CHAPTER 330

STRUCTURAL RESTORATION OF CORAL REEFS DAMAGED BY VESSEL GROUNDINGS

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ABSTRACT

In 1995, a unique project was completed in which two coral reef sites in the Florida Keys were structurally restored after having sustained severe damage from the groundings of large vessels. The project, believed to be the world's first major structural restoration of a damaged reef (vs. in-kind mitigation using artificial reefs), demonstrated numerous innovative materials and marine construction techniques. Restoration focused upon the stabilization of coral rubble and large craters which resulted from the vessel groundings. The project's intent was to re-create a stable foundation which closely emulates the adjacent natural seabed and which would foster future recruitment of local biota. Work at one site included the mechanical transfer of coral rubble back into the craters, placement of limerock boulders atop the rubble, and back-filling the boulders' voids with carbonate sand. Work at the other site included excavation of coral rubble and the precision placement of 40 pre-cast reef-replicating armor units into the crater. The gaps between the units and along the crater's perimeter were filled with a specially-designed, non-separable underwater concrete -- into which coral rubble and soft corals were impressed. Design was complicated by the sites' proximity to environmentally sensitive coral beds and shallow depths (2.5 to 11 m). During construction, semi- real-time video images of the underwater work were relayed to the Engineer's office via the Internet to augment construction review. Construction was successfully completed per the engineering plans with no consequent environmental damage amidst a very active tropical storm season.

BACKGROUND

In two separate incidents in 1989, the 40-m *M/V Alec Owen Maitland* and the 142-m *M/V Elpis* went aground upon living coral reefs in the Key Largo National Marine Sanctuary in the Florida Keys, U.S.A. The two sites were within 6.8-km of one another, about 10.4 km offshore of northern Key Largo; and, about 74 km south-southwest of Government Cut at Miami Beach. The Maitland and Elpis sites, respectively, are located in the vicinity of N 25°11'58.776", W 80°13'34.421"; and N 25°8'54.088", W 80°15'9.20" (see **Figure 1**).

The impact and weight of the vessels upon the reef fractured the underlying coral substrate; and the ships' screws created deep craters in the coralline seabed. Large amounts of coral rubble were created from the fractures and ejected from the craters. Monetary damages were paid by the vessels' operators to the U.S. federal government under the auspices of the National Marine Sanctuaries Act

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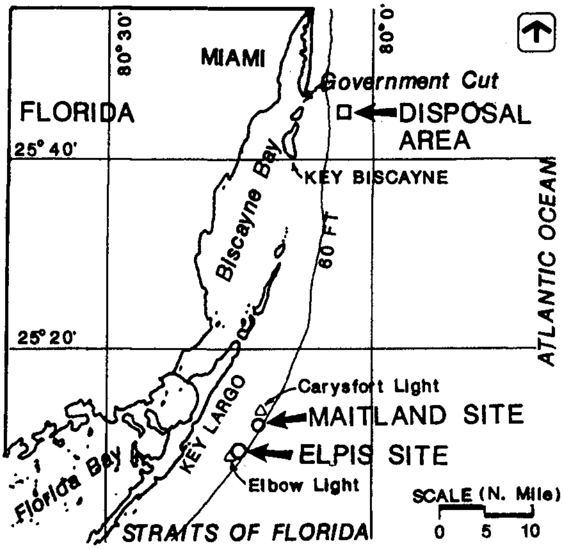

Figure 1: Location Map

for the purposes of site rehabilitation. The author was retained by the U.S. National Oceanic and Atmospheric Administration (NOAA) to quantitatively assess the sites' structural damage, and to design and supervise engineering works to structurally restore the damaged reefs.

ENGINEERING ASSESSMENT

Site Survey and Conditions. A precision survey of the two damage sites was undertaken in July, 1994 using tightly-gridded fathometer transects and diver measurements involving triangulation and taut-wire cross-sections of the craters' geometry and rubble piles. A multi-beam fathometer (such as SEABAT) would have been ideally suited for the remote survey work, but was not yet commercially available at the time of the study.

