REPORT ON THE DAMAGES TO THE SINES BREAKWATER, PORTUGAL

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ABSTRACT

Possible contributing factors to the 1978 failure of the massive main breakwater at Sines, Portugal are presented in a selective summary of the report of the Port Sines Investigating Panel. A failure scenario involving the impact breakage of unreinforced concrete armor units is developed.

INTRODUCTION

The final report of the Port Sinés Investigating Panel is summarized in this paper. The objective of the Panel, which was funded in part by the U.S. National Science Foundation, was to collect data concerning and to evaluate possible causes of the failure on February 26, 1978, of the massive rubble mound breakwater at Port Sines, on the Atlantic coast of Portugal.

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The breakwater at Port Sines is among the largest in the world. Further, it is situated in a previously untried combination of unusually deep water (about 50 meters at the seaward terminus) and a high-energy marine setting (the 100-year return period significant wave height was estimated to be 11 meters). Construction was nearly complete when critical damage was sustained in storm waves thought by most to be below the 11 meter significant wave height for which the structure was designed. The damage consisted of the loss of about two-thirds of the armor layer of 42 metric tons dolos units. At a few locations, the concrete superstructure was severely damaged as a result of undermining and of wave impact on the front face where loss of the dolos has occurred. Figures 1 and 2 illustrate some of the damage to the breakwater.

The structure has sustained further damage since the February 1978 storm. In December 1978 and in February 1979, storm action removed all armor protection, including some temporary remedial works placed in the fall of 1978, from the seaward 1.5 km of the breakwater. Much of the concrete superstructure has been lost.

The scope of the Panel's study, as delineated in the proposal to the National Science Foundation for the Sines investigation, covered four simplified failure possibilities: (1) that design criteria were exceeded by the February 1978 storm; (2) that the breakwater construction was faulty; (3) that the materials used for breakwater construction were sub-standard; (4) that the procedures followed during the design of the breakwater were incomplete or incorrect for this specific set of environmental conditions.

The investigation undertaken by the Panel was based on two site visits and on discussions with responsible Portugese authorities, the design engineers, the engineers of the Portuguese hydraulic laboratory (LNEC), and the officials of the construction company. The objective of the investigation was to report on possible problems, omissions, and errors that could have contributed to the failure of the Sines breakwater. It is the hope of the Panel that engineers will be able to benefit from the experience at Sines in the design of future breakwaters.

PROJECT DESCRIPTION

The Sines breakwater is the most critical single component of a vast industrial complex planned by the Portuguese government. The Atlantic deepwater port and extensive landside facilities depend on the efficient, safe operation of the port, which in turn depends on the breakwater. Port Sines, about 100 km south of Lishon on the Atlantic coast, lies along the present international routes for crude oil and iron ore carriers. The site has the steep ocean falloff needed for a supertanker port; required depths for an oil terminal occur within 0.5 to 1.5 km of the shore.

Development of a major port at Sines involved the construction of the main breakwater in depths of up to 50 meters. A layout of the port

Figure 1 Damage to the wavewall and dolos, taken immediately after the February 1978 storm (photo from GAS)

Figure 2 Dolos removed from the front of the wavewall and broken dolos and superstructure (photo from GAS)

facility is given in Figure 3. Design was begun in 1972 by a consortium (BCL) of Bertlin and Partners of the United Kingdom and Consulmar and Lusotechna, both of Lisbon; the contractor chosen was Societa Italiana per Condotte d'Acqua of Italy. Construction began in mid-1973.

The breakwater is a dual-purpose structure, supporting oil pipelines as well as providing shelter from the Atlantic for the port. A quarry fill core is armored with heavier-cut stone, and on the seaward side that "selected" stone is blanketed with 42 metric concrete dolos. A concrete superstructure includes a wave wall, an inner (portside) roadway, and support for the oil pipelines. The latter are intended to serve the three harbor-side berths, built on caissons and connected to the breakwater. The three berths, beginning with the closest to shore, are intended to accommodate 100,000, 350,000 and 500,000 DWT tankers, respectively. A cross-section of the final breakwater design is shown on Figure 4.

About 160 square miles of inland facilities also depend on the port. These included an oil refinery, a steel mill, a pyrite plant, a petrochemical complex, and other industry, both heavy and light. Yet another aspect of the master plan is a "new town", for which a population of about 100,000 has been projected. Over 5,000 dwellings are complete, and the construction of schools, recreation centers, shopping facilities and related infrastructure are all underway.

