# REMR Technical Note CO-RA-1.2

# Concrete Armor Unit Performance Survey

## Introduction

In 1992, the Coastal Engineering Research Center, Waterways Experiment Station, began conducting routine performance and breakage surveys of US concrete armored structures, as listed in Table 1. The surveys consist of field inspections with the types and locations of armor breakage documented and logged on previously made aerial photographs.

## Purpose and Objectives

The purpose of the surveys is to document performance of concrete armor, verify and expand recently developed armor design guidance, and refine guidance on concrete armor construciton practices. The survey objectives are (a) to gain insight into concrete armor unit (CAU) failure mode and causal relationships; (b) to evaluate gross structural elements in order to identify critical areas of the breakwaters; and (c) to compare breakage counts to a previous survey conducted at several sites in 1983, with an intent to establish trends for use in design of rehabilitations and evaluation for repair.

## Survey Findings

Seven structures have been surveyed to date. Both dolos and tribar CAUs were inspected. Dolos sizes range from 2 to 42 tons, and tribar sizes range from 6 to 50 tons. Both reinforced and unreinforced CAUs are in service on these structures.

### Unit failure

One component of the study was to assess armor unit failure modes by cataloging all in situ broken armor units.

a. *Dolos failures*. The failure modes for broken dolosse were categorized as either flexure or torsion dominated. Figure 1 shows the percentage of the total failures that were either torsion- or flexure-dominated. As this graph indicates, flexure is the dominant failure mode. Breakage was observed throughout the dolos but occurred predominantly at the shank (Figure 2). Figure 3 shows a typical example of a shank failure that is

**Table 1**
**CAU Breakage Survey Results**

| Structure Identifier | CAU Type, Size, Location, Date Identifier[1] | No. of Units Placed | No. of Units Broken | | Percent of Units Failed | |
|---|---|---|---|---|---|---|
| | | | 1992 or 1993 | 1984 | 1992 or 1993 | 1984 |
| Cleveland[2] | DO-2-CL-80 | 29,700 | 782 | 487 | 2.6 | 1.6 |
| Cleveland[2] | DO-4-CL-87 | 250 | 7 | N/A[3] | 2.8 | N/A |
| Crescent City[2] | DO-42-CC-86 | 760 | 12 | N/A | 1.6 | N/A |
| Humboldt N[2] | DO-42-HN-72 | 1,292 | 8 | 11 | 0.6 | 0.9 |
| Humboldt N[2] | D0-43-HN-72 | 967 | 8 | 11 | 0.8 | 1.1 |
| Humboldt S[2] | D0-42-HS-72 | 1,090 | 9 | 6 | 0.8 | 0.6 |
| Humboldt S[2] | D0-43-HS-72 | 1,445 | 9 | 6 | 0.6 | 0.4 |
| Kahului E | TP-33-KE-56 | 200 | N/A | 4 | N/A | 2.0 |
| Kahului E | TB-35-KE-66 | 827 | 2 | 6 | 0.2 | 0.7 |
| Kahului E | TB-50-KE-66 | 43 | 0 | 0 | 0.0 | 0.0 |
| Kahului E | D0-20-KE-77 | 164 | 0 | 2 | 0.0 | 1.2 |
| Kahului E | D0-30-KE-77 | 610 | 0 | 1 | 0.0 | 0.2 |
| Kahului E | D0-06-KE-77 | 455 | 9 | 6 | 2.0 | 1.3 |
| Kahului E | TB-09-KE-84 | 755 | 0 | 0 | 0.0 | 0.0 |
| Kahului W | TP-33-KW-56 | 400 | N/A | 9 | N/A | 2.3 |
| Kahului W | TB-50-KW-66 | 173 | 1 | 0 | 0.6 | 0.0 |
| Kahului W | TB-35-KW-66 | 181 | 0 | 2 | 0.0 | 1.1 |
| Kahului W | TB-19-KW-69 | 260 | 6 | 15 | 2.3 | 5.8 |
| Kahului W | TB-19-KW-73 | 80 | 0 | 0 | 0.0 | 0.0 |
| Kahului W | TB-35-KW-73 | 25 | 0 | 2 | 0.0 | 8.0 |
| Kahului W | D0-20-KW-77 | 291 | 13 | 18 | 4.5 | 6.2 |
| Kahului W | D0-30-KW-77 | 257 | 8 | 3 | 3.1 | 1.2 |
| Kahului W | TB-25-KW-84 | 10 | 0 | 0 | 0.0 | 0.0 |
| Kahului W | TB-11-KW-84 | N/A | 0 | 0 | N/A | N/A |
| Kahului W | TB-06-KW-84 | 540 | 0 | 0 | 0.0 | 0.0 |
| Nawiliwili | TB-18-NI-59 | 598 | 16 | 0 | 2.7 | 0.0 |
| Nawiliwili | D0-11-NI-77 | 485 | 40 | 0 | 8.2 | 0.0 |
| Waianae | D0-02-WE-79 | 6,633 | 222 | 170 | 3.3 | 2.6 |