Damage at the shallower Maitland site (-1.8 to -3.0 m, MLW) consisted primarily of a 370-m^2 crater, varying in relief from 0.1 to 1.0 m, relative to the ambient seabed. The crater was formed by the ships' screw when an attempt was made to free the vessel under her own power. Since its creation, the crater had partially infilled with rubble, but had also doubled in size from what was originally two separate holes. The expansion of the crater was due to wave- and current-induced erosion of its coralline perimeter -- a thin (< 1.5-m) semi-continuous crust overlaying 15-m of densely-packed gravelly-sand. The volume of the crater, measured below the ambient seabed grade, was about 115 m^3. The seabed of the crater featured a matrix of sand and 7- to 20-cm diameter, loose coral rubble with scattered larger pieces measuring up to 50-cm.

Damage at the deeper Elpis site (about -11 m, MLW) primarily included two adjacent craters, measuring 69 m^2 and 163 m^2, likewise formed by the ships' screws as she tried to free herself. The depth of the craters, below ambient grade, varied from 0.5 to 2.3 m. The volumes measured 127 m^3 and 200 m^3. The craters' seabed was composed of sand and coral rubble similar to that of the Maitland site, but featured numerous large coralline boulders of up to 1.8-m diameter. The sand fraction was carbonate, with d_{50} = 0.6 mm. Adjacent to the craters were three berms consisting entirely of relic *Acropora cervicornes* (elkhorn) coral rubble that had been initially ejected from the craters. This naturally branched rubble, primarily 10- to 25-cm long by 3-cm diameter, was interlocked but easily succumbed to dismantling by hand or jet probe. The berms' relief varied from 0.3 to 1.2 m with crest widths of 0.6 to 1.5 m, and totalled about 30 m^3 in volume.

Scattered across a 0.5 by 1.5 km^2 area centered about the craters were over a dozen patches of fractured coral rubble. These patches, varying in size from 3-m diameter to 230 m^2, traced the inbound and outbound paths of the Elpis as her hull clipped and crushed higher-relief coral spurs. The weight of the vessel upon these spurs caused the coral to fracture deep below its surface. As a result, the surface rubble (about 10 to 20 cm) was loose and fairly easily dislodged by hand or jet probe. However, once exposed, the underlying coral could *also* be dislodged -- to an apparently limitless depth -- because of the dense cracks which permeated the substrate. By volume, the rubble measured about 15% at 18 cm, 30% at 13 cm, 20% at 9 cm, 25% at 5 cm, with the remaining 10% being sand. The total area of the rubble fields was estimated to be over 450 m^2.

Both sites, being at the seaward edge of the Florida Keys reef tract, were exposed to ocean waves. Annual average heights and periods were hindcast as about 1.0 m and 5.0 seconds. The largest waves, associated with tropical storms, were assumed to be depth-limited conditions, with nominal 2-m storm surge levels. Both sites featured daily tidal currents on the order of about 0.3 m/s. Hourly wind observations for an 8-year period were analyzed to discern those weeks for which the average hourly-sustained wind speeds were less than 5-, 10- and 15- knots. These data were later utilized to determine the statistically optimum window(s) during which on-site construction activities would be best undertaken. (In brief, the optimum window was found to be July 22 - August 18, with the most expansive window being June 17 - September 22.)

Conceptual Design Alternatives. A range of conceptual engineering alternatives was developed for the sites' structural restoration (Bodge and Creed, 1993). These were evaluated by the Sanctuary's Trustees (the National Oceanic and Atmospheric Administration (NOAA)) in terms of stability, construction feasibility, aesthetics, potential for biotic colonization, and probable cost (Sheehy, Bodge, and Finch, 1995).

The no-action alternative was ultimately not favored primarily because (1) there was little indication that the two sites' injuries were rapidly, naturally healing; (2) there was no indication that the shallower Maitland site's crater would cease its expansion; and (3) there was potential for additional injury by mechanical damage associated with the sites' mobile rubble. (That is, in storm conditions, rubble colonized by juvenile coral larvae would overturn and destroy the colonies and, perhaps, other established corals.) Other alternatives considered for the sites, but ultimately declined in favor of the preferred alternative (described below), included a continuous concrete cap, concrete-filled pillow mats, gabions, cable- and non-cable-stayed revetment mats, conventional boulder fills, and soil stabilization. Particularly at the shallower Maitland site, it was essential that the restoration structurally secure the crater's friable perimeter, and that the work physically fit into the shallow and irregular relief of the crater.