The Gabinete da Area de Sines (GAS) has been the responsible Covernment agency for the entire Sines development since the project inception over a decade ago. At the time of the failure in February 1978, the Portuguese government is reported to have spent $176,000,000 on the breakwater alone.

PANEL REPORT

The report prepared by the Panel includes discussions of the project, the physical setting and environment, the design and construction of the breakwater, the storm of February 1978, the status of the breakwater after the storm, studies performed after the failure, and considerations in evaluation of the failure. The report also includes appendices containing official replies to investigative inquiries, photographs of the damaged sections, records of dolos placement, summaries of wave climate during construction, and the like. The report is currently in final review by the Coastal Engineering Research Council of the American Society of Civil Engineers and should be available to practicing engineers and other interested parties in the near future.

No attempt has been made in this paper to completely summarize the report. Rather, the following sections present factors which may have contributed to the failure of the breakwater and a failure scenario which appears to fit the available evidence. It is recommended that the report and other published information be studied carefully by coastal engineers charged with the design and construction of future major shore protection structures.

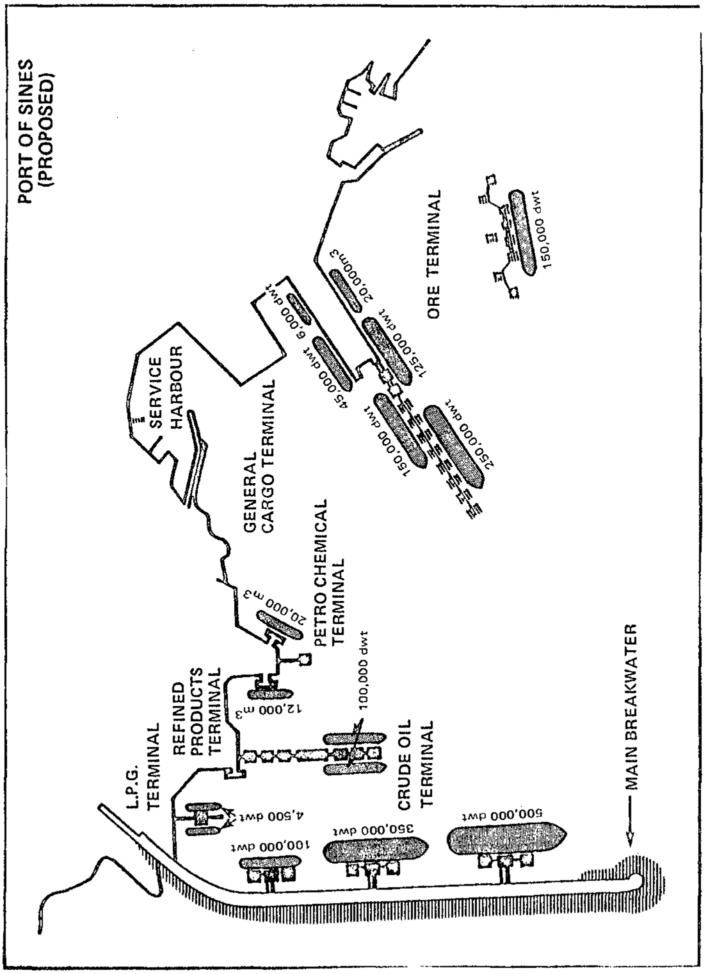

FIGURE 3 Proposed layout of the Port of Sines

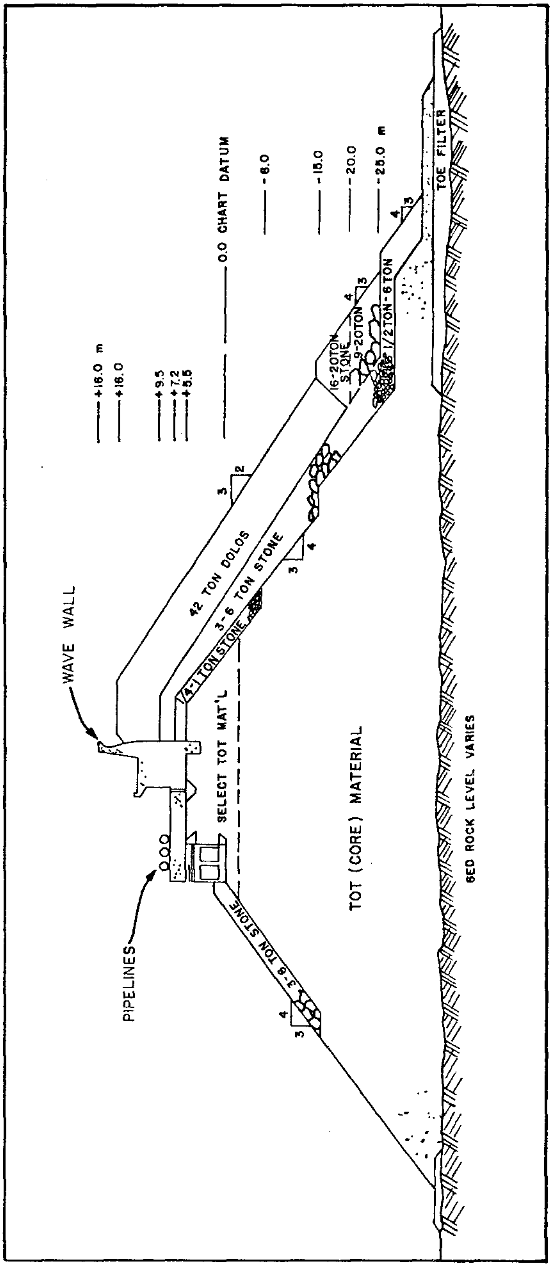

Figure 4 Cross-section of the final design

POSSIBLE FACTORS CONTRIBUTING TO FAILURE

In a project this complex, there are many possibilities for uncertainties in design and construction. What follows is a compilation of possible contributing factors mentioned to or observed by the Panel. Some appear to be difficulties inherent in any large construction project; others are more specifically related to the Sines project. They are all a legitimate part of the Sines data and should be taken into account when additional study of the Sines failure is in order and when future projects of this sort are considered. It is stressed that the list of factors should not be interpreted as identifying the cause(s) of failure.

Owner-Designer-Contractor Relationships

The designer (BCL) felt the primary area of concern was that they had no control over the execution of their plans during construction. In many cases, the designer is retained for inspection purposes or is the technical agent dealing with the contractor for the client. In the case of Sines, the Gabinete da Area de Sines (GAS) retained all inspection and technical supervision of the project. It may also be important to note that all official communication was in Portuguese. This may have contributed to difficulties in communication among the English design firm, the Italian contractor, and the Portuguese authorities.

