CHAPTER 260

Rehabilitation of the West Breakwater - Port of Sines, Portugal

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Introduction

In 1978, construction of what is now termed the "West Breakwater" at the Port of Sines, Portugal, was nearing completion when it suffered severe damage from a large storm having significant wave heights estimated at nine meters. In February 1979, a subsequent storm with significant waves near the design height of eleven meters virtually destroyed the breakwater. The breakwater, armored with 40 ton dolosse, was approximately 1.7 km long and extended generally southward from the mainland to provide the primary wave protection for the Port of Sines as shown in Figure 1.

Sines is about 120 km south of Lisbon. Water depths of 50 meters exist close to shore at this site making it a viable site for a deep water port. The site is exposed to waves approaching generally from the west to northwest. The spring-tide range is about 3.6 meters. Cargo entering the port includes oil and coal (Dias & Toppler 1993). Petrochemicals and refined petroleum products are exported. Tankers off load their oil at berths 2 and 3 located immediately leeward of the west breakwater shown in Figure 2. With a water depth of 28 meters, berth 2 accommodates tankers up to 350,000 dwt. Berth 1 in the original design could have accommodated tankers up to 500,000 dwt, however, the severe storm damage to the breakwater and a reassessment of port development vis-a-vis changes in the world's tanker fleet resulted in abandoning berth 1. In addition to providing berths itself, the west breakwater shelters a number of other facilities within the harbor complex including the refined products loading berths, coal terminal, break bulk and the proposed container cargoes.

Emergency Repairs

In August 1979, following the damaging storms, emergency repairs were started on the west breakwater so that port operations could continue while final rehabilitation plans for the breakwater were developed. Emergency repairs to a 500 meter-long section of the west

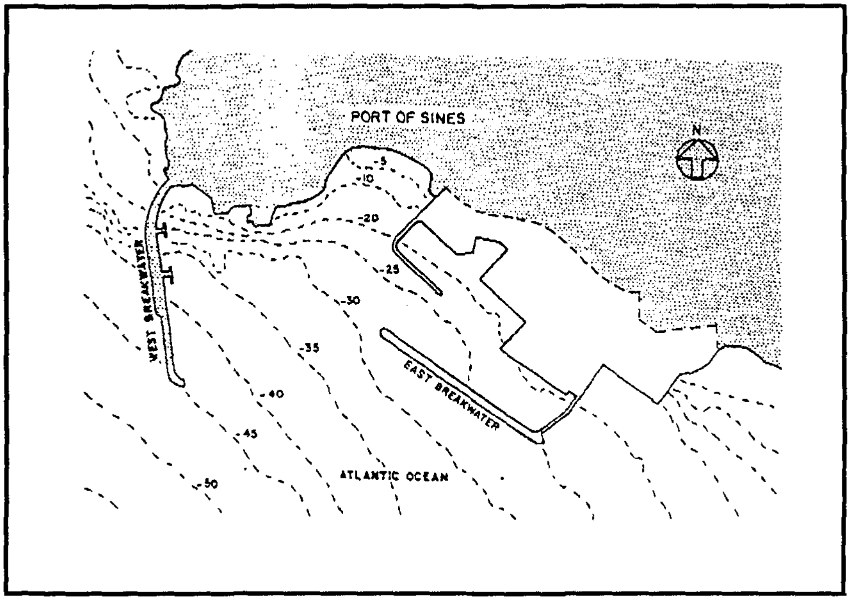


Figure 1. Final Port Master Plan 1985, Sines, Portugal (After Dias and Toppler, 1993)

