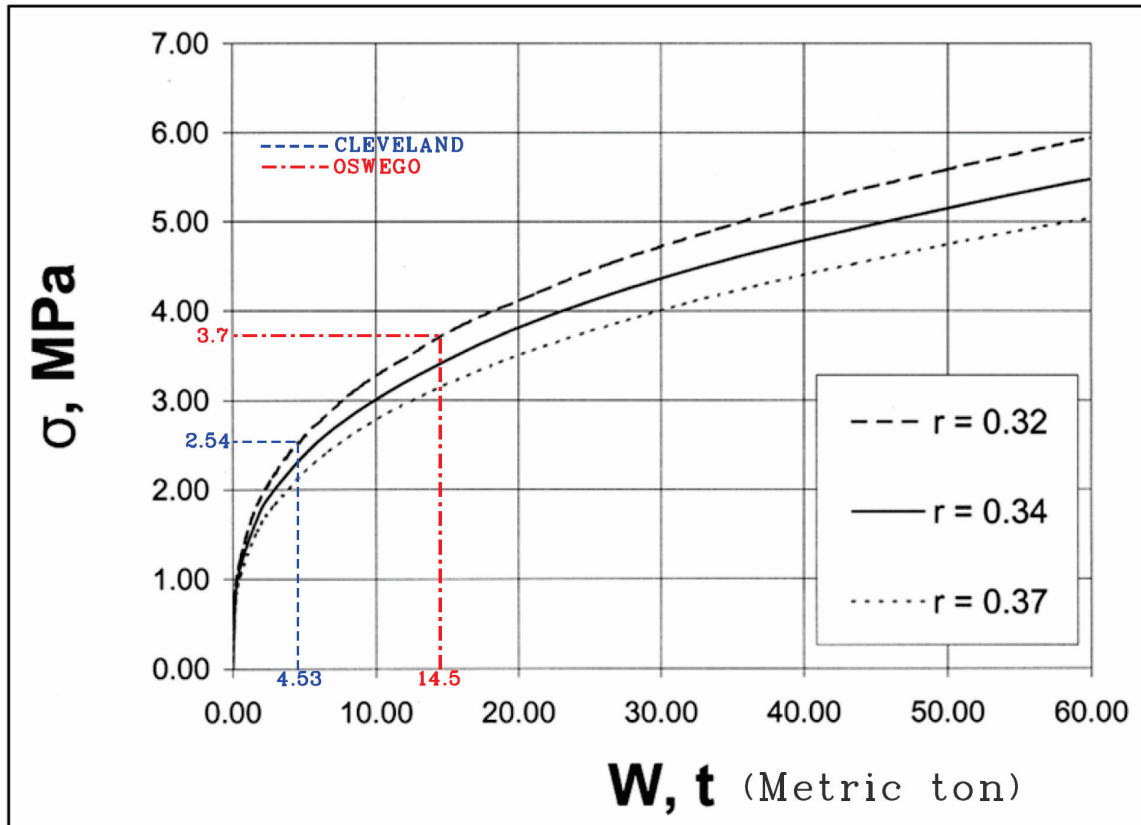
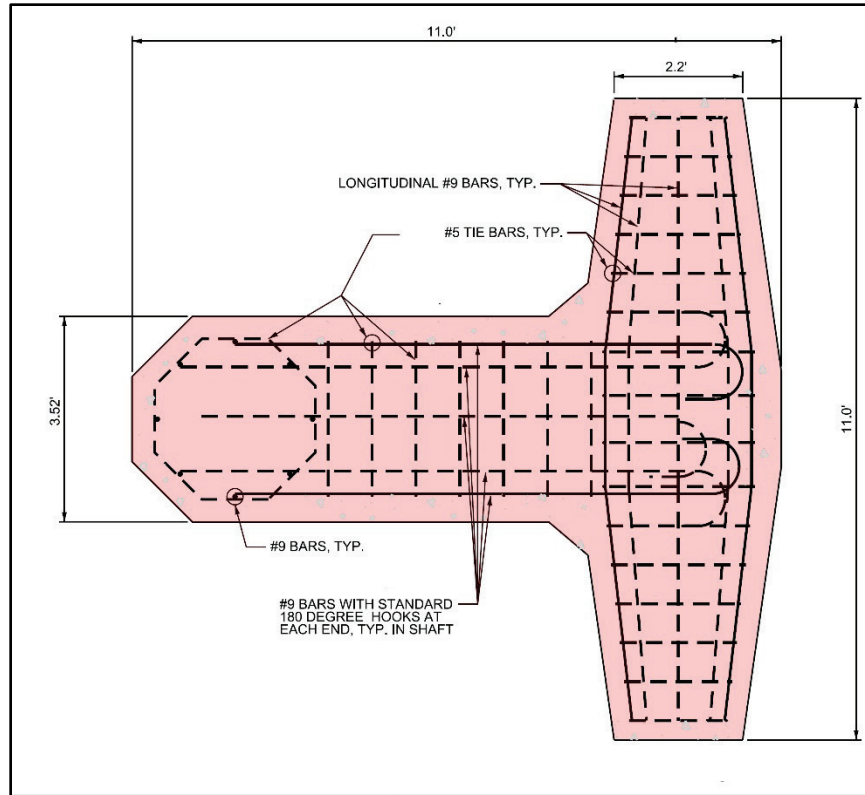


Figure 2-6. 16-ton dolos with steel reinforcement.



**Typical sections and scale models**

The typical repair sections for the dolos overlay for the Cleveland East Breakwater and the Oswego Detached Breakwater are presented in Figure 2-7 and Figure 2-8, respectively.

Figure 2-7. Cleveland East Breakwater typical repair section with 6.5-ton dolosse.

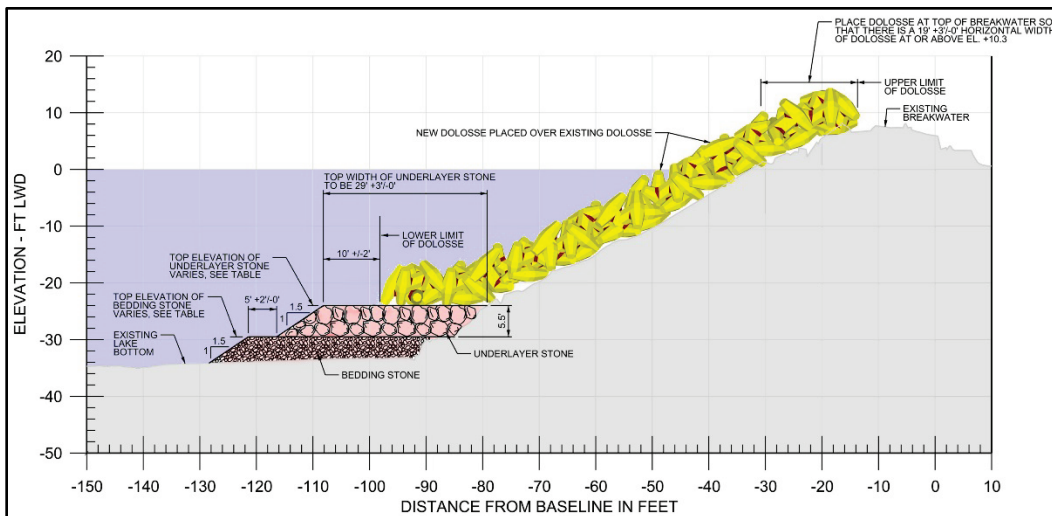
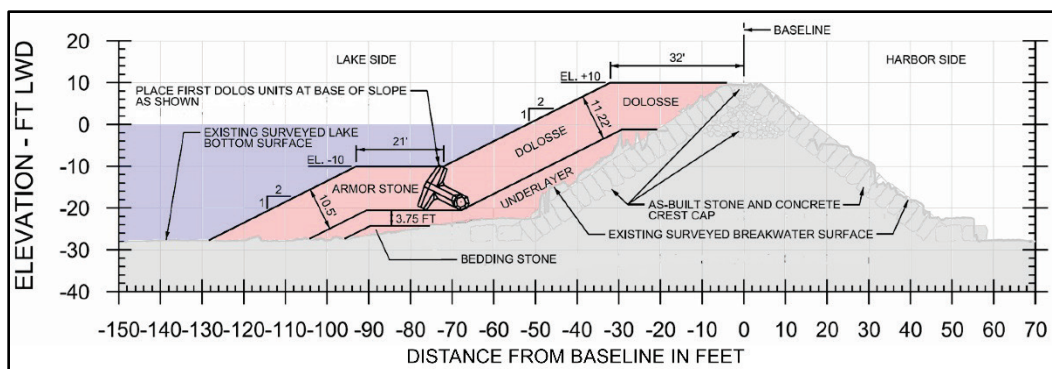


Figure 2-8. Oswego Detached Breakwater typical repair section with 16.0-ton dolosse.



The typical section for the Cleveland dolos overlay was based on the previously constructed dolos overlay. The existing dolosse provided a rough slope for the random placement of the new dolos overlay. This random placement encouraged proper interlocking of the new dolosse. The typical section for the Oswego dolos overlay is an initial placement over a laid-up stone breakwater. The laid-up stone posed as a concern for slope stability. The specific placement of the toe dolosse was to ensure a stable slope, and the proper interlocking of the remaining dolosse would occur.

As the use of dolos units is rare in the Great Lakes, it was deemed important to construct a scale model of the typical section for each project to acquaint the potential bidders with the proposed repair. The models were scaled based upon the number and size of available model dolosse supplied by ERDC. The Cleveland model used a sloping wooden surface at 1V:2H to represent the existing dolos surface, was approximately 40 in. long × 9 in. high × 16 in. wide, and was scaled at 1 in. = 2.455 ft. The Oswego model used an open box design approximately 30 in. long × 10.5 in. high × 13 in. wide, and was constructed using 0.5 in. thick medium density fiberboard with an 8 in. × 10 in. Lexan™ side viewing window, and was scaled at 1 in. = 4.889 ft. Selection of bedding, underlayer, and stone armor material was limited to prepackaged stone material from local home improvement centers, and while hand-sorting of the material was done to most closely scale the material, an approximate stone sizing was achieved. The dolosse models resided at the respective project office, allowing the contractors to deconstruct and reconstruct the model, giving them a better sense of the placement process and visually demonstrated that proper interlocking consists of touching at least two other dolosse. The Cleveland model is shown in Figure 2-9, and the Oswego model in Figure 2-10 and Figure 2-11.

Figure 2-9. Cleveland East Breakwater scale model.



Figure 2-10. Oswego Detached Breakwater scale model with viewing window, side view.

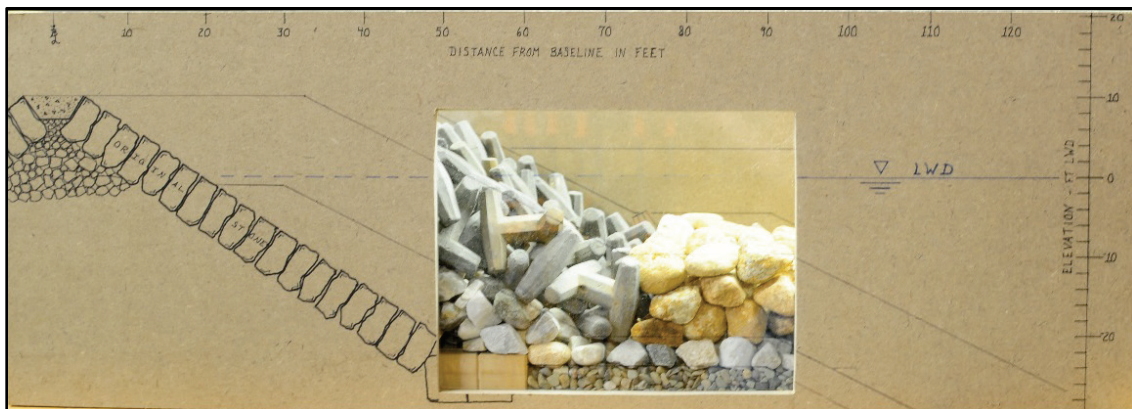


Figure 2-11. Oswego model, front view.