The selected alternative for the deeper *Elpis* site involved temporary relocation of the existing coralline boulders (i.e., those with existing biota), from the craters to the surrounding seabed. The coral rubble berms would then be mechanical relocated back into the craters from which the rubble was ejected. An armor layer of 1.2-m marine limerock boulders (totalling 400 tons) would be then placed atop the rubble. The voids were then to be partially filled with aragonite sand (approx. 60 m^3). The temporarily relocated coralline boulders, originally salvaged from the crater, would be then replaced atop the imported boulders and sand fill. (See **Figure 2**.)

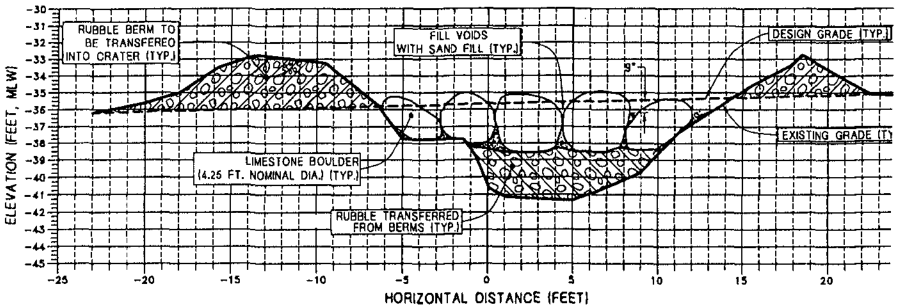

Figure 2: Typical section of Elpis site restoration.

The selected alternative for the shallow *Maitland* site (-2.5 m MLW) involved precision placement of 40 pre-cast "Reef Replicating Armor Units/Living Foundations" (RRAULF's) into the crater, and an underwater pour of specially-designed non-separable concrete (approx. 45 m^3) intended to bind the fragile coral perimeter to the armor units and to fill the gaps between the units (**Figure 3**). The finished elevation of the work was designed to match that of the natural seabed (**Figure 4**). Steel bar, driven into the seabed, and limerock boulders were to be placed between the units and the crater's perimeter to help secure and dress the concrete, respectively (**Figure 5**). Limerock gravel and coral berms were to be used as termination forms for the concrete where necessary (**Figure 6**). As for the Elpis design, the overall stability of the work was designed for a 50-year storm event using stream function wave theory and considerations of drag, inertia, lift and frictional resistance. For stability, the minimum coefficient of friction between an independent armor unit and the seabed was computed as $\mu_f \geq 0.5$ (conservative $C_{Lift} = 0.73$) or $\mu_f \geq 0.38$ ($C_{Lift} = 0.4$).

Each of the 40 armor units featured a highly irregular surface of limerock boulders and exposed aggregate in order to emulate the ambient seabed (**Figure** 7). The units, each 8300 kg (dry weight), were formed in six different sizes to accommodate the irregular shape and depth of the crater. Steel reinforcement for each unit was designed as a perimeter box beam such that each could be cantilevered 50% in any direction -- in anticipation of the irregular seabed. A standard Portland cement mix was specified for the armor units.

Mix design and specifications for the underwater non-separable concrete were developed by Ben C. Gerwick, Inc. (BCG) of San Francisco, CA. The design mix is summarized in **Table 1**. Details of the mix design are available from the author, Bodge (1995), or BCG ((415) 398-8972).