[1] Type = DO for dolos, TB for tribar, and TP for tetrapods; size = armor size in tons; date = year placed. Cleveland 1987 rehabilitation number of units is approximate.
[2] Survey was completed in 1993; otherwise, surveys were completed in 1992.
[3] N/A = not available.

considered torsion-dominated, whereas Figure 4 shows a flexure-dominated shank failure. Figure 5 shows a typical fluke failed due to bending-induced shear.

b. *Tribar failure*. Tribars tend to fail at their central node. The slender spars typically fail in flexure (Figure 6), but can fail in torsion. Also noted were failures of the cylindrical legs.

c. *Spalling*. Two types of spalling were observed. Unstable units that were obviously rocking under wave loading showed signs of spalling due to repeated impact. Spalling was observed both on tribars and dolosse. Reinforcement-induced corrosion spalling was in evidence in both CAU types. The steel reinforcing bar had corroded and expanded, causing sections of the overlying concrete to spall. Figure 7 shows spalling on a dolos from corrosion of underlying reinforcing bars.

### Transitions observations

Information on breakage location on the slope of the structure was also collected. In general, most breakage occurs near the still-water level. However, there appears to be localized damage at transitional areas, both at size/type of CAU interfaces and at armor/crown interfaces.

*a. Dolos-to-tribar transitions.* Breakwaters surveyed having several rehabilitations using different armor unit types include Kahului, Nawiliwili, and Crescent City. On the Kahului West Breakwater, a transition from 19- and 35-ton tribars to 20- and 30-ton dolosse exists. In this area, 11 tribars and 7 dolosse are broken.

*b. Large-to-small dolosse transitions.* On the Kahului East Breakwater, a transition was made between 6- and 20-ton dolosse. At this interface, a cluster of three broken 6-ton dolosse was found.

*c. Armor unit-to-ribbed cap transitions.* The Nawiliwili breakwater and both of the Kahului breakwaters have ribbed caps. The caps have functioned well, with only slight cracks in the longitudinal members between ribs (Figure 8). They not only provide access along the structure for tracked vehicles, but also serve as a buttress for armor units at the crown, without buildup of wave pressures. All three structures do exhibit some downslope separation between the armor units and the cap.

## Comparison with Past Survey

In order to establish trends, the survey is compared with those results compiled in 1984 (Markle and Davidson 1984). Both data sets are presented in Table 1.

## Conclusions

CAU breakage can be primarily attributed to several factors: lack of adequate concrete quality control, rough handling, improper placement techniques, wave-induced rocking, and static loading with severely constrained boundary conditions. For Corps structures, breakage of armor appears to be due to a broad mixture of these items, with each structure having a different combination. All of the present Corps structures were built prior to the recent development of CAU structural design guidance. Consequently, nearly all structures appear to be slightly underdesigned with respect to strength.

For main armor that is not near a transition and is constructed correctly with sufficient strength concrete, breakage appears to be primarily the result of movement. Randomly placed armor layers will always have some movement, and breakage of these noninterlocked units is acceptable as long as the surrounding interlocked armor is not affected. Stable dolos and tribar slopes will tyically have between 1 and 2 percent of the units rocking during design conditions. Without significant reinforcement, these units will likely fail, but the remaining slope can remain intact.

The Humboldt jetties have very little breakage for their age. The conventionally flexure-reinforced dolosse show no cracking and might therefore perform equally well without reinforcement. The lack of breakage appears to be due to a combination of high concrete tensile strength and shiplap placement of the dolosse, where upslope units overlie downslope units. If strictly adhered to, this placement configuration can significantly reduce the amount of movement and therefore breakage.