### 3 Dolos Construction Techniques

This section describes the minimum concrete requirements, the creation of the dolos forms, the making and testing of the dolosse, and their final placement (USACE 2014e, 2014f).

#### Contractor information

The contractors for the Cleveland East Breakwater 6.5-ton dolos repair were the following:

##### Dolos Forms and Test Dolos

Lindsay Concrete Products Company  
6845 Erie Avenue NW  
Canal Fulton, OH 44614  
[www.lindsayprecast.com](http://www.lindsayprecast.com)

##### Dolos Production

Allega Anthony Cement Contractor  
5585 Canal Rd  
Cleveland, OH 44125  
[www.allega.com](http://www.allega.com)

##### Dolos Placement

Great Lakes Dock and Materials, LLC  
1800 Lakeshore Drive  
Muskegon, MI 49441  
[www.greatlakesdock.com](http://www.greatlakesdock.com)

The contractors for the Oswego Detached Breakwater 16-ton dolos repair were the following:

##### Dolos Forms, Test Dolos, and Dolos Production

Lakelands Concrete Products, Inc.  
7520 E Main St  
Lima, NY 14485  
[www.lakelandsconcrete.com](http://www.lakelandsconcrete.com)

## Dolos Placement

Kokosing Construction Company  
 Durocher Marine Division  
 958 N Huron Street  
 Cheboygan, MI 49721  
[www.kokosing.biz](http://www.kokosing.biz)

## Minimum concrete requirements

It was required that the precast concrete producers were certified by the Precast/Prestressed Concrete Institute Plant Certification program prior to and during the production of the dolosse. The contractor was to select the mix proportions for normal weight concrete according to the minimum requirements in Table 3-1.

Table 3-1. Cleveland and Oswego minimum concrete requirements.

Parameter	Cleveland		Oswego	
28-Day Strength, $f'_c$	5,000 lb/in. <sup>2</sup>		5,000 lb/in. <sup>2</sup>	
28-Day Flexural Tensile Strength	500 lb/in. <sup>2</sup>		Not specified, since steel reinforced	
Weight	140 lb/ft <sup>3</sup>		145 lb/ft <sup>3</sup>	
Water-to-Cement Ratio	0.45 or less		0.45 or less	
Air Content	Nominal Maximum Aggregate Size, in.	Air Content, %	Nominal Maximum Aggregate Size, in.	Air Content, %
	0.38	6.0 to 9.0	0.38	6.0 to 9.0
	0.50	5.5 to 8.5	0.50	5.5 to 8.5
	0.75	4.5 to 7.5	0.75	4.5 to 7.5
	1.00	4.5 to 7.5	1.00	4.5 to 7.5
	1.50	4.5 to 7.0	1.50	4.5 to 7.0

## Dolos forms

As in any casting operation, the forms used must be robust (steel sufficiently thick to limit flexing) and reusable, must ensure complete filling with no air pockets or segregation of the concrete, and must allow easy extraction of the dolosse. This was especially true for the Cleveland project wherein a very large number of dolosse were required. To confirm the creation of a quality dolos, each contractor was required to produce a sample dolos. These dolosse were subjected to visual inspection, strength testing, and destructive testing.

The creation of the 6.5-ton dolos forms are presented in Figure 3-1, Figure 3-2, and Figure 3-3.

Figure 3-1. Constructing Cleveland 6.5-ton dolos forms.



Figure 3-2. Constructing Cleveland 6.5-ton dolos forms.



Figure 3-3. Completed Cleveland 6.5-ton dolos forms.



Figure 3-4 and Figure 3-5 present images of the forms for the Oswego 16-ton dolos. Note the presence of the external ribs for additional strength. Dolos steel reinforcement is seen in the form in the latter image.

Figure 3-4. Oswego Detached Breakwater 16-ton dolos form.



Figure 3-5. Oswego Detached Breakwater 16-ton dolos form.



Casting the dolos was accomplished by placing the concrete through the top of the form (vertical fluke end). Once cured, the dolos was removed by loosening the bolts and latches, opening the top horizontal fluke form flaps and the side wings, placing a strap around the shaft center, and lifting. This sequence, captured from videos<sup>1</sup> or still photos, is shown in Figure 3-6 through Figure 3-11. Note that yard handling of the Oswego 16-ton was accomplished by using a spreader beam of the straddle crane that attached to the precast eyes in the dolos (Figure 3-12).

<sup>1</sup> Faces of individuals are intentionally blurred to mask their identities.

Figure 3-6. Placing concrete for Cleveland 6.5-ton dolos.



Figure 3-7. Loosening bolts and opening latches on Cleveland 6.5-ton dolos form.



Figure 3-8. Opening Cleveland 6.5-ton dolos form fluke flaps.



Figure 3-9. Opening Cleveland 6.5-ton dolos form side wings.



Figure 3-10. Lifting Cleveland 6.5-ton dolos out of form.



Figure 3-11. Cleveland 6.5-ton dolos empty open form.



Figure 3-12. Lift method when moving Oswego 16-ton dolos.



After having made the sample dolos, the contractor cut the dolos (in the presence of a government representative) to check for voids and other imperfections in the following manner:

- Flukes from both ends were cut from the dolos at the shank.
- One fluke from each end was cut into three equal pieces cross-sectionally.
- The remaining flukes were cut in half, longitudinally.
- The shank was cut in half, cross-sectionally.
  - One half was cut into three equal parts, cross-sectionally.
  - The other half was cut in half, longitudinally.

Figure 3-13 and Figure 3-14 show a Cleveland 6.5-ton dolos being cut with a circular saw and an Oswego 16-ton dolos being cut with a wire saw, respectively. Photo inserts show a cut sample. For each project, the tests demonstrated that there was no segregation of aggregates, there were no large voids or air pockets within the mass, and for the 16-ton dolosse there was good concrete bond to the rebar.

Figure 3-13. Cutting Cleveland 6.5-ton dolos and cut sample.

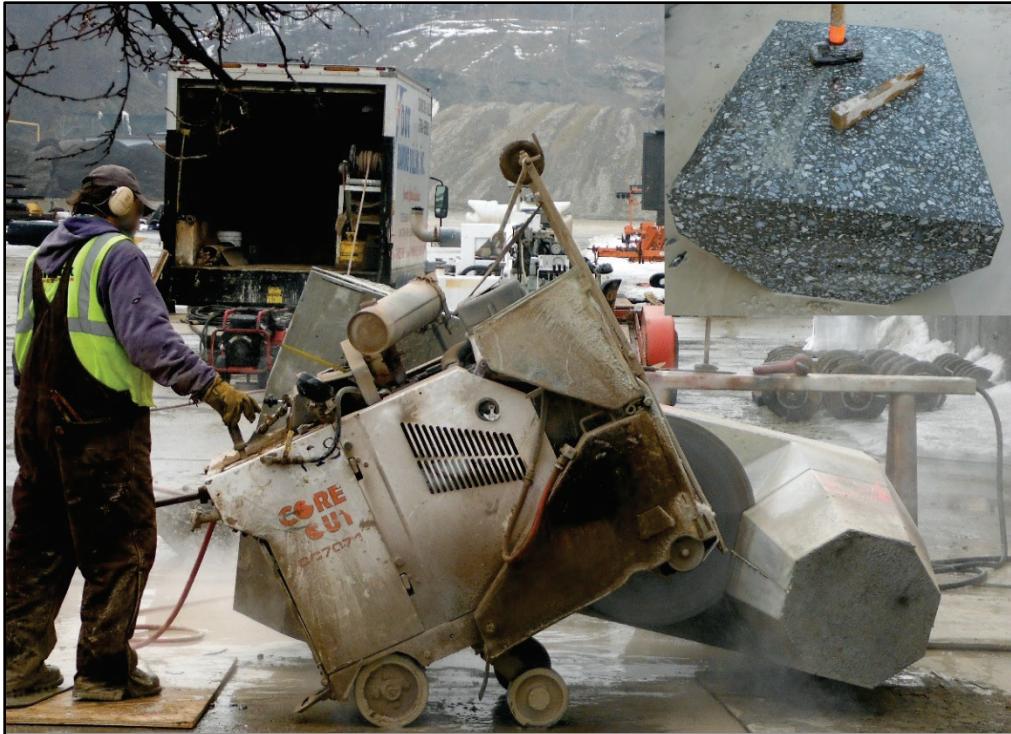


Figure 3-14. Cutting Oswego 16-ton dolos and cut sample.



## Dolos production

### Production rate

The Cleveland East Breakwater repair required the placement of 18,259 6.5-ton dolosse. To produce such a large number within the 2-year construction window, Allegra Concrete used 54 forms, and the dolosse were made outside in the Allegra Concrete yard. Concrete was mixed in 10.5 cubic yards (yd<sup>3</sup>) batches, filling approximately three forms per batch. The mix design was modified for the units to be safely removed from the forms each half day (12 hr). The yard space used to make and store the dolosse until they could be shipped was approximately 5.5 acres (Figure 3-15).

Figure 3-15. Ground view of Allegra Concrete forms and curing dolosse, June 2015.

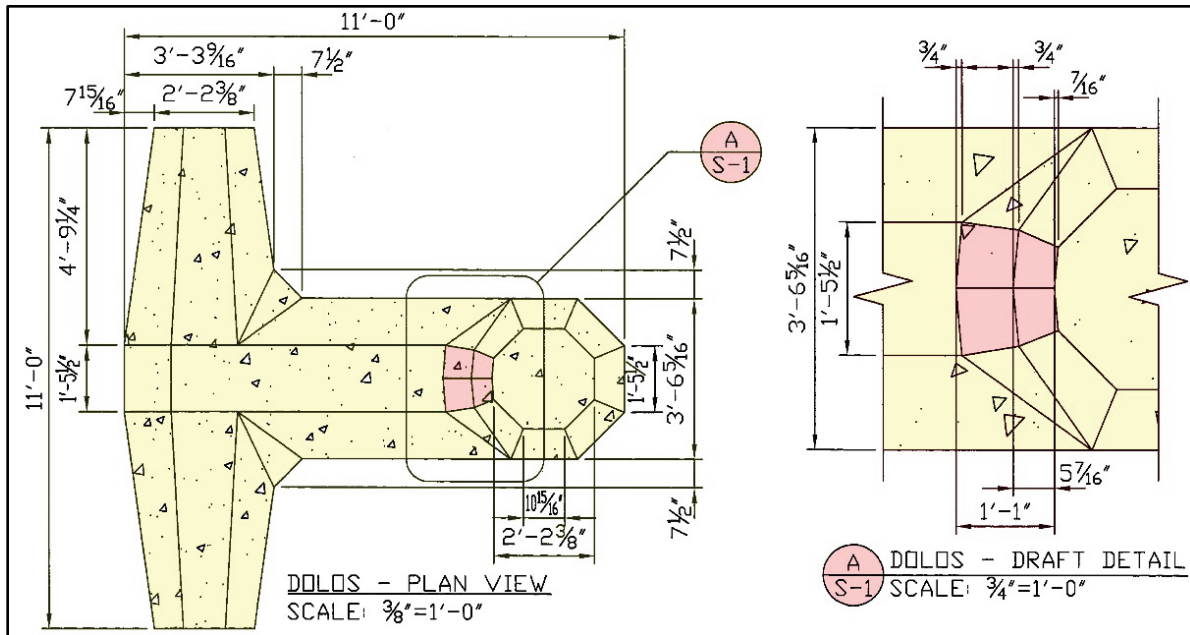


The Oswego Detached Breakwater required 973 16-ton dolosse. Lakelands Concrete chose to build the steel reinforcement cages and cast the dolosse inside the its plant using eight forms. The concrete mix was designed to allow the dolosse to be removed from the forms each day (24 hr), with the outside designated dolos storage area occupying approximately 2.5 acres (Figure 3-16). The contractor requested a slight change to the dolos shape by chamfering the inner facet of the vertical fluke (orientation when casting) to aid in the removal from the form, which added a slight addition of material (Figure 3-17).