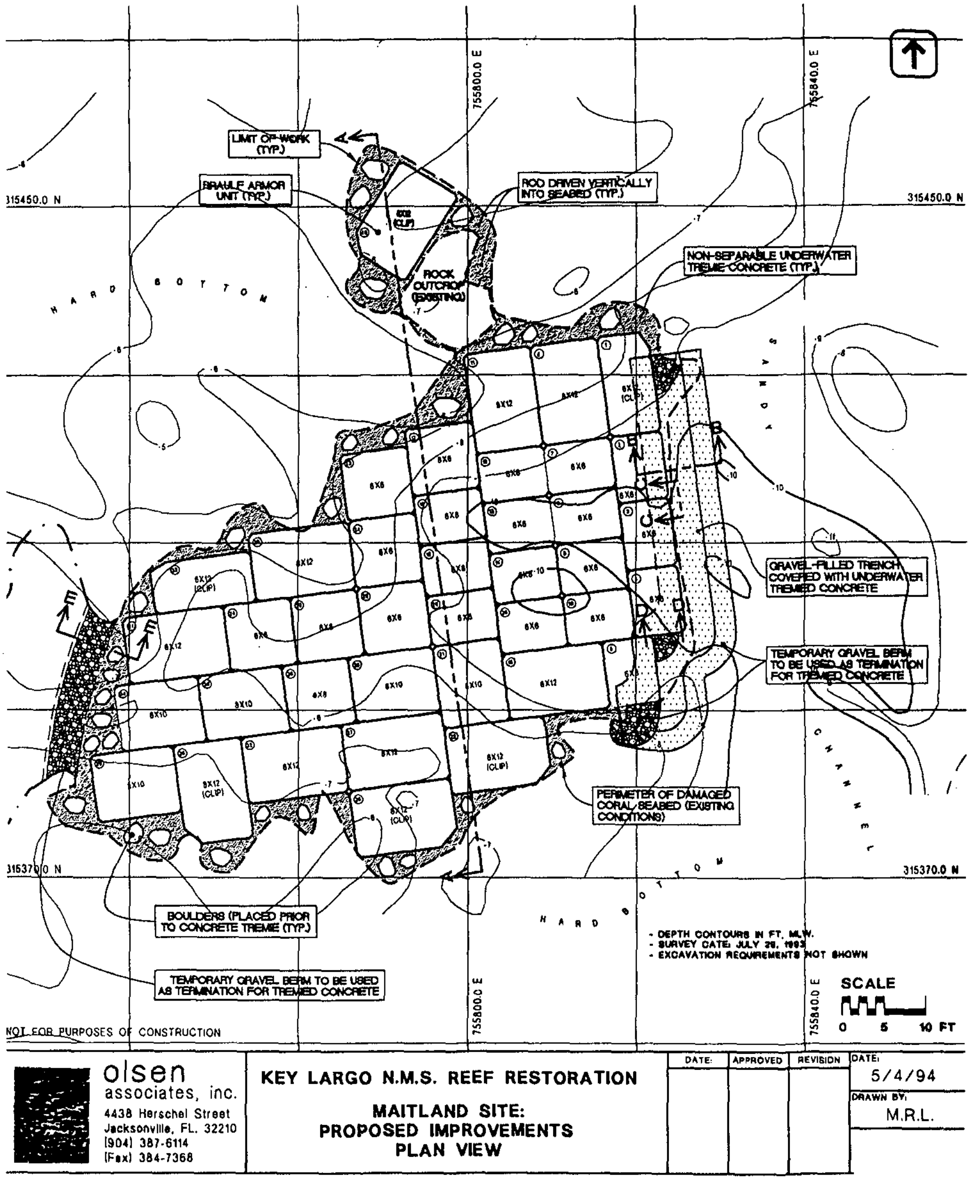

Figure 3: Plan view of Maitland site restoration.

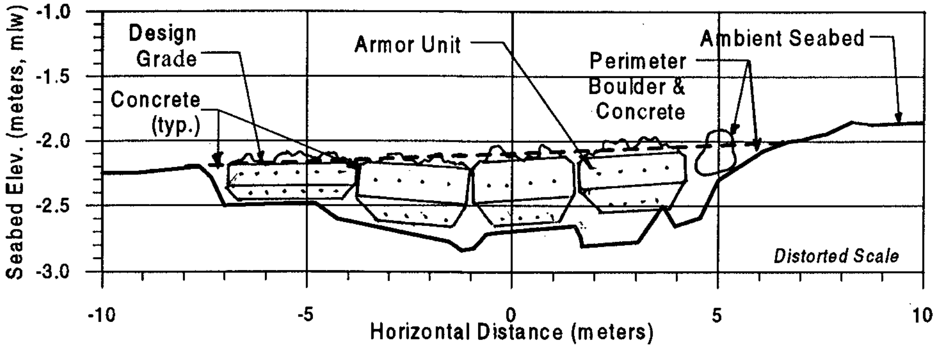

Figure 4: Maitland site restoration (typical section).