Selection of Design Waves

Wave data available for the initial design of the Sines breakwater were sparse. Even by the end of the design process only a minimal amount of wave data were available. Thus it was difficult to estimate the design wave conditions with a high level of statistical reliability. The 100-year storm design wave belongs to a different statistical population than the non-storm design wave commonly measured along the Atlantic coast of Portugal. Moreover, it is commonly accepted that the extrapolation of extreme value events should not extend more than two or three times the total length of record. Nevertheless, project demands do at times dictate that insufficient data be used. Under these conditions, the designer's recourse is to perform a detailed error or confidence analysis of the data.

The effects of refraction and wave groupings were not considered in the selection of the design wave. Zwamborn (1979) says that:

> "it appears that no tests were done on the final design,... using irregular waves of sufficient duration (say 6 to 12 hours prototype) with a significant wave height equal to or exceeding the design wave height of 11 m."

Furthermore, Zwamborn cites studies done by the French hydraulic laboratory (LCHF) after the failure:

> "recent tests carried out by the LCHF showed that for wave periods between 16 to 18 s and wave heights in excess of 11 m, the vertical

upward water velocity near the still water line could be the same order of magnitude as the terminal settling velocity of 42-t dolosse in still water. As a result, groups of dolosse could be lifted from the slope by these long and high waves, a phenomenon frequently observed in model tests."

Three particular items that escaped consideration in the design wave selection were: (1) climatic analysis, an overall review that would show protection of the Portuguese coast by the Azores high and show the dependency of the results of a climatic analysis on the phenomenon; (2) error analysis, identification of the accuracy of the design wave; and (3) shallow water effects on the available recorded wave data and on the waves approaching the Sines area.

Storm of February 26, 1978

As indicated in the Panel's report, it is extremely difficult to identify the size of the waves that occurred on February 26 and those that preceded that day. The data measured at Cabo da Roca indicate waves with a significant height of 8 to 9 m. Refraction analyses by LCHF indicate significantly larger waves may have occurred at the structure. Because the wave recorder was not working, an indisputable definition of the wave field will never be available.