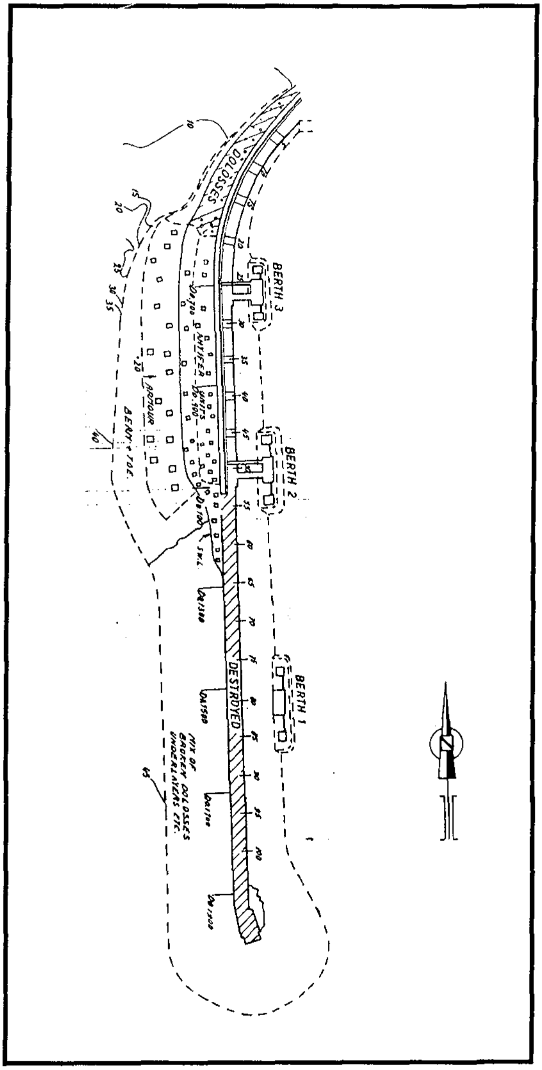
breakwater were completed in May 1981. Repairs to the breakwater included the placement of 40 ton dolosse from the landward end of the breakwater out to berth 3 and the placement of 90 ton "Antifer" cubes between berth 3 and berth 2 on a slope flatter than that of the original breakwater.

Subsequent to construction, hydraulic model tests of the emergency repairs were made in 1981 at a 1:12 scale (the results of these tests are summarized by Mol, et al., 1983). Generally, the model tests showed that no modifications to the armor adopted for the emergency repairs were necessary. The gaps between the armor blocks and the parapet could be filled to reduce wave impact pressures. The tests also showed that the pipelines on the west breakwater needed protection from overtopping and that improvements to the breakwater from its landward root to berth 3 were necessary.

These results were preliminary to the design of the definitive breakwater rehabilitation, however, the emergency repairs undertaken between 1979 and 1981 imposed some constraints on the final rehabilitation.(Ligteringen, van der Meer and Rita, 1993)

The Final Design

Additional studies were undertaken for the final breakwater rehabilitation including a reassessment of the wave climate at Sines based on hindcasts for the period 1956-1980 and for 20 major storms, numerical and physical model refraction analyses, additional hydraulic model stability tests -- including some with instrumented armor blocks to measure armor block



accelerations, prototype- scale Antifer cube impact tests to assess the conditions under which the cubes might break, geotechnical modeling and a study to establish the optimum length of the rebuilt breakwater and its effect on port operations.

The wave height distribution adopted for the design condition has a significant height with a return period of 100 years of H_s = 14 meters. A 50 year return period of H_s = 13 meters, and a 10 year return periods of H_s = 11 meters. While refraction coefficients as high as 1.1 were found for some incident wave periods and directions, no increase in wave height due to refraction was assumed for the design. Design criteria adopted for the outer section of the breakwater trunk (between berths 2 and 3) allow 2% to 3% armor damage by the 100 year event (H_s = 14 meters), based on a project lifetime of 50 years, and 10% damage by the 300 year event (H_s = 15.5 meters). These levels of damage were those established in the earlier hydraulic model tests.

Figure 2. Sines West Breakwater Following Emergency Repairs, April 1981 (After Ligteringen, van der Meer and Rita, 1993)

The probability that minor damage (2%-3%) would occur at least once during the project's lifetime was 40% and the probability of major damage at least once was 15%. Therefore, based on previous tests of armor unit breakage, a velocity of 3 meters/sec was adopted as the impact velocity causing breakage to the breakwater. (Ligteringen, Ramos, van der Meer and Rita, 1993)

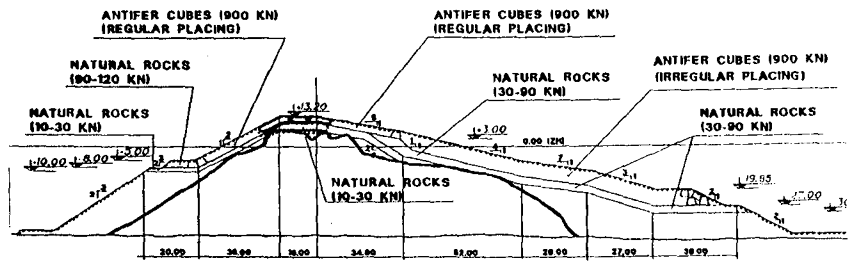


Figure 3. Sines West Breakwater Cross Section Through the Rehabilitated Trunk
(After Condotte d'Acqua, 1993)

The measurements of armor unit movement in the hydraulic model tests were used to estimate the number of units that would have broken during a simulated storm (i.e. whenever an armor cube's velocity exceeds 3 meters/sec, multiple impacts at lower velocities also were found to cause some breakage).