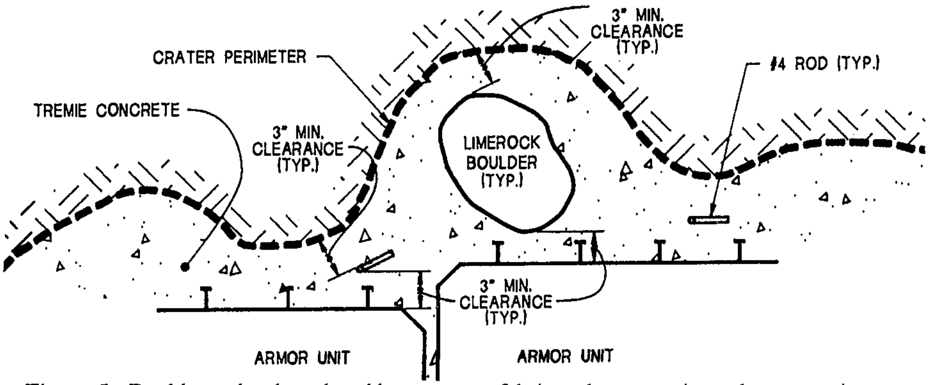

Figure 5: Boulder and re-bar placed between pre-fabricated armor units and crater perimeter.

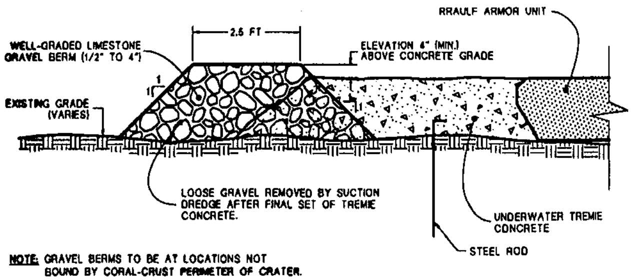

Figure 6: Limerock gravel and coral rubble used as a termination berm for the underwater concrete pour.

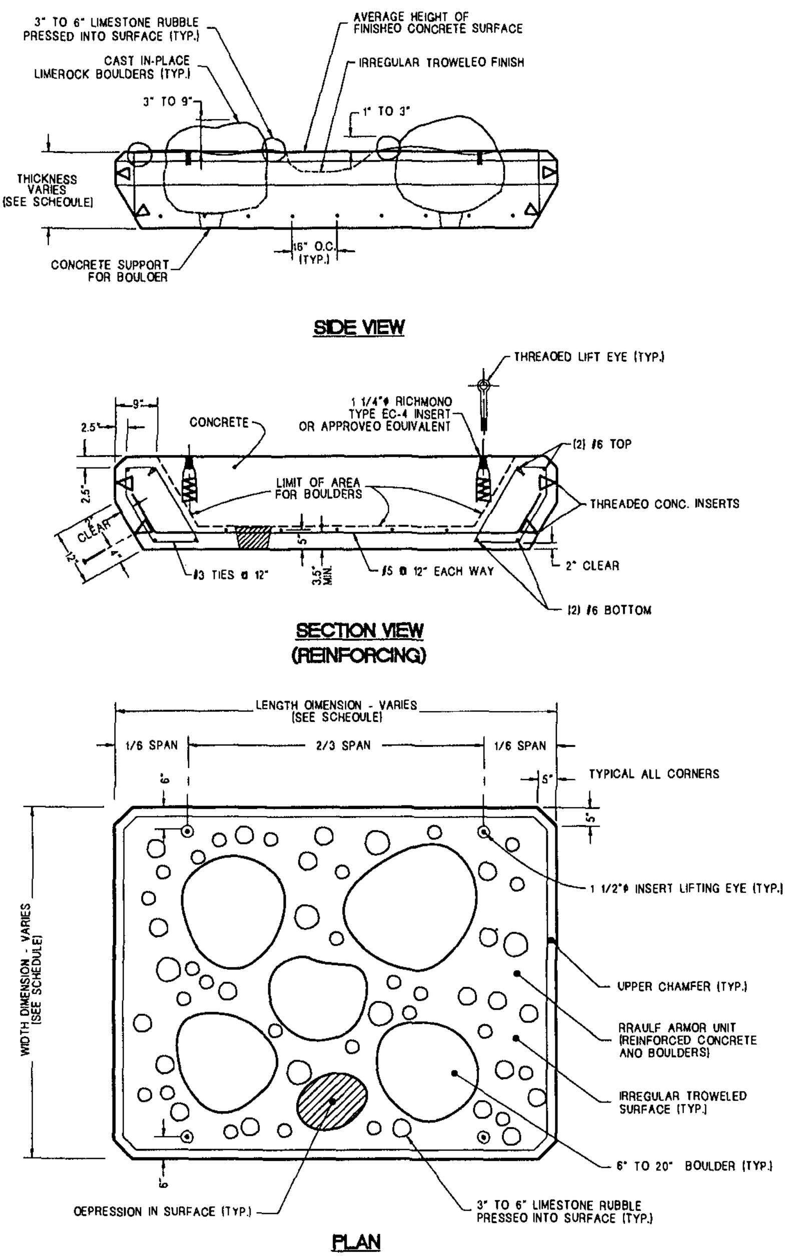

Figure 7: Pre-fabricated (RRAULF) armor unit design for the Maitland site, typical.