Figure 3-16. Lakeland storage yard for Oswego 16-ton dolosse, February 2015.



Figure 3-17. Minor modification to Oswego 16-ton dolos shape.



## Concrete mix

The Anthony Allega Concrete Corporation formed the 6.5-ton dolosse for the Cleveland East Breakwater using the concrete mix presented in Table 3-2.

**Table 3-2. Cleveland 6.5-ton dolos concrete mix, 140 lb/ft<sup>3</sup>, no reinforcement.**

Material	Weight	Source
Cement	700 lb	St. Marys Type 1, St. Marys, ON, Canada
Fine Aggregate	1,290 lb	Natural sand, Shelly Materials, Mantua, OH
Coarse Aggregate - #8 Limestone	652 lb	Carmeuse Lime and Stone, Cedarville, MI
Coarse Aggregate - #57 Limestone	978 lb	Carmeuse Lime and Stone, Cedarville, MI
BASF Masterair AE 200 <sup>1</sup>	0.8 oz	N/A
BASF Masterglenium 7710 <sup>2</sup>	8.2 oz	N/A
Water	266 lb (31.9 gallons)	Local

<sup>1</sup>MasterAir AE 200 is an air entraining admixture, conforming to ASTM C260, that imparts improved resistance to damage from cyclic freezing and thawing. (Found at <https://www.master-builders-solutions.basf.us/en-us/products/masterair/1497>.)

<sup>2</sup>BASF Masterglenium7710 is an admixture that provides fast setting and high-early compressive strength development. MasterGlenium 7710 admixture meets ASTM C494 compliance requirements for Type A, water-reducing, and Type F, high-range water-reducing, admixtures. (Found at <https://www.master-builders-solutions.basf.us/en-us/products/masterglenium/1729>.)

Lakeland Concrete Corporation formed the 16-ton dolosse for the Oswego Detached Breakwater using the concrete mix presented in Table 3-3.

**Table 3-3. Oswego 16-ton dolos concrete mix, 150 lb/ft<sup>3</sup>, steel reinforcement.**

Material	Weight	Source
Cement	560 lb	Lafarge Type III, Bath, ON, Canada
Slag	140 lb	Lafarge, Stoney Creek, ON, Canada
Fine Aggregate	1,500 lb	Hanson Aggregates, Victor, NY
Coarse Aggregate (#1's)	1,410 lb	Hanson Aggregates, Victor, NY
ADVA 585 <sup>1</sup>	56 oz	W.R. Grace & Co., North Bergen, NJ
Daravair 1000 <sup>2</sup>	13.65 oz	W.R. Grace & Co., North Bergen, NJ
Water	275 lb (33.0 gallons)	Town of Lima, NY
Water/Cement Ratio	0.4	N/A

<sup>1</sup>ADVA® Cast 585 high-range water reducer imparts improved workability to the concrete (enhanced concrete cohesiveness with low viscosity for rapid placement) and to also achieve high early compressive strength. Meets requirements of ASTM C494 Type A and F admixture. (Found at <https://www.beyondconstruction.com/beyond-knowledge/article/grace-construction-adv-a-cast-575-14747.html>.)

<sup>2</sup>Daravair® 1000 is a liquid air-entraining admixture, conforming to ASTM C260, that provides freeze-thaw resistance, yield control, and finishability performance. (Found at <http://www.buildsite.com/pdf/wrgrace/Daravair-1000-Product-Data-447803.pdf>.)

## Concrete testing

Concrete was tested according to the schedule presented in Table 3-4.

Table 3-4. Concrete testing requirements.

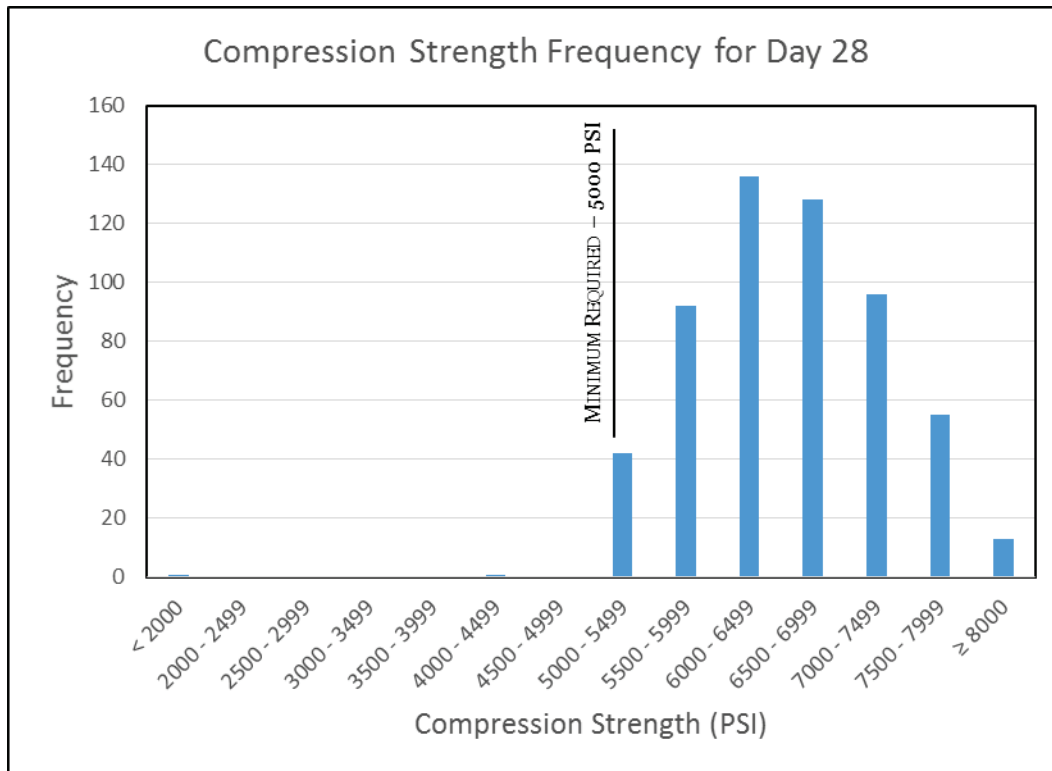
Test	Cleveland	Oswego
Slump – ASTM C143/C143M (ASTM 2012b)	Each 150 yd <sup>3</sup> of concrete produced or once a day.	Each 150 yd <sup>3</sup> of concrete produced or once a day.
Temperature – ASTM C1064/C1064M (ASTM 2011)	Test whenever slump, air, or compressive tests are made.	Test whenever slump, air, or compressive tests are made.
Compressive Strength – ASTM C31/C31M (ASTM 2012e); ASTM C192/C192M (ASTM 2012d); ASTM C39/C39M (ASTM 2012f)	Make at least four compressive strength specimens for each 150 yd <sup>3</sup> of concrete, but not less often than once per day.	Make at least four compressive strength specimens for each 150 yd <sup>3</sup> of concrete, but not less often than once per day.
Flexural Strength – ASTM C31/C31M (ASTM 2012e); ASTM C192/C192M (ASTM 2012d); ASTM C78/C78M (ASTM 2013)	Make at least four flexural strength specimens for each 150 yd <sup>3</sup> of concrete, but not less often than once per day.	N/A
Air Content – ASTM C231/C231M (ASTM 2010) or ASTM C173/C173M (ASTM 2012c)	Test each 150 yd <sup>3</sup> , but not less often than once per day.	Test each 150 yd <sup>3</sup> , but not less often than once per day.
Unit Weight – ASTM C138/C138M (ASTM 2012a)	Test a minimum of once per week to verify the yield of batch mixes.	Test a minimum of once per week to verify the yield of batch mixes.

For the Cleveland dolosse, so that the manufacturer could safely remove from the forms each half day (12 hr), the mix was modified to result in higher early strength. The resulting unit weight of 147 lb/ft<sup>3</sup> was slightly higher than the design unit weight of 140 lb/ft<sup>3</sup>, resulting in an actual dolos weight of 6.8 tons. The mean 28-day compressive strength of 6,562 lb/in.<sup>2</sup> was 130% of the minimum required. Table 3-5 presents the 28-day compressive strength descriptive statistics, and Figure 3-18 shows a histogram of the compressive strength results.

**Table 3-5. Cleveland dolos 28-day compressive strength test statistics.**

Mean	6,562
Standard Error	33
Median	6,549
Mode	6,980
Standard Deviation	777
Sample Variance	603,855
Kurtosis	4
Skewness	1
Range	7,564
Minimum	1,046
Maximum	8,610
Sum	3,701,051
Count	564

**Figure 3-18. Cleveland dolos 28-day compressive strengths.**



The actual mean 28-day flexural strength of 1,192 lb/in.<sup>2</sup> was more than double the minimum required tensile strength of 500 lb/in.<sup>2</sup>. Table 3-6 presents the 28-day compressive strength descriptive statistics, and Figure 3-19 is a histogram of the flexural strength results. Figure 3-20 presents a plot of actual measured flexural versus compressive strengths with the American Concrete Institute (ACI) equation also shown. Figure 3-21 presents a photo of the testing equipment with a failed specimen at 1,302 lb/in.<sup>2</sup>.

**Table 3-6. Cleveland dolos 28-day flexural strength test statistics.**

Mean	1,192
Standard Error	4
Median	1,197
Mode	1,244
Standard Deviation	104
Sample Variance	10,826
Kurtosis	4
Skewness	0
Range	980
Minimum	855
Maximum	1,836
Sum	674,686
Count	566

Figure 3-19. Cleveland dolos 28-day flexural strengths.

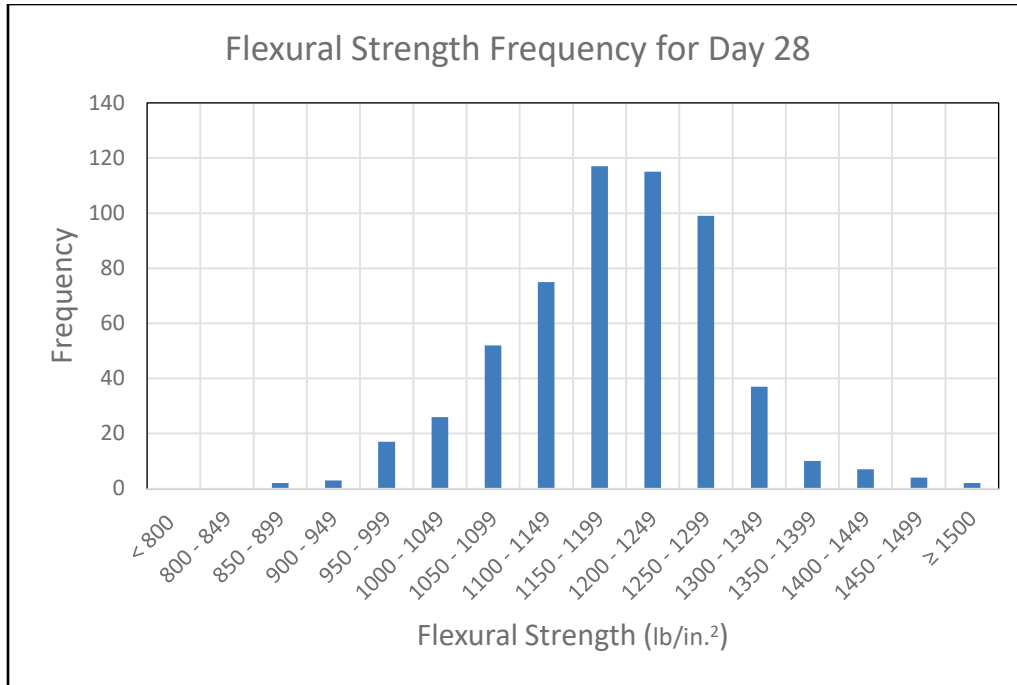


Figure 3-20. Cleveland dolos flexural versus compressive with comparison to ACI equation.

