Rock Borer Attack on Juaymah Trestle Concrete Piles

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SYNOPSIS Rock boring mollusks and sponges are infesting the concrete cylinder piles supporting the Juaymah NGL Trestle located in the western Arabian Gulf. The calcareous aggregate used in pile fabrication provides a favorable substrate for borer activity. Rock boring organisms are common in the Arabian Gulf and typically inhabit nearshore reefs and exposed limestone bottom areas. Although the entire trestle wetted area is subject to attack, infestation is concentrated in the area adjacent to reefs and limestone, on the down current pile face and near the water surface. Boring organisms pose a significant threat to the trestle structural integrity, in that boreholes will deteriorate concrete and expose outer pile reinforcement to corrosive sea water. Serious pile damage is imminent. The entire submerged portion of the structure will be adversely effected if repairs are not performed. Pile deterioration to date has been retarded by the excellent durability of the concrete cylinder piles. Several pile repair systems have been evaluated. Molded fiberglass jackets with epoxy grout fill were selected on the basis of borer and abrasion resistance, low profile, service life and favorable open sea installation characteristics.

INTRODUCTION

Rock boring mollusks and sponges were discovered in the Juaymah NGL Trestle concrete cylinder piles during a crack inspection performed in April 1982, about four years after construction. This unexpected form of environmental attack was found on all of the piles inspected, throughout the wetted area. Infestation seemed to be concentrated near the water surface, in the quadrant extending from south through west. Apparently the Juaymah Trestle is the first structure of major consequence to suffer serious damage from rock borers.

Shortly after the rock borers were discovered efforts were made to identify the organisms, determine growth rates, assess the present degree of deterioration, project potential damage and select a repair system.

FACILITY DESCRIPTION

The Juaymah NGL Trestle is located on the east coast Saudi Arabia and extends approximately 9.8 kilometers into the Arabian Gulf, connecting the onshore Juaymah Gas Plant to an offshore loading facility (See Figure 1). The trestle consists of a precast concrete pipeway/roadway supported on precast post-tensioned concrete cylinder piles fabricated in Ras Al-Khaimah, United Arab Emirates. Existing water depths along the trestle vary from about 4 meters to 25 meters Indian Spring Low Water. (ISLW).

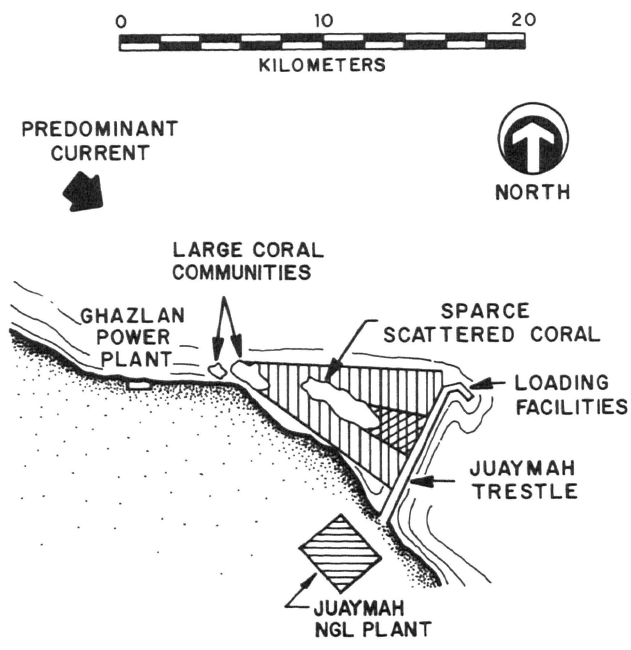

Figure 1 Location Plan Juaymah NGL Trestle

Pile installation was begun in February 1978 and was completed in March 1979. During this period 258 pile bents, consisting of 1503 concrete cylinder piles were installed. 1171 piles are 1.37m outside diameter and 332 piles are 1.68m in diameter. Most pile bents consist of four cylinder piles with more piles at batter pile bents and expansion loop bents (See Figures 2 and 3).