IMPLEMENTATION

Permits. Environmental permits for the work were issued by the U. S. Army Corps of Engineers, pursuant to Section 10 of the Rivers and Harbors Act, and Section 103 of the Marine Protection, Research and Sanctuaries Act of 1972. (The latter was required because it was proposed that surplus rubble removed from the sites would be disposed of at an existing ocean disposal site offshore of Miami.) The NOAA Sanctuaries and Reserves Division (SRD) likewise issued a permit for operation within the marine sanctuary. The State of Florida (DEP) was contacted, but did not issue a permit because the activity was outside of State waters (i.e., 4.8-km limit from shore).

Table 1: Nominal mix design for underwater, non-separable marine concrete.

Cement	600 lbs./cu.yd.
Fly Ash (class F)	90 lbs./cu.yd.
Silica Fume	43 lbs./cu.yd.
Coarse Aggregate (3/8")	1105 c.y. (40%)
Fine Aggregate	1685 c.y. (60%)
Water	250 lbs/cu.yd.
HRWRA (Sikament 300)	1.3 gals./cu.yd.
AWA (Sikamix 100 SC)	0.6 to 0.9 gals./cu.yd.
Water/Cement Ratio	0.4 ± 0.01
Slump	10" (spec); 9" - 11" (typ.)
Unit Weight (typ.)	142 lb/cu.ft.
% Washout Loss	<1.5%
Initial Setting Time	60 minutes (approx.)
4-day Strength (typ.)	5425 lbs/in^2
28-day Strength (typ.)	6110 lbs/in^2

Contracting. In mid 1994, NOAA entered into a cooperative agreement with the U. S. Army Corps of Engineers, Jacksonville District, by which the Corps would solicit and manage the construction contract for the work. Final construction plans and specificatons for the work were prepared by the author for the Corps by December, 1994. Procurement was based upon a "best overall value" approach, whereby potential contractors concurrently submitted separate Technical Proposals and Cost Proposals. The former included the Contractor's response, by prescribed form, to specific questions regarding their corporate and personnel experience (among other factors), and their narrative proposals describing their probable technical approach to the work. The offerors' responses were ranked according to prescribed evaluation criteria, previously prepared for the Corps by the author. Cost was to be used only as a "tie-breaker" among the most technically-qualified offerors (which, ultimately, was not necessary). Five proposals were received. The work was awarded to Team Land Development, Inc. of Pompano Beach, FL, in March, 1995.

Construction. Project construction was initiated in April, 1995. The Maitland site's 40 armor units were cast in the Contractor's south Florida yard over a 30-day period using about a dozen wooden forms. The limerock boulders and gravel were locally quarried. The carbonate sand for the Elpis site was oolitic aragonite, imported from the Bahamas and stockpiled in Fort Pierce, FL.

On site, the Contractor utilized conventional shallow draft barge (12 m by 43 m with 1.1-m draft at 150-ton nominal payload), and 27-m tug (1.4 m draft) as the primary work platform. A 10-m pusher tug (0.8 m draft) was used to maneuver the work barge over the shallow Maitland site. At nightfall, the 8- to 12-man work crew bivouaced ashore, at Key Largo, via small workboats.

Virtually all aspects of the work were primarily accomplished or directed by one or two surface-air-supply divers. These divers' communications were audible to the crane operator on the barge deck.

A 3-point mooring was used at the Elpis site, with 120-degree separation at 120-m distance, each, from the work site. Each mooring consisted of a 61-cm, 1.3-cm steel plate anchored to the seabed via four 3-cm, 1.2-m long threaded rods located at the corners of the plate. The rods were anchored to the seabed by pre-drilling deep holes into the coral seabed, placing the rods therein, and grouting with pre-mixed hydraulic cement carried to the seafloor in a 10-cm PVC tube. The plate was secured to the rods by a lockwasher and nut. A padeye was welded to the center of each mooring plate. To each padeyc was attached a 3-cm shackle and a buoyant (9-cm polypropylene) mooring line for the barge. Each of the four threaded rods at the corner of each mooring plate was load-tested to vertical pull-out resistance in excess of 66.8 N (15 kip). The barge moorings for the Maitland site consisted of three 61-cm dia. by 1.3-cm wall steel pipes driven approximately 6-m into the seabed by vibro-hammer. Here, the barge was moved offsite at night, during particularly low tides, or in advance of approaching squalls.