Most Corps CAU layers have more than 2-percent breakage. The majority of this additional breakage appears to be due to instability at transition areas and rough handling during construction. The instability at transitions can be minimized through buttressing and careful attention to interlocking. Cap or crown transitions may require additional attention for structures that are frequently overtopped.

Finally, although this performance survey is by no means comprehensive and requires further research, recent research results combined with the survey indicate that using recent Corps CAU strength and stability design guidance coupled with strict quality control measures during construciton should significantly reduce CAU breakage.

## Future Developments

The collection of field data relating to CAU performance is an ongoing process. The remainder of Corps concrete-armored structures were surveyed during the summer of 1993, and a concrete core sample collection was begun in order to assess in situ CAU strength. The performance database on in-place CAUs is sparse, and any information on past projects using CAUs (concrete testing, unique problems during construction, etc.) would be of great value to the points of contact.

## Reference

Markle, D. G., and Davidson, D. D. (1984). "Breakage of concrete armor units; survey of existing Corps structures," Miscellaneous Paper CERC-84-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS

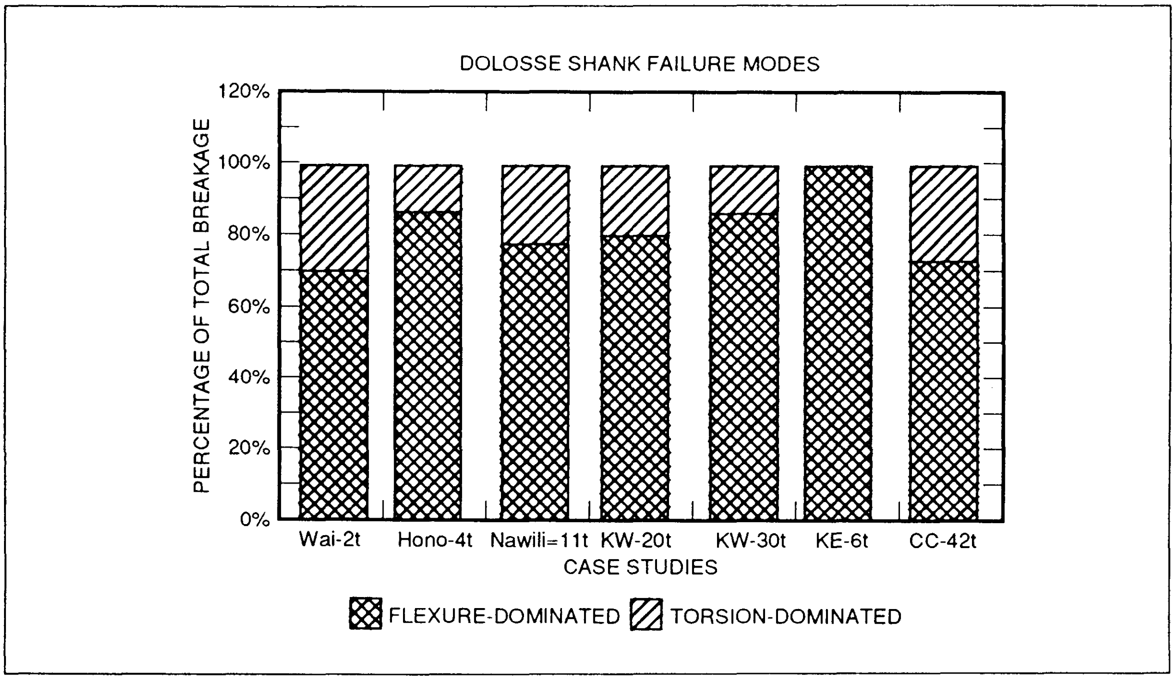


Figure 1. Dolosse failure modes

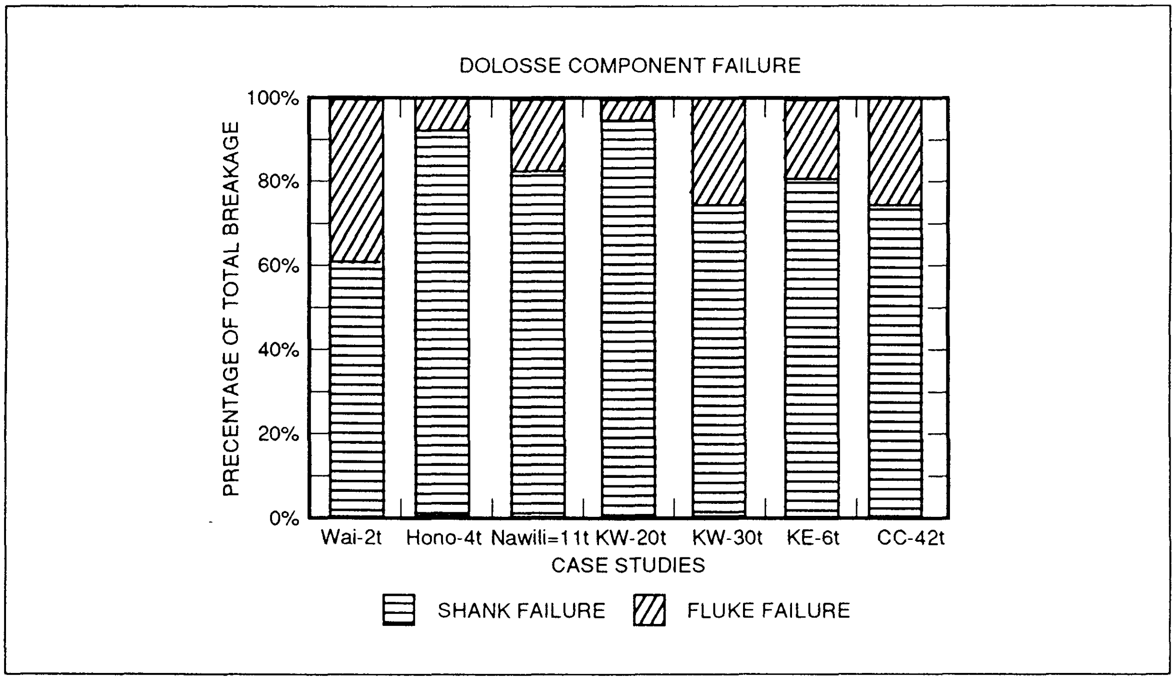


Figure 2. Dolos component failure

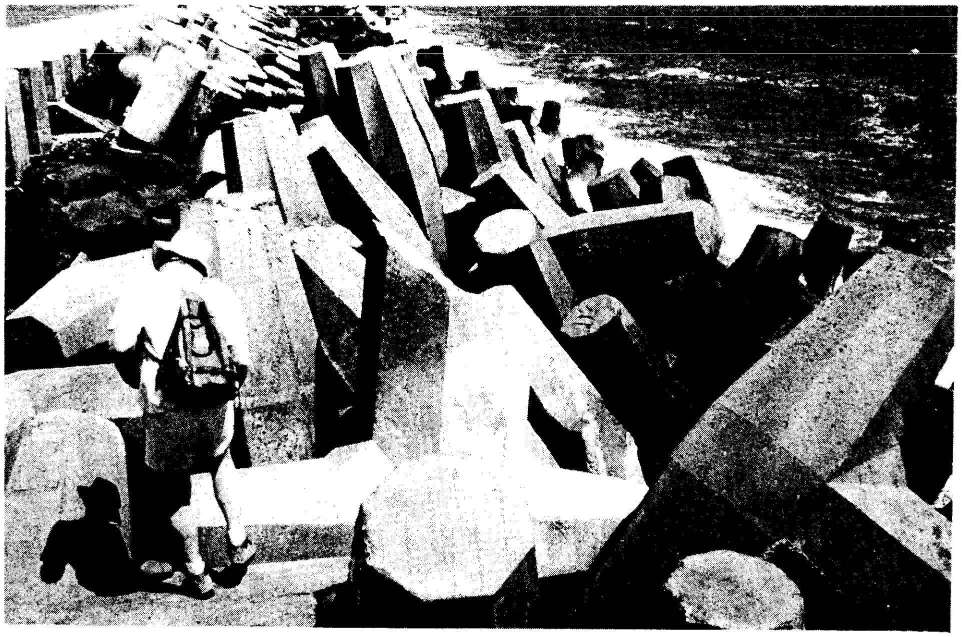

Figure 3. Typical torsion break of dolosse shank

Figure 4. Typical flexure failure of dolos shank

Figure 5. Dolos with fluke section sheared off

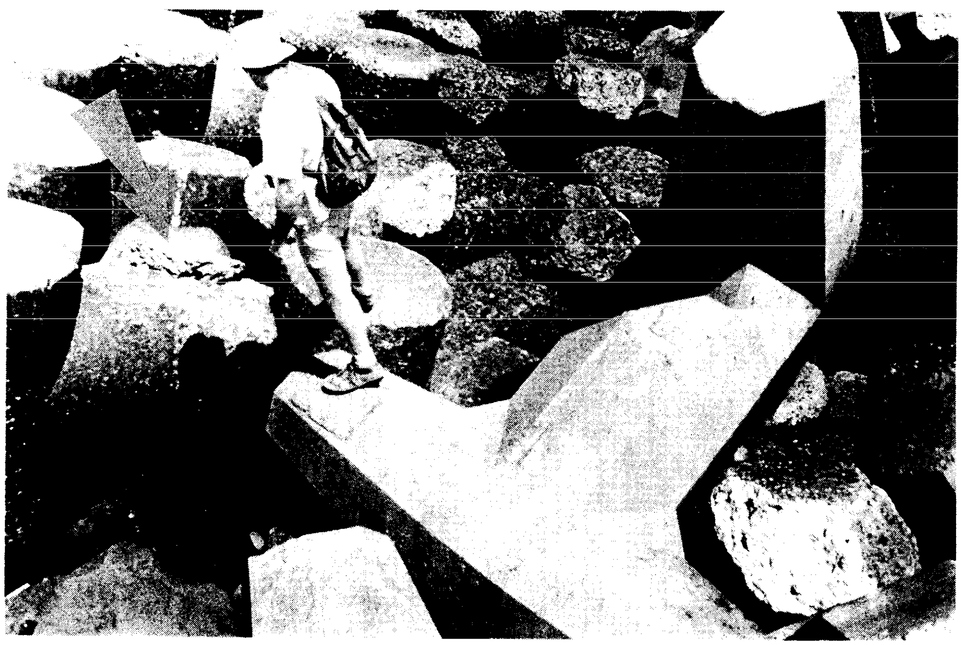

Figure 6. Tribar failure at central node

Figure 7. Corrosion of rebar causing spalling of dolos

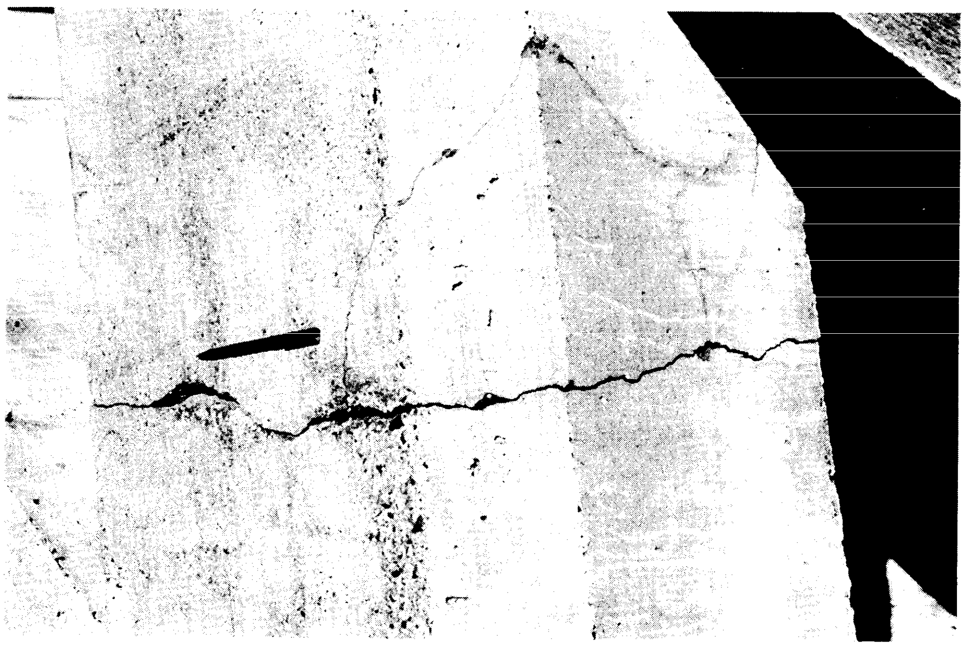

Figure 8. Crack in concrete rib cap at Kahului West