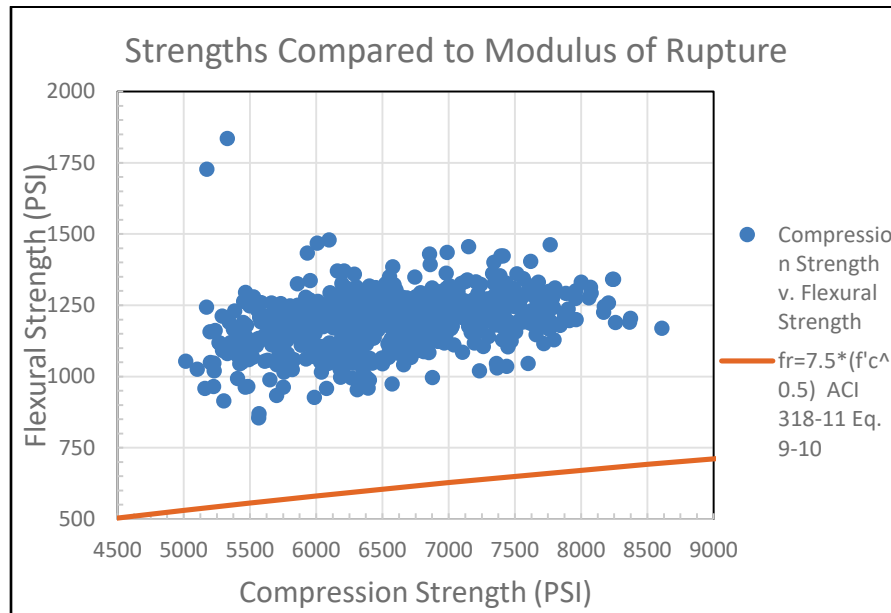


Figure 3-21. Cleveland dolos 28-day flexural strength test (sample failed at 1,302 lb/in.<sup>2</sup>).



For the Oswego dolosse, so that the manufacturer could safely remove from the forms each day (24 hr), the mix was modified to result in a higher early strength. This resulted in a unit weight of 143.2 lb/ft<sup>3</sup> for the concrete. For the 1-day compressive strengths, 26.7% of the tests were greater than the minimum required 28-day strength of 5,000 lb/in.<sup>2</sup>, 99.7% were greater than the minimum by the eighth day, and all test results were greater than the minimum requirement by 28 days. The testing apparatus could only measure to 7,003 lb/in.<sup>2</sup>, and 96.2% of the 28-day strengths were greater than that value. Note that the quality assurance testing, which could measure values above 7,003 lb/in.<sup>2</sup>, indicated an average 28-day compressive strength of 8,580 lb/in.<sup>2</sup>, with test results ranging from 7,735 lb/in.<sup>2</sup> to 9,690 lb/in.<sup>2</sup>. Table 3-7 and Table 3-8 present a summary of dolos strengths greater than 5,000 lb/in.<sup>2</sup> and 7,003 lb/in.<sup>2</sup>, respectively. The quality assurance tests results are presented in Figure 3-22.

Table 3-7. Oswego dolos compressive strength tests greater than 5,000 lb/in.<sup>2</sup>.

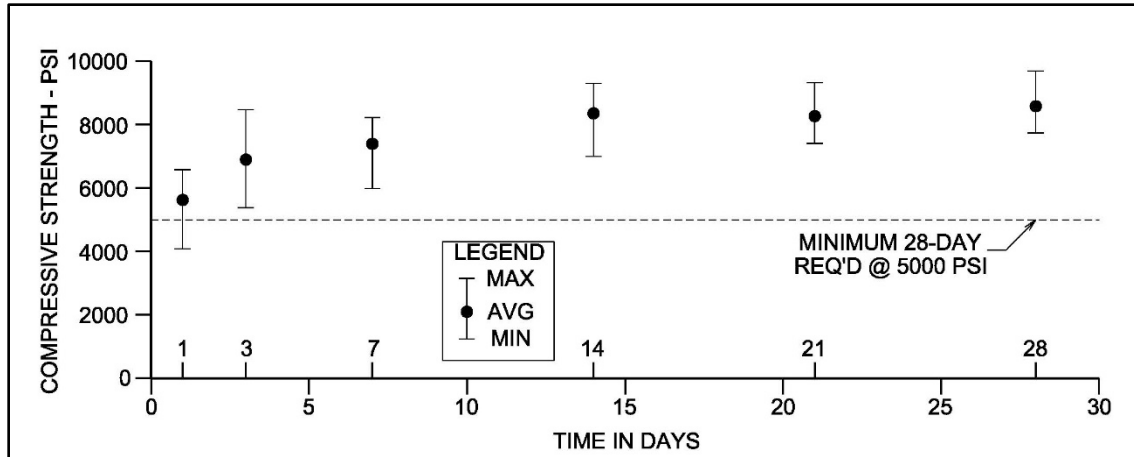
Days	Number of Tests >5,000 <sup>1</sup>	Cumulative Number of Tests >5,000	Total Number Tests	Cumulative Total Tests	Cumulative Tests >5,000, %
1	209	209	783	783	26.69
2	16	225	16	799	28.16
3	182	407	190	989	41.15
4	16	423	16	1005	42.09
5	4	4	4	24	
6	18	22	18	42	
7	912	934	914	956	
8	8	942	8	964	97.72
27	14	659	14	659	
28	356	1015	356	1015	100.00

Note: Tested on day 1, 2, 3, or 4; and 5, 6, 7, or 8; and 27 or 28.

Table 3-8. Oswego dolos compressive strength tests greater than 7,003 lb/in.<sup>2</sup>.

Days	Number of Tests >7,003	Cumulative Number of Tests >7,003	Total Number Tests	Cumulative Total Tests	Cumulative Tests >7,003, %
1	0	0	783	783	0
2	0	0	16	799	0
3	12	12	190	989	1.21
4	8	20	16	1005	1.99
5	4	24	4	24	
6	16	40	18	42	
7	604	644	914	956	
8	1	645	8	964	66.91
27	14	659	14	659	
28	317	976	356	1015	96.16

Figure 3-22. Oswego dolos quality assurance compressive test results.



**Dolos transportation**

The Cleveland dolosse were transported by flatbed truck approximately 11 miles from the manufacturer to Port of Cleveland (Figure 3-23) where they were temporarily stored awaiting loading onto the contractor’s barge. During this process, two dolosse were deemed unsuitable for placement, and two dolosse were broken in transit. Similarly, the Oswego dolosse were transported by flatbed truck approximately 90 miles from the manufacturer to the Port of Oswego (Figure 3-24) where they were temporarily stored awaiting loading onto the contractor’s barge.

Figure 3-23. Dolosse at Port of Cleveland, Ohio.



Figure 3-24. Dolosse at Port of Oswego, New York.



## 4 Dolos Placement Techniques

In addition to using quality materials, excellent placement is required to ensure a quality product. Since most of the dolos placement occurs underwater and is not visible, it was necessary to specify a method that would guarantee proper density, even distribution, and good interlocking (individual dolos orientation randomness) of the dolosse. Prior to full-scale placement operations, a 25 ft length of breakwater was completed as a test of the proper placement and maximum interlocking of the dolosse. The contractor was not allowed to proceed until the test area was completed and approved by the government.

### Dolos placement system

Each dolos had a number spray painted on it. The contractor was required to use an AUPPS when placing all dolosse. The system needed to combine Real Time Kinematic (RTK), Global Positioning System (GPS), and Global Navigation Satellite System (GLONASS) positioning technologies and attitude sensors to produce a three-dimensional (3D) image of the dolos units being placed in real time and be capable of guiding the crane operator to place dolosse in their designated positions with interlocking control. The system needed to be based on topography and not use acoustic communication or video. The system had to operate equally well above and under water to the same degree of accuracy, down to water depth in excess of 75 ft. There were to be no limitations when operating close to water surface. A 3D image of the unit in real time had to be simultaneously displayed on a monitor within the crane cab and on a wireless laptop away from the crane. The image resolution had to be constant and not affected by zooming. All viewing directions were to be possible. The complete armor unit placement and positioning system, including all components and software, had to be provided by a single company that had been manufacturing armor unit placement and positioning systems for a minimum of 5 years.

The AUPPS system basic requirements were that it contained, and integrated, the following:

1. A positioning reference station based on RTK, GPS, and GLONASS satellites.
2. A control and command system installed in the crane cabin.
3. A wireless laptop with WIFI communication.

4. A reference frame, including cables orientation, verticality and distance measurement.
5. One recoverable and reusable measurement module for attitude measurement of each armor unit.

Although there were other software alternatives available, such as CodaOctopus<sup>1</sup>, contractors for both projects selected the POSIBLOC™ system developed by MESURiS<sup>2</sup>, which met all of the aforementioned criteria, and is a topographical 3D system for optimum placement control of armor units above or below water. A recoverable attitude sensor (BIB [MESURiS term]) is attached to the armor unit prior to placement with three small plastic pins. The BIB has internal sensors and micro-controller software that has positional accuracy of 15 centimeters (cm) (5.9 in.) or  $h/12$ , whichever is greater ( $h$  = block height). Given dolos dimensions of 8.33 ft and 11 ft, the estimated positional accuracy is 8.3 in. and 11 in. for the Cleveland and Oswego dolosse, respectively. To recover the BIB after the unit has been placed, the quick release hook is activated, and the POSIBLOC sling removes the BIB from the dolos, following the lifting of the main sling (Mouquet 2009). During placement, the crane operator and the Placement Plan Control Specialist could see the 3D image of the unit being placed in real time in addition to seeing previously placed units and the target points for dolosse not yet placed. A position indicator showed the  $x$ ,  $y$ ,  $z$  differences between the real-time and target coordinates.

Coupled with the VISIBLOC™ software, each dolos trajectory was monitored and recorded, out-of-profile units detected, the placement density for any selected area determined, screenshots of dolosse in any direction generated, the center of gravity coordinates stored for each placed dolos unit along with attitude and conditions of placing (positioning quality, speed, first or last attitude selected), and the time and date stored for each dolos unit placed.

Figure 4-1 shows the general POSIBLOC system. Figure 4-2 is a typical view from the crane during the Oswego construction. Figure 4-3 is a closeup view of the operator's computer screen.

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<sup>1</sup> Coda Octopus Products Limited, 38 South Gyle Crescent, Edinburgh, EH12 9EB, UK, <http://www.codaoctopus.com/products/usehttp%3A>

<sup>2</sup> MESURiS, 37 rue de l'Océan - 56470 SAINT-PHILIBERT - FRANCE, <http://www.mesuris.com/en/systems-2/posibloc.html>

Figure 4-1. POSIBLOC system.