At the Elpis site, the rubble berm material was transferred into the cranters using both a crane-operated grapple and diver-operated water jet. The latter was more succesful, by far, than the former. The limerock armor boulders were placed individually by grapple. The fill sand was placed by a crane-supported, diver-operated 3.5-m^3 hopper. Tidal currents carried some of the sand as much as 150-m downcurrent, and resulted in the upcurrent crater being filled with sand to a notably lesser degree than the downcurrent crater (see **Figures 8 and 9**, respectively). As seen in Figure 9, local fishes were attracted to the work within hours of its completion.

Attempts were made at the Elpis site to remove unconsolidated coral rubble using both a 15-cm suction dreged with deck-mounted pump and a 10-cm water lift discharging into metal baskets lowered to the seabed. Neither technique proved satisfactory for the work because the rubble was scattered and productivity was very poor. Larger rubble (>8 cm) frequently jammed the intake. [Subsequent rubble removal activities undertaken with suction dredging and water lifts at other grounding sites -- where the rubble was more spatially concentrated and completely unconsolidated (i.e., where the vessel grounding had occurred within the previous year) demonstrated far greater success than at the Elpis site.]

At the Maitland site, the Contractor preferred to use gravel fill to level the crater's seabed (in preparation for the units' placement) rather than excavation. This choice was primarily dictated by the cumbersome difficulty in excavating the dense rubble/sand matrix of the crater's coralline seabed. Excavation around the crater's perimeter, however, was nonetheless necessary to ensure that the upper surface of the perimeter armor units (thickness < 36 cm) would not extend above the adjacent, ambient seabed grade. Coral rubble excavated from within the crater was used to construct a berm around the crater to serve as an additional termination form for the underwater concrete, and to help blend the units' perimeter with the ambient seabed.

After precision placement of the 40 armor units (placed with 5-cm maximum allowable gap between units, and tighter tolerances for vertical differential), and placement of the perimeter boulders and coral/gravel berms, the underwater concrete was placed using a swing-tube pump with 5-cm hose, PVC nozzle, and diver-operable ball-valve. The concrete was batched aboard the barge using a portable ("junior") mixer.

Figure 8:
Photograph of upcurrent Elpis site crater immediately after restoration. Voids between the boulders provided extensive fish habitat and vertical facing for coral larvae recruitment, but resulted in an aesthetic that contrasted with the ambient seabed.

Figure 9:
Photograph of downcurrent Elpis site crater immediately after restoration. Voids between the boulders were more effectively filled with carbonate sand, resulting in an excellent aesthetic match with the ambient seabed.

Figure 10 (next page) is a photograph of the *M/V Maitland* hull aground upon the reef in 1989. **Figure 11** depicts one of the pre-cast armor units being lowered from the barge deck to the Maitland site seabed. **Figures 12 and 13** are typical photographs of the Maitland site restoration, taken about a week after the work was completed.

Site work was conducted between June 19 and July 12 at the Elpis site, and between July 13 and September 1, 1995, at the Maitland site. For about half of this time, however, no site work was undertaken because of relentlessly bad seas. In all, the 1995 season was the second worst on record in terms of Atlantic tropical storm activity. At one point in August, there were five tropical storms simultaneously lined-up across the Atlantic, moving toward the Florida peninsula.

Construction Review. Real-time construction review was conducted and coordinated by the Corps, with direct participation of NOAA/SRD personnel and the Design Engineer (Olsen Associates, Inc.). The unique and complex relationship between the project's many parties was facilitated, from the outset, by a 2-day *partnering* conference organized by the Corps prior to construction.

Figure 10:
Photograph of Maitland aground on the reef, 1989. The ship screw is seen resting amidst the coral rubble caused by the grounding.

Figure 11:
Photograph of one of the 40 pre-cast reef-replicating armor units being lowered to the seabed. The lifting eyes were unscrewed from the units' threaded inserts after installation.

Figure 12:
Photograph of the top surface of the Maitland site repair, taken several days after project completion. The ambient seabed is in the far background. A grouted joint between adjacent armor units is discernible below the fish, in the foreground.