The geotechnical analysis indicated that the leeward side of the breakwater trunk had to be flattened to a slope of 1:2 for seismic stability. The leeward side was then armored with a single layer of 90 ton Antifer cubes and 9-12 ton dolosse rock was placed below the elevation of -5 meters CD (CD -- chart datum is approximately 2 meters below MSL). The crest elevation was lowered from +14 meters CD to +13.2 meters CD -- allowing more overtopping but improving stability. The pipelines were designed to withstand overtopping by the 100 year event and the gap in front of the parapet wall on top of the breakwater trunk was filled with large rock to reduce impact pressures and 90 ton Antifer cubes were extended down across the outer berm of the breakwater trunk as shown in Figure 3.

Several alternatives for the 500 meter-long shoreward end -- the root of the breakwater, were considered. Initially, a submerged berm in front of the existing rehabilitated breakwater was considered (Condotte d'Aqua, 1993) in order to reduce significant wave heights at the breakwater root, however, to provide access for equipment to the west breakwater during construction, repair operations, and maintenance; a wider, more robust cross section for the existing structure was finally adopted. The existing 40 ton dolosse which had undergone additional breakage in the intervening years were covered with 90 ton Antifer cubes. Equivalent stability for the root is now reclaimed since the Antifer cubes were placed on a flatter slope and also because the sedimentation in front of the root reduced the incident wave heights. Design wave heights are depth-limited and range from 6 to 9 meters in this area.

The outer end of the breakwater, beyond berth 2, underwent continued deterioration following the 1978-1979 storms and the design of the new rebuilt breakwater head would have to include some of the remaining debris. See Figure 4. Some of the debris was removed by blasting and excavating, but most of the debris formed the new base of the breakwater head. An optimization study led to the decision to rebuild 500 meters of the outer portion of the west breakwater -- out to the location of the former berth 1, rather than just 300 meters as had originally been planned. This new, round head was armored with 105 ton Antifer cubes having the same dimensions as the 90 ton cubes. Concrete with a density of 3.1 ton/m^3 was used to produce the heavier cubes. The final design, which uses three layers of high density Antifer cubes over the entire breakwater head section, was not model tested.

Monitoring Program

An extensive monitoring program is currently underway which measures waves, currents, tides, wind, etc., and their effect on the breakwater cross sections (Pita, et al., 1993). Periodic visual and photographic inspections are made from the top of the west breakwater and by boat. These inspections are made monthly between the months of October through April and in the mid-summer -- for a total of 8 inspections per year. In early spring, a yearly inspection is made by scuba divers to determine underwater conditions. Additional data includes: yearly hydrographic surveys, aerial photography/photogrammetry and topographic of the breakwater's cross section. Additionally, special surveys are conducted after storms with significant wave heights greater than 5 to 8 meters. A storm with a 5 meter wave height triggers a visual inspection of the breakwater, while a storm with 8 meter waves triggers a complete set of visual topographic, hydrographic, and photographic measurements.

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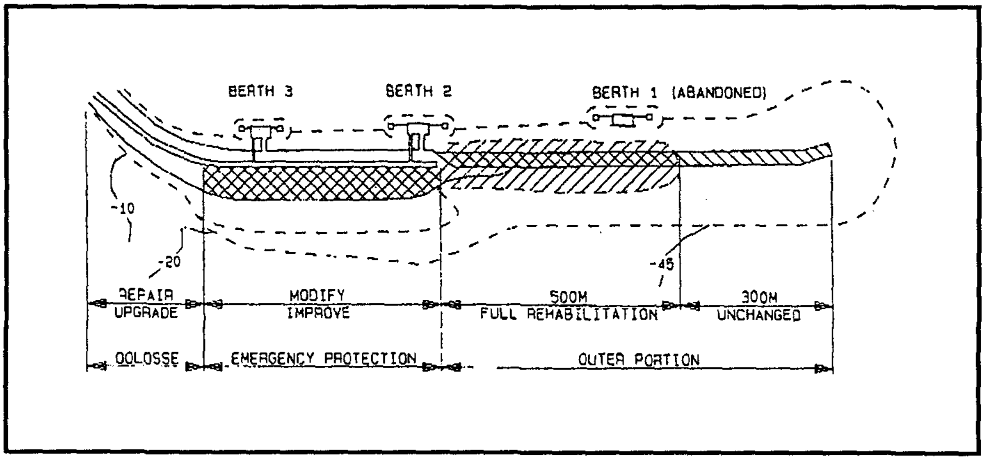

Figure 4. Sines West Breakwater After Complete Rehabilitation
(After Dias and Toppler, 1993)

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