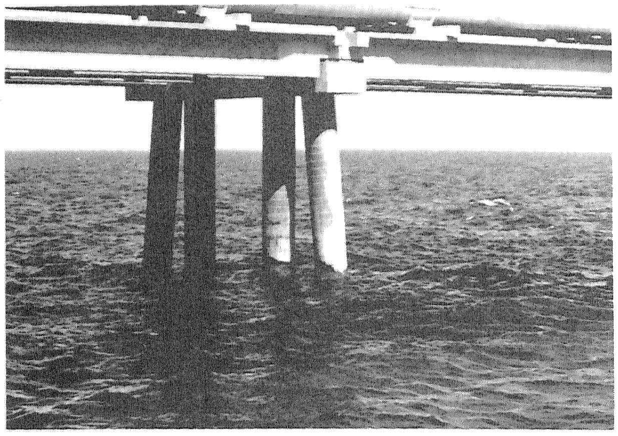

Figure 2 Typical Four Pile Bent

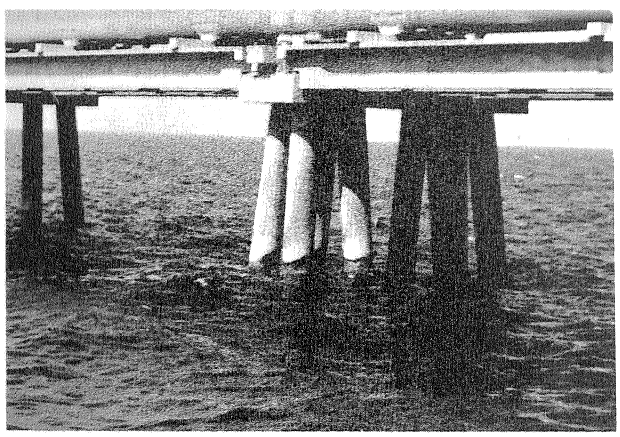

Figure 3 Typical Batter Pile Bent

Structural Summary

Trestle piles consist of centrifugal cast concrete cylinders, 2.44m and 4.88m long, assembled to provide piles between 18.6m and 50.3m in length. Pile reinforcement consists of 6mm ASTM-82 spiral steel and #3 bars as longitudinal spiral spacers. Minimum cover over the spiral reinforcement is 38mm.

Assembled piles were post tensioned using two 13mm diameter, Grade 270, ASTM A-416, steel strands per cable conduit, post tensioned to 128.6 KN each. Typical 1.37m OD piles contain between 16 and 24 cables centered in a nominal 127mm pile wall. 1.68m OD piles contain 24 to 32 cables centered in a nominal 152mm pile wall. Subsequent to post tensioning, both cylindrical section joints and post tensioning strand conduits were sealed with a cement based grout.

Pile concrete contained approximately 49 percent coarse aggregate, 24 percent sand and 27 percent cement/water paste by volume. Coarse aggregate and sand were each about 96 percent calcareous material, yielding a total concrete volume with greater than 70 percent calcareous material. Comparing the Juaymah piles to other cylinder piles cast around the world, the calcareous aggregrate content is markedly higher in the Juaymah piles.

Compression tests performed during construction showed that the concrete consistently exceeded the specified 48.3 MPa compressive strength.

Geotechnical Summary

Preconstruction soil borings drilled at 300 meter centers along the trestle alignment indicate a gradually sloping bottom extending from about -1 meter ISLW at the inshore trestle terminus to approximately -11 meters ISLW at about 7.6 kilometers from shore (See Figure 4). At this point the bottom slope steepens, dropping from -11 meters at an apparent natural reef to about -25 meters ISLW at the trestle terminus.

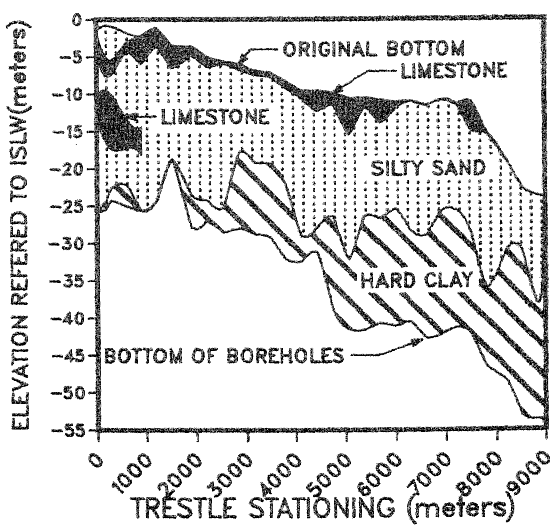

Figure 4 Interpolated Soil Profile

The existing bottom along the inshore 6.0 kilometers of the trestle is generally characterized by surface limestone 0 to 5 meters thick, overlying between 5 to 20 meters of fine to silty fine carbonate sand. Beneath the sand strata lies a mildly undulating hard clay, typifying a Pleistocene erosional surface.

Prior to pile installation the existing bottom was dredged to -4 meters ISLW for construction barge access. Dredging extended about 2 kilometers from shore. Existing surface limestone was removed in the immediate vicinity of the trestle throughout this length.