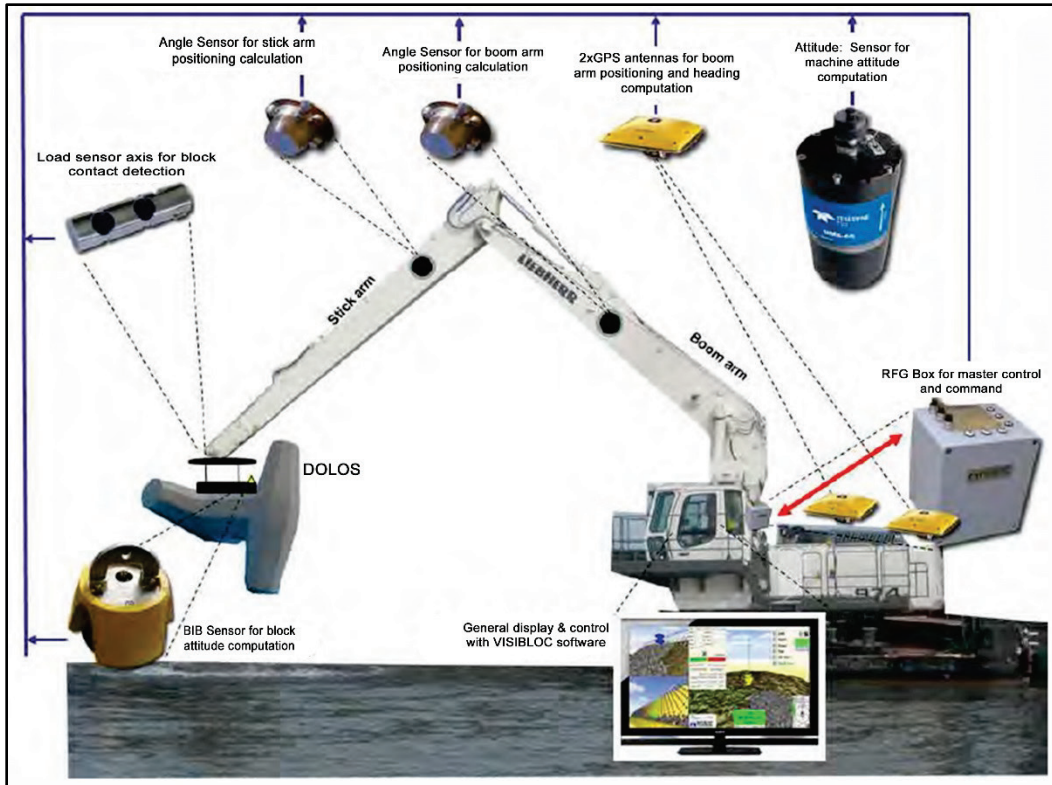


Figure 4-2. Crane operator's view of Oswego dolos placement.

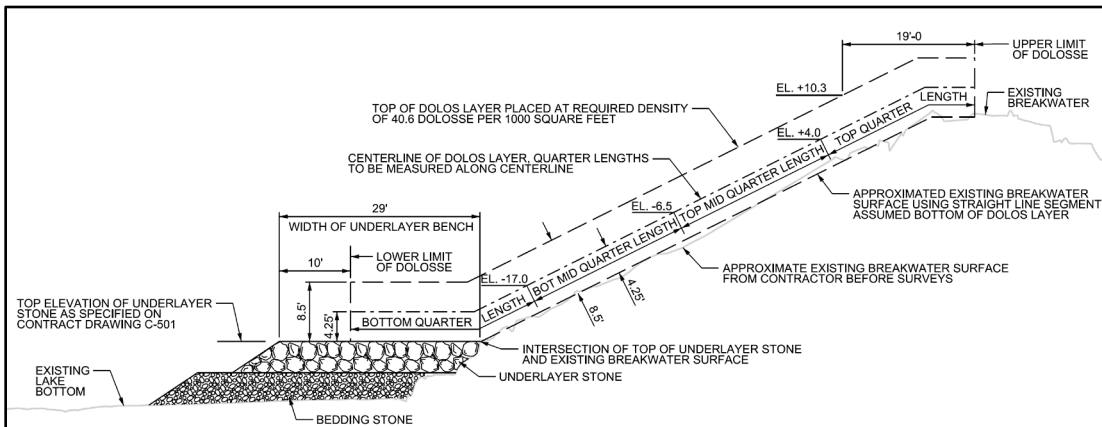


Figure 4-3. Crane operator’s view of computer screen during Oswego dolos placement.



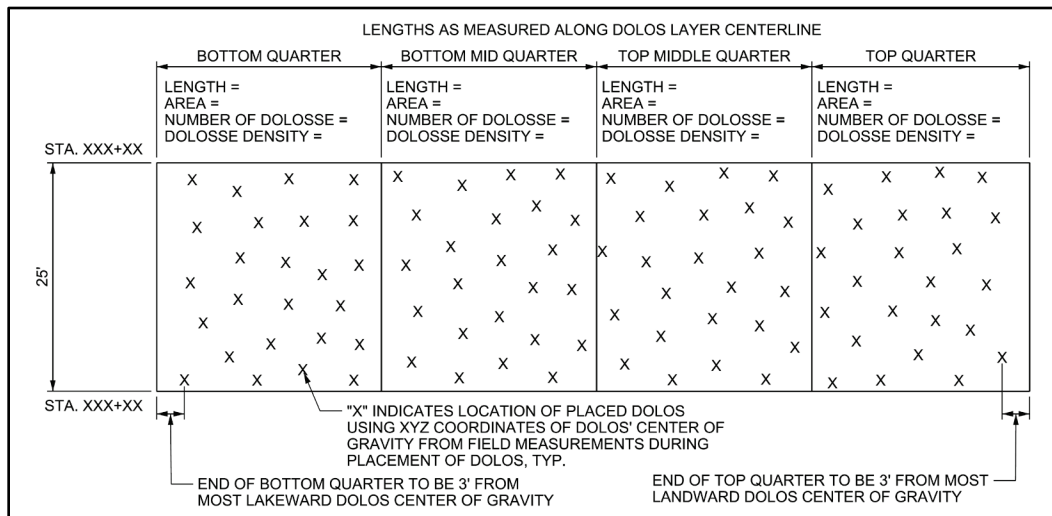
The contractors were also required to (1) use the provided EXCEL spreadsheet to determine the dolosse placed in each 25 ft length of breakwater by quarters, (2) track the number of placed dolosse and their coordinates, and (3) calculate the density of the placed dolosse. A separate table for each 25 ft length was updated daily and divided into quarters as shown in Figure 4-4.

Figure 4-4. Cleveland Breakwater repair section definition of estimated quarter lengths.



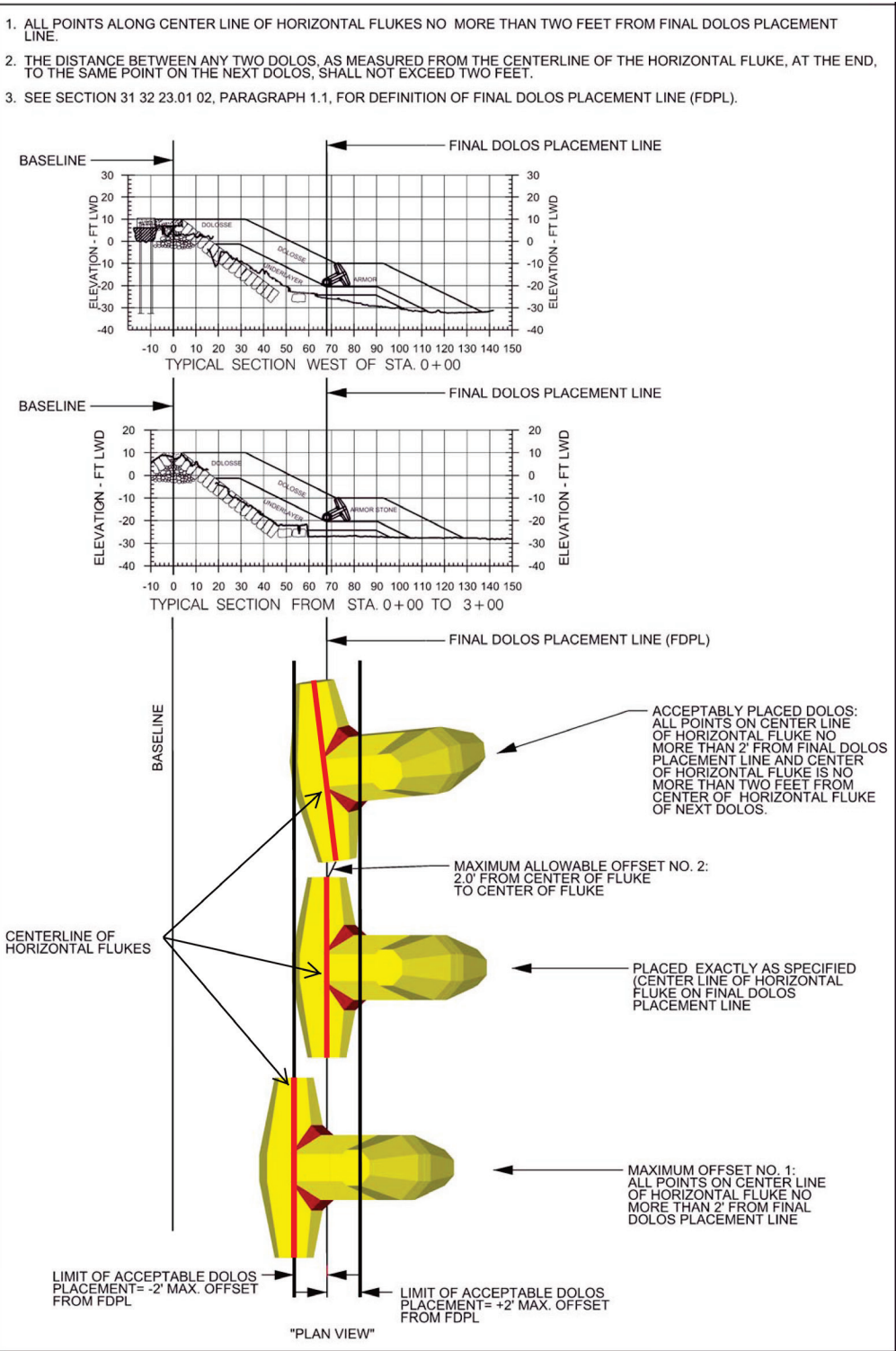
The contractor plotted each placed dolos daily as shown on the typical template presented in Figure 4-5. For Cleveland, the dolosse had to be placed at an average density of 40.6 per 1,000 ft<sup>2</sup> with a minimum density of 38.6 per 1000 ft<sup>2</sup>, but no more than a maximum of 42.6 per 1000 ft<sup>2</sup>. To ensure maximum interlocking, each quarter could not reach the required density until dolosse were placed at least 5 ft into the adjoining quarter (both within the 25 ft length and adjoining 25 ft lengths), where possible. As each quarter was completed, any dolos density outside of the acceptable dolos density tolerance was to be brought to the immediate attention of the government. Extreme limits of the density tolerance were not to be continuous over an area greater than 1000 ft<sup>2</sup>. If the density were below the tolerance, then the government could direct the contractor to place additional dolosse, at the contract bid item price. If the density were above the tolerance, then the extra dolosse placed would be at no cost to the government. For Oswego, the required density of dolosse was 23.3 dolosse per 1,000 ft<sup>2</sup> with a tolerance of  $\pm 1$  dolos per 1,000 ft<sup>2</sup>.

Figure 4-5. Cleveland plan of placed dolos centers of gravity.



Since the bottom row of Oswego dolosse were specially oriented to ensure slope stability, an additional requirement for placement tolerance was specified as illustrated in Figure 4-6.

Figure 4-6. Allowable offsets for the placement of the first row of Oswego dolosse.



The actual placement values for the bottom row of the Oswego dolosse are presented in Table 4-1.

Table 4-1. Oswego first-row placement descriptive statistics.

Statistic	Distance from End 1 and Final Dolosse Placement Line	Distance from End 2 and Final Dolosse Placement Line
Mean	1.016	1.283
Standard Error	0.099	0.105
Median	1.05	1.5
Mode	1.3	1.6
Standard Deviation	0.765	0.811
Sample Variance	0.585	0.657
Kurtosis	-0.653	-0.099
Skewness	0.197	-0.355
Range	3.3	4.0
Minimum	-0.6	-1.0
Maximum	2.7	3.0
Sum	60.93	77.0
Count	60	60

## Dolos placement equipment

Prior to placement of the dolosse, the BIB (sensor for block attitude computation) was calibrated on the first unit of the day to ensure the system was recording properly (Figure 4-7).

Figure 4-7. Calibrating BIB on Oswego dolos.