Breakwater Design

Although the breakwater was designed using available methods, the design still may not have been sufficient to resist the forces exerted by the February 1978 storm; this is not a criticism of the design but of the available references for design. The design for this very deep site which is exposed to deep ocean waves was predicated on an extension of the procedures which were well-understood for small breakwaters in shallow water conditions. Another aspect of the design that causes some concern is the complexity of the breakwater cross-section; the section would be difficult to inspect, as well as to construct, in these extreme water depths.

Dolos Placement

One item of concern is the ability of the floating cranes to adequately place the dolos above and below the water in characteristically rough conditions. The dolos were not placed by location but by density (instead of a coordinate for a particular dolos, a certain number were to be placed in a given area). Underwater inspection of dolos placement was infrequent because of the heavy seas during most of the year. Zwamborn (1979) reports that between 3.5 and 16.8 percent of the dolos in a sampled section were broken by August 1977 as a result of placement, settlement of the structure, and/or previous storms. Arrangement of the dolos was generally random (not with 60 percent having the vertical leg seaward as specified in the design, although the significance of this criteria has been discounted).

Dolos Reinforcement

The dolos were not reinforced. Subsequent to the February 1978 storm, some reinforced units were used as a test for the outer layer of dolos, to prepare the breakwater for the coming winter; both reinforced and unreinforced units sustained extreme damage in the 1978-1979 winter. This application of reinforced armor units (of both types) should not be considered a true test of the response of the original structure to storm waves.

Model Studies

The official model studies were done by Laboratorio Nacional de Engenharia Civil (LNEC) for CAS and not for the designer. Therefore, indirect communication resulted. The results of the irregular wave tests were not available to the designer before the design was complete. The model tests did not account for the effect of wave grouping that occurs in the wave data recorded at Sines. Refraction was also not analyzed or considered in the model studies. The model tests were not designed to simulate structural properties of the dolos armor units.

Permeability of the Core

The permeability of the quarry run (TOT) material in the core may have been significantly less in some sectors than that used in the model tests and specified in the contract. This difference may have resulted in added wave run-up on the face of the breakwater; and this, in turn, may have had an adverse effect on the stability of the armor layer. It is important to recognize that the stability of the armor layer might be jeopardized by the increased wave run-up that would result from a lack of permeability of the core. The volume of both wave uprush and the return flow down the face of the breakwater would impose a greater force on the individual breakwater armor units and could cause their dislodgment from the protective layer.

OFFICIAL STATEMENTS OF CAUSE

Several investigations have been conducted, at various levels of effort, to understand and identify the causes of failure. One of the first assessments was made by a team of Dutch engineers. They concluded that a likely cause of failure was the removal of the 16 to 20 t stone from the toe by the larger waves; subsequent to the removal of these stones the dolos layer shifted and was damaged.

The National Research Institute for Oceanography, South Africa, noted the cause of failure as follows:

> "...the main causes of the damage and part failure of the Sines main breakwater during the February 1978 storm are the particularly damaging effect of the large waves in the spectrum which, because of the great water depth in front of the breakwater, could reach the structure without being reduced by prior breaking.

With a probable incident significant wave height during the peak of the storm of 9.5 to 10 m, maximum incident wave heights of at least 14 to 17 m must have occurred which, although infrequent, caused excessive movements of dolosse, probably resulting in breakages, particularly at and just below the still water level, thereby weakening the armor. In addition, the wave heights of the longer waves (peak periods at the height of the storm were 18 to 20 s) were locally increased due to wave refraction causing both the significant and the maximum wave heights in the failure areas to increase by, on average, 20 percent, that is to about 12 m and 17 to 20 m, respectively. These waves resulted in the removal and further breakage of the dolosse causing the collapse of the superstructure in the failure areas." (Zwamborn, 1979).

The official comments from the design team (BCL) have been included in the Panel's report. In these comments the problem is focused on project management, supervision, and construction. Mr. Peter Mornement of Bertlin & Partners, in an interview with the New Civil Engineer, said "we are sure inaccurate placing of the dolos and the supporting toe were the main causes of failure."