Between site visits, the Engineer (author) was kept abreast of the work by viewing underwater images that had been video-taped by his on-site representative (Mr. Mark Schroeder, Continental Shelf Associates, Inc.). Selected videotape images were captured as a single frame by Mr. Schroeder, then transmitted from his boat via laptop computer, cellular phone, and E-mail to the author's Jacksonville office -- usually within 20- to 30-minutes of the original photography. On several occassions, the Engineer's access to virtually real-time construction photos permitted timely, cost-saving corrections to the work; or, alerted the Engineer to situations that required an immediate trip to the site and/or instructions to the site-representative.

Environmental Monitoring. Turbidity was monitored using concepts of "exposure" by which "cumulative NTU-hours" were measured and tabulated. There was no observed environmental degradation resulting from the work -- despite the fact that the work was conducted in the midst of sensitive coral resources. Fishes, soft and hard corals have begun re-colonizing the sites (Harold Hudson, NOAA/SRD - personal communication).

Project Cost and Completion. The project's construction cost (bid) was U.S. $1,047,000, with subsequent change orders resulting in a net additional cost of $19,600. The total construction cost was about 10% less than the Engineer's estimate. Overall, the project was completed on-time, within budget, in accordance with the design intent, and with no apparent net adverse impact to the environment.

Figure 13:
Photograph of exposed side-face of Maitland restoration, where the repair was terminated adjacent to an existing sandy channel. The restoration is on the left, the ambient seabed is on the right.

CONCLUSION

To the author's knowledge, this experimental project represents the first large-scale, in-situ structural restoration of a coral reef damaged by mechanical impact. Innovative methods introduced, or resurrected, during this project included

- development of structurally sound seabed restoration with emphasis on aesthetic blending with the ambient environment;
- further application of new non-separable underwater marine concretes,

- contract award by the Corps using "best-overall-value" procurement,
- unique cooperation between multiple federal agencies and the private sector, and
- semi-real-time construction review using underwater-taped video images via the Internet

among other items. The unfortunate, increasing frequency with which vessels ground upon coral resources -- and other environmentally sensitive seabed resources -- suggest that the lessons learned as part of this project will be of increasing utility to future restoration projects.

ACKNOWLEDGEMENT

The engineering assessment, design, and construction review work described herein were conducted in principal part by Olsen Associates, Inc. under subcontract to Industrial Economics Inc. (IEc), Cambridge, Massachussets, as authorized by the U. S. Dept. of Commerce, National Oceanic and Atmospheric Administration (NOAA), Contract No. 52-DGNC-1-00007, under Task Order Nos. 50062 and 50089. The leadership of Dr. Dan Sheehy, of IEc, in this project is specifically noted. Initial site survey work was coordinated by Mr. Keith Spring of Continental Shelf Associates, Inc. (CSA), of Jupiter, Florida. The Engineer's on-site technical representative was Mr. Mark Schroeder, also of CSA. Hydrographic survey work was conducted by ARC Surveying & Mapping, Inc., of Jacksonville, FL. Mr. Chris Creed, of Olsen Associates, Inc., greatly assisted in the site survey, data analysis and preparation of the engineering assessment. The innovative internal structural design and specifications for the Maitland site armor units was principally created by Mr. Steve Klecka of SK Engineering, Inc., Jacksonville, FL. The highly succesful concrete mix design and specifications were provided by Dr. Dale Berner of Ben C. Gerwick, Inc. (BCG), of San Francisco, California; and then field-reviewed by Mr. Patrick Durnal of BCG. Construction management was executed by the U. S. Army Corps of Engineers, Jacksonville District. Construction review for environmental protection was directed by Messrs. Harold Hudson, Bill Goodwin, and John Halas of the NOAA Sanctuaries and Reserves Division, Key Largo. The construction contractor was Team Land Development, Inc., Pompano Beach, Florida; Mr. Ron Coddington, President. For the contractor, Mr. Charles Calloway was the lead engineer. On behalf of the project's sponsor, NOAA, Mr. Tim Osborn (National Marine Fisheries/Restoration Center), Dr. Charles Wahle (Sanctuaries and Reserves Divsion), Ms. Darlene Finch (Damage Assessment Center), and Lt. John Tokar (contracting officer) each managed principal aspects of the project, each with great patience and faith.

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