For the Cleveland dolosse, the contractor created a special lifting mechanism that used a hydraulic cam system to tighten and release the lifting cables. This unit also housed the BIB (Figure 4-8). For the lifting assembly to be placed at the same location on the dolos, the saddle (positioning jig) was first placed, and then the lifting mechanism was butted up against this template. Figure 4-9 through Figure 4-13 present a sequence of views captured from video that show a dolos being placed. Note the saddle in Figure 4-9, which is subsequently removed (Figure 4-10) once the lifting cables are taut.

Figure 4-8. Cleveland dolos lifting arrangement.

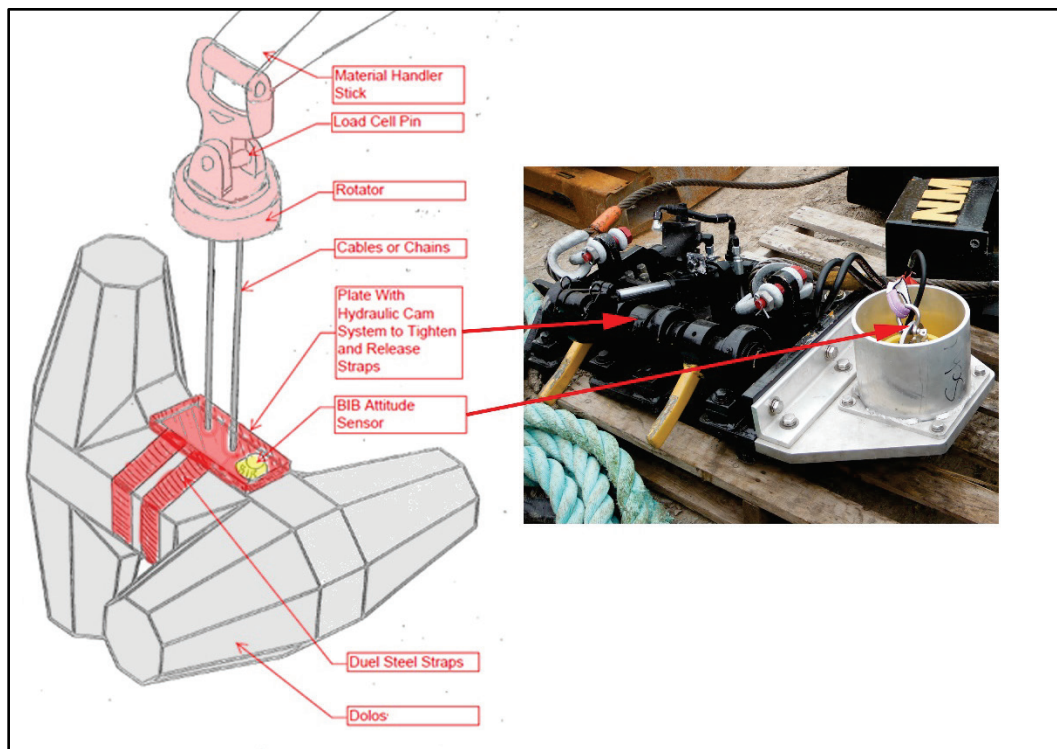


Figure 4-9. Aligning Cleveland dolos lifting mechanism with saddle (video time 0:00 minute:second [min:sec]).

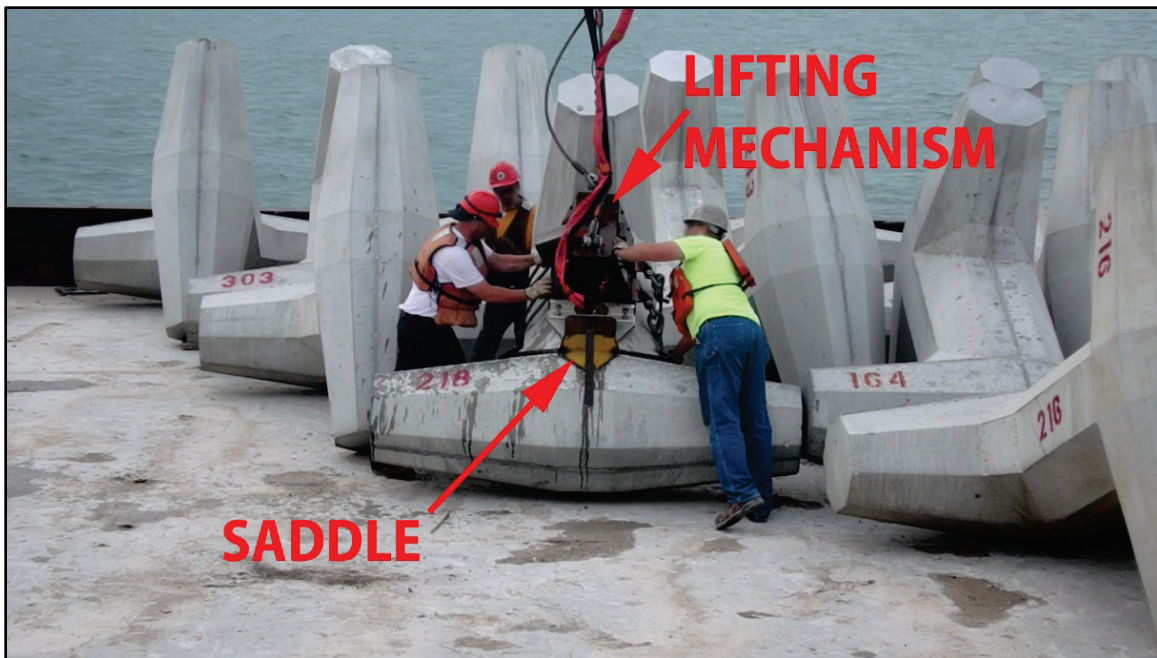


Figure 4-10. Removing saddle from Cleveland dolos prior to lifting (video time 0:21 min:sec).



Figure 4-11. Placing saddle from Cleveland dolos at toe of section (video time 1:32 min:sec).



Figure 4-12. Cleveland dolos lifting mechanism returns for next dolos (video time 4:17 min:sec).



Figure 4-13. Next Cleveland dolos is being lifted for placement (video time 5:39 min:sec).



In addition to the crane operator who was placing the dolosse, a Placement Plan Control Specialist was assigned to execute the placement plan by monitoring dolosse placement densities, updating the reporting form as dolos were being placed for each 25 ft length of repair, providing a geo-referenced properly scaled plan view electronic image showing all dolosse placed that day and any photographs taken, providing daily files for 3D viewing where all dolosse were placed, and performing any other duties that might increase productivity and quality of dolosse placement. During the Cleveland project, the specialist was seated adjacent to the crane operator and had his own computer screen showing placement of the dolosse (Figure 4-14).

Figure 4-14. Placing Cleveland dolos.



For the Oswego dolosse, the contractor elected to use cables with the BIB temporarily attached to the dolosse with plastic pins (Figure 4-15 and Figure 4-16).

Figure 4-15. Oswego dolos lifting arrangement.



Figure 4-16. Oswego dolos lifting arrangement.



Despite significant project planning and communication among parties to avoid unexpected complications during placement, a complication still arose. An unexpected problem with the Oswego AUPPS arose with the steel reinforcement within the dolosse interfering with the attitude sensor (electromagnetic compass) in the BIB, requiring the sensor to be calibrated for each unit to show actual pitch and roll. The contractor worked on solutions to insulate the BIB and finally settled on placing the BIB on a removable stanchion (riser pipe). This may be seen in Figure 4-16, center top photo. Due to the potential project delays from having to recalibrate the BIB on each dolosse, it was agreed to recalibrate only those at the base that formed the specially oriented toe. Despite this setback, the AUPPS accurately showed the center of gravity for density computation, and by placing the dolosse at random orientations, good interlocking was assured.

The contractor supplied laptops during the construction period to the government with the VISIBLOC software, which allowed for 3D visualization of the placed dolosse and confirmation of the placement, orientation, and density. Prior to the onset of construction, the contractor, the U.S. Army Corps of Engineers (USACE), and design personnel received training on the use of the VISIBLOC software from a MESURiS company

representative. During construction, USACE designers were given VISIBLOC software files for the actual placement of the dolosse so that dolos placement could be reviewed as construction progressed. Figure 4-17 through Figure 4-20 present a sequence of views captured from a VISIBLOC video, which shows a dolos being placed on the Cleveland East Breakwater. The upper-left menu presents the dolos information, the *current* position, the planned location, and the difference from the current and planned position of the dolos. The actual track that the dolos followed is shown by the white line. The dolos changed color depending upon the proximity to the target location. The view orientation could be changed using the menu in the upper right.

Figure 4-17. Cleveland dolos VISIBLOC placement view.

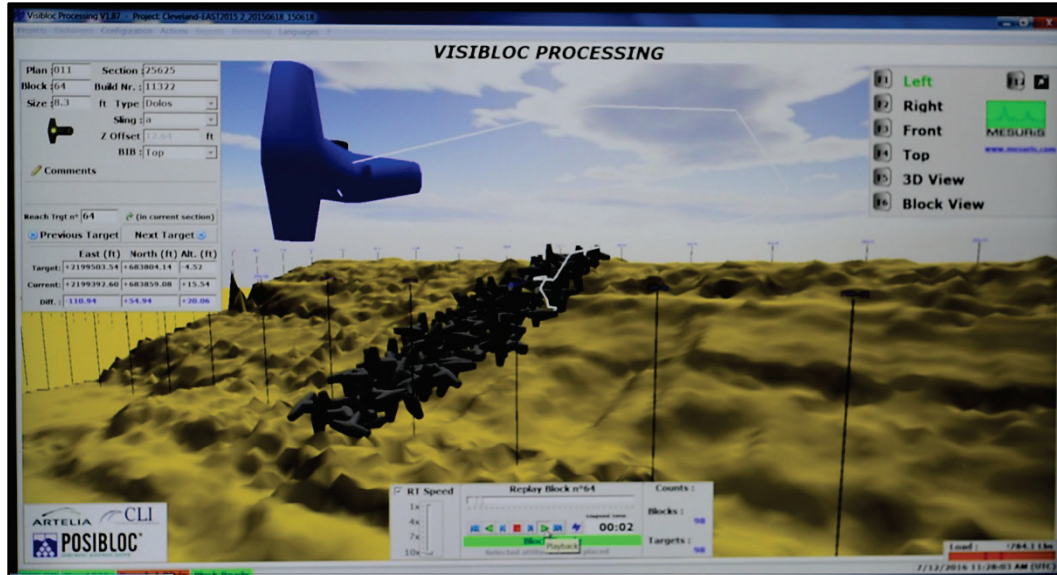


Figure 4-18. Cleveland dolos VISIBLOC placement view.

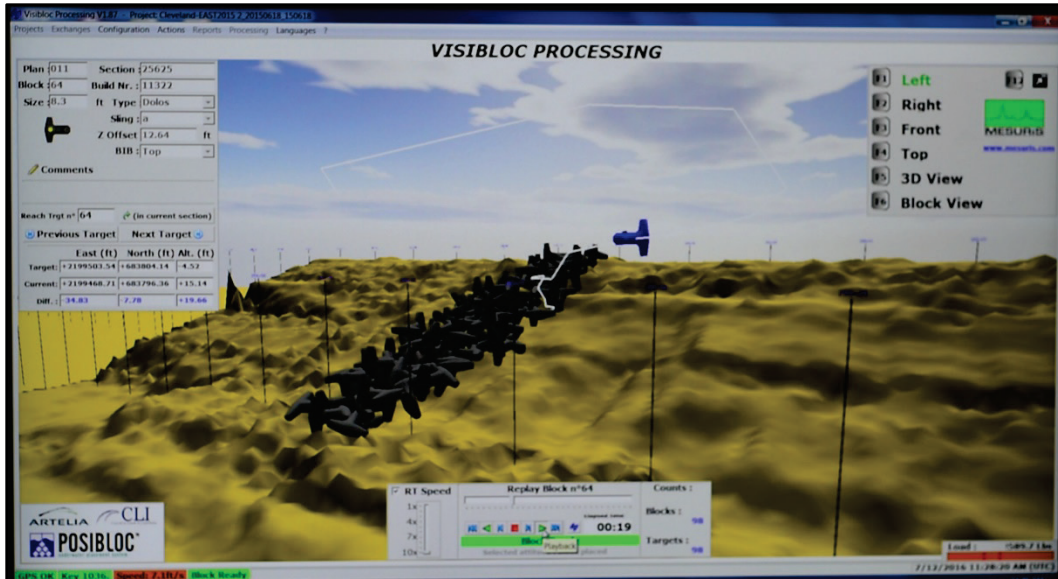


Figure 4-19. Cleveland dolos VISIBLOC placement view.