The official Portuguese investigation team filed their report with the Government in April 1979. Some of their conclusions are presented below:

- Structural fragility of the dolos was the primary cause of failure.
- There were serious shortcomings in the design wave selection.
- The design of the breakwater was "theoretical" and difficult to build.
- Consideration was not given to refraction of wave energy.
- The LNEC was not exhaustive enough in its testing program.
- The reliability of the dolos should have been questioned.
- Gabinete da Area de Sines did not have the capability to plan and execute a marine project of such magnitude.
- There were shortcomings in the management and supervision of the project by CAS.
- LNEC should have had a more active role in the design phase.

A FAILURE SCENARIO

The causes of failure and the sequence of events leading to the failed armor layer during the storm of February 26, 1978 will never be completely defined. This is because of the scarcity of information concerning the exact state of the structure prior to the storm, the wave conditions at the breakwater during the storm, and the condition of the breakwater during the storm. Many explanations of the cause of failure have been proposed, and the state of the breakwater following the storm was such that any number of events might have caused or contributed to the failure.

A description of the probable pattern of events leading to the destruction of the armor layer is proposed by the authors. The critical observations leading to the failure scenario are those on the extensive breakage of the dolos, the profile of the damaged breakwater, the model tests with irregular waves which showed rocking of dolos, the model tests with the artificially weakened dolos, and personal experiences with other breakwaters. It is the Panel's opinion that this description is plausible in that it fits with the available evidence. It is recognized that other failure scenarios can be proposed from the available data.

In the early stages of the storm, when the significant wave height reached 6 m, some dolos units began to move in the vicinity of the mean water level. These units were the ones which had been placed in a relatively unstable position and had little support from the adjacent units. (It is practically impossible to place dolos so that every unit is in a stable position.) The initial movements occurred when a larger wave ran up through the armor layer.

As the wave height and period increased, the movements became more severe and the units were accelerated to the velocity of the uprushing wave. The following impact with adjacent units produced stresses in the units that exceeded the strength of concrete. This resulted in breakage, and frequently the pieces were carried away by the uprushing or downrushing wave. During this process, the pieces themselves collided with other units, in some cases causing additional breakage.

At the peak of the storm, when the significant wave height exceeded 8 m, a large number of units located just below the water level broke. As the pieces were carried away, adjacent units were free to move and a rapid disintegration of the armor layer occurred. Initially the greatest damage occurred immediately below the mean water level. The broken pieces were moved by water motion and gravity from the armor layer to the lower part of the mound. The slope of the seaward side of the breakwater below the water level then became flatter.

During the final stages of the storm the armor layer was completely removed at some locations. The broken dolos pieces were displaced to the base of the armor layer and the underlying stone layers were exposed. Wave action then moved these exposed stones over the broken dolos pieces. Continuing wave action eroded the core material and began to undermine the superstructure.

As the concrete superstructure was undermined it tilted forward. In some instances, the structure broke in the base (where the pipelines carrying petroleum from the berths to shore would be located) and at some of these locations the wave wall at the top of the structure was snapped off and thrown back as a result of wave impact.

The reasoning leading to the above scenario of the failure of the Sines breakwater suggests the following:

- The dolos units rocked, broke and moved in the armor layer under the wave conditions that existed during the storm of February 26, 1978.
- The dolos units were of sufficient strength to withstand the forces of wave action except when they moved. In movement, however, they were unable to resist the impact stresses produced.

Support for the argument that the damage occurred as a result of breakage of dolos units is provided by model studies, prototype testing of dolos strength, and observation of damage to the Sines and other breakwaters.

CONCLUSIONS

In recent years, coastal and nearshore rubble mound structures (both proposed and constructed) have become much more massive and have been sited in deeper water than ever before. Examples of this sort of structure include breakwaters for petroleum terminals and offshore power plants and artificial islands for petroleum exploration and production facilities.

For critical facilities such as these, many traditional assumptions of rubble mound design and construction are being reexamined in response to environmental and safety concerns and the harsh economic consequences which accompany disruptions in energy supplies. One example of the design profession's recognition of these concerns is the recent emphasis on the evaluation of extreme wave conditions and their potential effect on the integrity of the structure, especially in cases where concrete armor units are utilized; another is the renewed interest in the management of design, construction, and inspection services.

The case history of the failure of the main breakwater at Port Sines is believed to be an important addition to coastal engineering knowledge. The members of the Panel hope that engineers will be able to benefit from the Sines experience in the design and construction of future breakwaters.

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