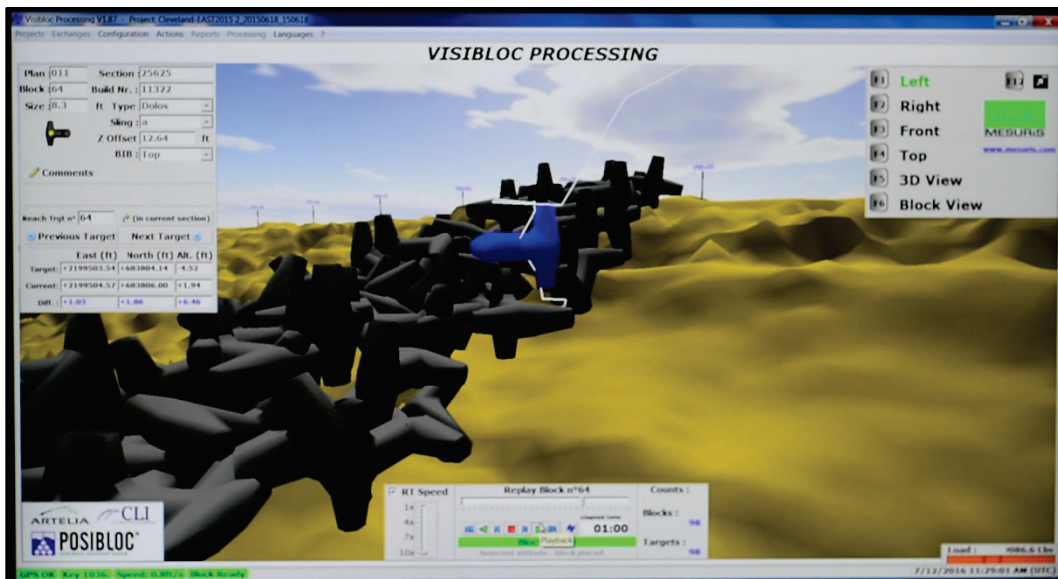
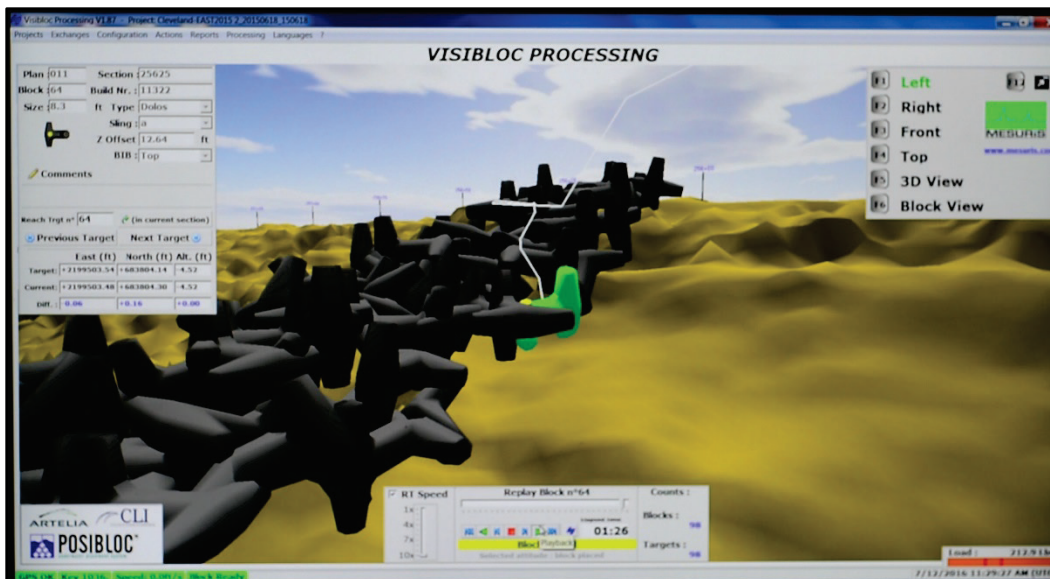


Figure 4-20. Cleveland dolos VISIBLOC placement view.



## Dolos placement rate

Mesuris<sup>1</sup> indicated that POSIBLOC allows placement of an average of 60 to 80 blocks every 10 hr whatever the size of the unit. The quality of placement is perfectly controlled, with no risk of removal for non-compliance. The system was reported to result in a reduction in the placement duration. USACE (2014e) states that the industry standard for full production placement rate for concrete armor is 8 units/hr, assuming that the contractor has no constraints. It was recommended to be conservative and assume 4 to 6 units/hr. Placement rate could be as slow as a few per day during the first week. Poor slinging technique is a hindrance. Releasing the dolos must be done so that the sling does not bind and then lift the unit. Chains tend to get stuck in the layer resulting in lifting on release. A claw-type apparatus also tends to bind. Fabric slings or wire ropes are the most common.

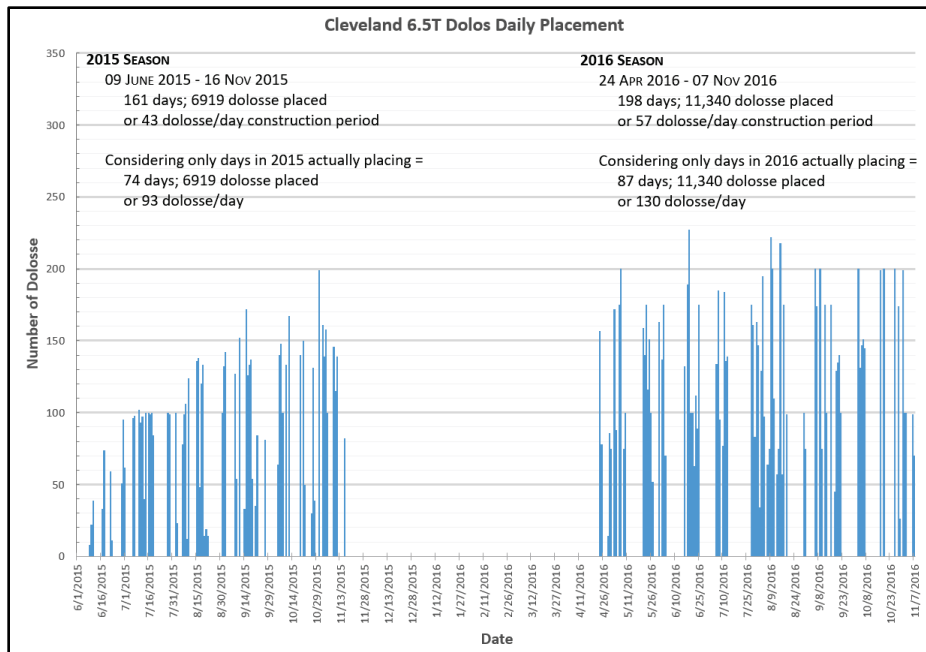
## Cleveland dolos placement rate

The Cleveland East Breakwater repair required the placement of 18,259 6.5-ton dolosse, which occurred over two construction seasons. Minimal breakage during handling and placement occurred and resulted in only four dolosse to be deemed unsuitable. During the 2015 season, 09 June to 16 November, which spanned 161 calendar days, 6,919 dolosse were placed

<sup>1</sup> MESURIS, 37 rue de l'Océan - 56470 SAINT-PHILIBERT – FRANCE,  
<http://www.mesuris.com/en/systems-2/posibloc.html>

for an average of 43 dolosse/day. However, during that time period, the contractor placed dolosse only during 74 of those days suggesting an average rate of 93 dolosse/day. During the 2016 season, 24 April to 07 November, which spanned 198 calendar days, 11,340 dolosse were placed for an average of 57 dolosse/day. However, during that time period, the contractor placed dolosse only during 87 of those days suggesting an average rate of 130 dolosse/day. The minimum placement rate occurred on the first day when only 8 dolosse were placed, and the maximum placement occurred when 227 dolosse were placed. Figure 4-21 presents the daily placement rate. Table 4-2 presents the Cleveland dolos daily placement rate descriptive statistics.

Figure 4-21. Cleveland 6.5-ton dolos placement rate.



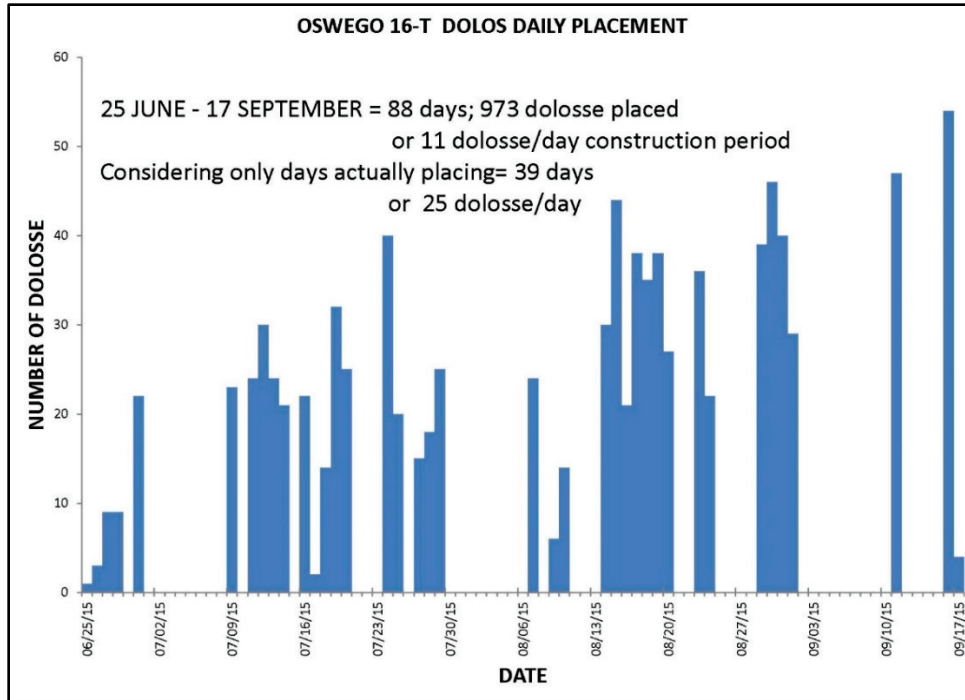
**Table 4-2. Cleveland 6.5-ton dolos daily placement rate statistics.**

Mean	113
Standard Error	4
Median	100
Mode	100
Standard Deviation	52
Sample Variance	2,756
Kurtosis	-1
Skewness	0
Range	219
Minimum	8
Maximum	227
Sum	18,214
Count	161

### **Oswego dolos placement rate**

The Oswego Detached Breakwater repair required the placement of 973 16-ton dolosse during one construction season. During the period 25 June to 17 September 2015, which spanned 88 calendar days, 973 dolosse were placed for an average of 11 dolosse/day. However, during that time period, the contractor placed dolosse only during 39 of those days, suggesting an average rate of 25 dolosse/day. The minimum placement rate occurred on the first day when only 1 dolos was placed, and the maximum placement occurred on the next-to-last day when 54 dolosse were placed. Figure 4-22 presents the daily placement rate.

Figure 4-22. Oswego 16-ton dolos placement rate.



## 5 Summary

### Background

Hurricane Sandy caused extensive damage to federal harbor structures on the Great Lakes. Extensive damage occurred along the eastern 4,400 ft of the Cleveland East Breakwater on Lake Erie, which had been repaired between 1979 and 1980 with 2-ton dolos armor units. Damage also occurred on the 850 ft Oswego Detached Breakwater on Lake Ontario, which is a laid-up cut stone structure built in 1958–1960. Dolosse were selected to repair both structures due to the presence of dolos on the Cleveland East Breakwater and the large design wave for the Oswego Detached Breakwater.

### Dolos design

The Cleveland East Breakwater repair called for the placement of 18,259 6.5-ton unreinforced dolosse. To produce such a large number within the 2-year construction window, 54 forms were used. The mix design was modified to allow the units to be safely removed from the forms each half day (12 hr).

The Oswego Detached Breakwater required 973 16-ton steel reinforced dolosse. The steel reinforcement cages and casting of the dolosse were done inside using 8 forms. The concrete mix was designed to allow the dolosse to be removed from the forms each day (24 hr). The contractor requested a sight change to the dolos shape by chamfering the inner facet of the vertical fluke (orientation when casting) to aid in the removal from the form.

As the use of dolos units is rare in the Great Lakes, it was deemed important to construct a scale model of the typical section for each project to acquaint the potential bidders with the proposed repair. The models were scaled based upon the number and size of available model dolosse supplied by ERDC. The models resided at the respective project office, allowing the contractors to deconstruct and reconstruct the model, giving them a better sense of the placement process and visually demonstrating proper interlocking.

## Dolos production

Prior to full production, the contractors were required to confirm the creation of a quality dolos, by producing sample dolosse. These dolosse were subjected to visual inspection, strength testing, and destructive testing.

For the Cleveland dolosse, for the manufacturer to safely remove the dolosse from the forms each half day (12 hr), the mix was modified to result in higher early strength. The mean 28-day compressive strength of 6,562 lb/in.<sup>2</sup> was 130% of the minimum required. The actual mean 28-day flexural strength of 1,192 lb/in.<sup>2</sup> was more than double the minimum required tensile strength of 500 lb/in.<sup>2</sup>. The resulting unit weight of 147 lb/ft<sup>3</sup> was slightly higher than the design unit weight of 140 lb/ft<sup>3</sup>, resulting in an actual dolos weight of 6.8 tons.

For the Oswego dolosse, for the manufacturer to safely remove from the forms each day (24 hr), the mix was modified to result in a higher early strength. For the 1-day compressive strengths, 26.7% of the tests were greater than the minimum required 28-day strength of 5,000 lb/in.<sup>2</sup>, 99.7% were greater than the minimum by the eighth day, and all test results were greater than the minimum requirement by 28 days. The quality assurance testing indicated an average 28-day compressive strength of 8,580 lb/in.<sup>2</sup>, with test results ranging from 7,735 to 9,690 lb/in.<sup>2</sup>.

## Dolos placement

In addition to using quality materials, excellent placement is required to ensure a quality project. Since most of the dolos placement occurs underwater and is not visible, it was necessary to specify a method that would guarantee proper density, even distribution, and good interlocking (individual dolos orientation randomness) of the dolosse. Prior to full-scale placement operations, a 25 ft length of breakwater was completed as a test of the proper placement and maximum interlocking of the dolosse.

Contractors for both projects used the POSIBLOC system developed by MESURiS, which is a topographical 3D system for optimum placement control of armor units above or below water. The system combines RTK, GPS, and GLONASS positioning technologies and attitude sensors to produce a 3D image of the dolos units being placed in real time and was capable of guiding the crane operator in placing dolosse in their designated

positions with interlocking control. A recoverable attitude sensor (BIB) was attached to the armor unit prior to placement with three small plastic pins. During placement, the crane operator and the Placement Plan Control Specialist could see the 3D image of the unit being placed in real time, in addition to being able to see previously placed units and the target points for dolosse not yet placed. A position indicator showed the  $x$ ,  $y$ ,  $z$  differences between the real-time and target coordinates.

Coupled with the VISIBLOC software, each dolos trajectory was monitored and recorded, out-of-profile units detected, the placement density for any selected area determined, screenshots of dolosse in any direction generated, the center of gravity coordinates stored for each placed dolos unit along with attitude and conditions of placing (positioning quality, speed, first or last attitude selected), and the time and date were stored for each dolos unit placed.

The Cleveland East Breakwater repair occurred over two construction seasons. During the 2015 season, 09 June to 16 November, the contractor placed 6,919 dolosse during 74 of those days, suggesting an average rate of 93 dolosse/day. During the 2016 season, 24 April to 07 November, the contractor placed 11,340 dolosse during 87 of those days, suggesting an average rate of 130 dolosse/day. The minimum placement rate occurred on the first day when only 8 dolosse were placed, and the maximum placement occurred when 227 dolosse were placed. Breakage of dolos units was minimal during the handling and placement and resulted in four dolosse to be unsuitable.

The Oswego Detached Breakwater repair occurred over one construction season. During the 2015 season, 25 June to 17 September, the contractor placed 973 dolosse during 39 of those days, suggesting an average rate of 25 dolosse/day. The minimum placement rate occurred on the first day when only 1 dolos was placed, and the maximum placement occurred on the next-to-last day when 54 dolosse were placed.

## **Lessons learned**

An unexpected problem with the Oswego AUPPS arose with the steel reinforcement within the dolosse interfering with the attitude sensor (electromagnetic compass) in the BIB, requiring the sensor to be calibrated for each unit to show actual pitch and roll. The contractor worked on solutions to insulate the BIB and finally settled on placing the

BIB on a removable stanchion (riser pipe). Due to the potential project delays from having to recalibrate the BIB on each dolosse, it was agreed to recalibrate only those at the base that formed the specially oriented toe. Knowing this, an alternative placement method using multibeam sonar and lidar in combination with the CodaOctopus software that created an image of the dolos using three axial points ( $x, y, z$ ) may have been more appropriate for placement. Despite this setback, the AUPPS accurately showed the center of gravity for density computation, and by placing the dolosse at random orientations, good interlocking was assured.

### **Future monitoring recommendations**

To correlate the degree of settlement, tilting, and rocking of each dolos under environmental forces to which it will be subjected, periodic surveys of the Cleveland East Breakwater and the Oswego Detached Breakwater repairs should be conducted on a 3- to 5-year interval. This will provide data for predicting future dolos movement to estimate remaining useful life of the structure, based on the probability of future storm events as projected from historical events. The time-dependent damage modeling approach being developed by the MCNP Work Unit “Reliability Analysis of Coastal Structures” allows for the assessment of structure performance throughout the structure lifetime for a wide range of forcing and design conditions, knowledge that is of particular interest for asset-management funding prioritization.

Recently developed technology and acquisition system allows for obtaining high resolution lidar terrain data coincident with red, green, and blue imagery utilizing an unmanned aerial system that is capable of acquiring high-resolution 3D topography. A high-resolution point cloud consisting of billions of points can be generated with an accuracy of 2 cm. The ability of an unmanned lidar survey system to make multiple passes and approach from various angles enables the data collection to fill in data *shadows* that previously have occurred during tripod lidar surveys (TLS) of breakwaters due to the stationary, down-looking vantage point of the TLS instrument from the top of the breakwaters.

## References

- ASTM International (ASTM). 2010. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. C231/C231M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2011. *Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete*. C1064/C1064M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012a. *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. C138/C138M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012b. *Standard Test Method for Slump of Hydraulic-Cement Concrete*. C143/C143M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012c. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*. C173/C173M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012d. *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. C192/C192M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012e. *Standard Practice for Making and Curing Concrete Test Specimens in the Field*. C31/C31M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2012f. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. C39/C39M. West Conshohocken, PA: American Society for Testing Materials.
- ASTM. 2013. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. C78/C78M. West Conshohocken, PA: American Society for Testing Materials.
- Burcharth, H. F., and Z. Liu. 1992. "Design of Dolos Armour Units." In *Proceedings of the 23rd International Coastal Engineering Conference*. American Society of Civil Engineers (1): 1053–1066.
- Carver, R. D. and M. S. Heimbaugh. 1989. *Stability of Stone and Dolos-Armored Rubble-Mound Breakwater Heads Subjected to Breaking and Nonbreaking Waves with No Overtopping*. Technical Report CERC-89-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Hudson, R. Y. 1958. *Design of Quarry-Stone Cover Layers for Rubble-Mound Breakwaters: Hydraulic Laboratory Investigation*. Research Report 2-2. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

- Lin, L., Z. Demirebilek, H. Mase, J. Zheng, and F. Yamada. 2008. *CMS-Wave: A Nearshore Spectral Wave Processes Model for Coastal Inlets and Navigation Projects*. ERDC/CHL TR-08-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Mouquet, A. 2009. "Armour Unit Placement and Positioning in 3D Real Time." In *Coast, Marine Structures, and Breakwaters*. Rennes, France: Mesuris Marine Systems.
- U.S. Army Corps of Engineers (USACE). 1984. *Shore Protection Manual*. 4<sup>th</sup> Edition. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- USACE. 1993. *Design Water Level Determination on the Great Lakes*. Detroit, MI: U.S. Army Corps of Engineers.
- USACE. 2011. *Coastal Engineering Manual*. Part VI, Chapter 5, "Fundamentals of Design." EM 1110-2-1100. Vicksburg, MS: U.S. Army Corps of Engineers. <https://www.publications.usace.army.mil/LinkClick.aspx?fileticket=uvxhTbX2AhA%3d&tabid=16439&portalid=76&mid=43544>.
- USACE. 2014a. *Wave Information Study*. Vicksburg, MS: U.S. Army Engineer Research and Development Center. <http://wis.usace.army.mil/hindcasts.shtml?dmn=lakesWIS>.
- USACE. 2014b. *Cleveland Harbor, Ohio East Breakwater Repair (Dolosse Section) due to Damage Caused by Superstorm Sandy; Appendix A, Coastal Engineering*. Buffalo, NY: U.S. Army Corps of Engineers.
- USACE. 2014c. *Oswego Harbor Detached Breakwater, NY Repairs Due to Damage Caused by Superstorm Sandy; Appendix A, Coastal Engineering*. Buffalo, NY: U.S. Army Corps of Engineers.
- USACE. 2014d. *Oswego Harbor Detached Breakwater, NY Repairs Due to Damage Caused by Superstorm Sandy; Appendix B, Structural Engineering*. Buffalo, NY: U.S. Army Corps of Engineers.
- USACE. 2014e. *Cleveland Harbor FY14 East Breakwater Repair (Dolosse): Cleveland, Ohio; Documents, Plans, and Specifications*. W912P4-14-B-0012. Buffalo, NY: U.S. Army Corps of Engineers.
- USACE. 2014f. *Oswego Harbor FY14 Detached Wall Repair (Stone and Dolosse): Oswego, New York; Plans and Specifications*. W912P4-14-C-0021. Buffalo, NY: U.S. Army Corps of Engineers.

# REPORT DOCUMENTATION PAGE

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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> After traveling up the eastern U.S. coastline, Hurricane Sandy made landfall on 29 October 2012 near Atlantic City, NJ, with winds of 80 mph. The backside of the storm moved inland, bringing high winds and rain far into the nation's interior. No longer a hurricane, but termed Superstorm Sandy, the winds were generally from the north over the Great Lakes, extending as far west as Lake Michigan, causing extensive damage to several federal harbor structures especially in the Lower Great Lakes, including Cleveland East Breakwater on Lake Erie and Oswego Detached Breakwater on Lake Ontario. Concrete dolos armor units were selected to repair damage on these two structures. During 2015, 6,919 6.5-ton unreinforced dolosse were placed, and an additional 11,340 dolosse were placed in 2016 on the Cleveland East Breakwater. During 2015, 973 16-ton steel-reinforced dolosse were placed on the Oswego Detached Breakwater. The dolos design process, creation of the forms, strength testing, and placement are described and documented. Knowledge gained from this initial placement and from future periodic monitoring will correlate dolos movement with environmental forces. This information will be used for reliability analysis of coastal structures in determining remaining useful life for asset-management funding prioritizations.					
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