Trestle piles were installed in predrilled holes and driven the final 1.5 meters to confirm end bearing capacity. The annulus that existed between the predrilled hole and the pile was left to cave in or fill with migrating sand. Hence, the sea floor immediately adjacent to the majority of these piles is locally depressed, exposing additional pile length. Compression, tension and lateral pile load tests were performed to verify pile capacity.

Summary of Littoral Forces

Environmental exposure along the trestle varies with water depth. Tidal excursions are semi-diurnal with a mean tidal range of 1.16 meters. Mean sea level is about 0.97 meters above ISLW.

Currents in the trestle area are both wind driven and tidal in nature. Waves are directional and depth limited along most of the trestle length. Wave directionality results from the highly predominant northwest winds.

DIVER INSPECTIONS

Two diver inspections were performed on various trestle piles. The first inspection was carried out in April 1982 as part of a general crack survey encompassing the trestle superstructure and piles. A total of 19 piles at various locations along the trestle were hand cleaned and carefully inspected by divers. Data gathered included a general description of surficial marine growth, video recordings, still photographs and spot measurements of bored holes in the piles.

Generally, inspection records indicate surficial marine growth consisting of white coral, barnacles, red coral and sponges. Cleaned pile surfaces contained small cracks, closely spaced shallow holes and more widely spaced deeper holes (See Figures 5 and 6). Cracks were usually faced with a hard white substance, indicative of calcium carbonate efflorescence (autogenous healing). Closely spaced sponge holes were observed at one location on the 19 piles inspected. Measurements indicated upto 1600 holes per 0.1 square meter, averaging about 15mm in depth. The pile surface in this area was reported to be slightly depressed as a result of surface slaking.
The more widely spaced holes were occupied by small mollusks. Spot measurements recorded concentrations of up to 200 holes per 0.1 square meter with an average count of about 5 to 10 holes per 0.1 square meter on the down current pile face. The measured holes ranged up to 35mm deep and 13mm diameter, but average infestation was about 20mm deep by 6mm diameter. For the most part, borer attack was concentrated on the down current side of the piles, on the south through west quadrant. Mollusk and sponge specimens were retrieved for identification and study.

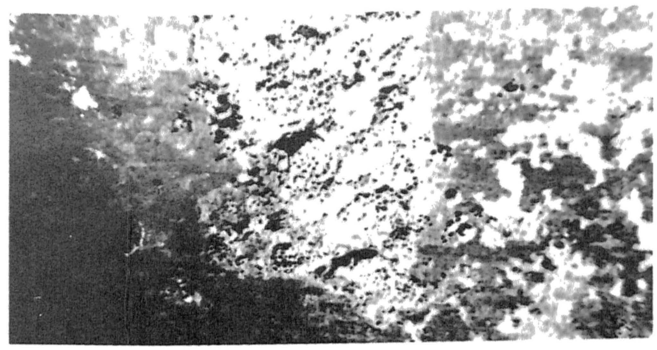

Figure 5 Pile Surface With Closely Spaced Sponge Boreholes

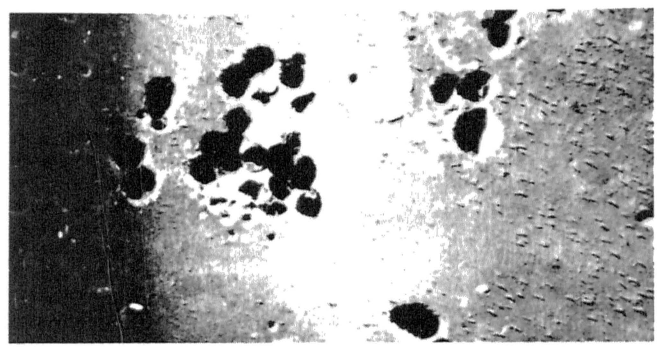

Figure 6 Pile Surface With Mollusk Boreholes

The second diver inspection was performed in November 1982. Four previously inspected piles were reinspected for changes with respect to the original observations. Pile surfaces had remained clear of major growth, permitting video, photographs and spot measurements as performed in the first inspection. Reinspection of piles indicated slightly increased infestation, apparently accelerated by cleaning.

RECOVERED PILE SECTION

A damaged concrete pile was discovered lying exposed on the gulf bottom along the outshore portion of the trestel during the November 1982 diver inspection. The water depth at the pile location was approximately 24 meters ISLW. Reportedly, the pile had been damaged during driving and was abandoned. Based on the pile installation records for the surrounding bents, it was estimated that the damaged pile had lay undisturbed since late November 1978, approximately four years.

A section of the damaged pile approximately 4.6 meters long, was retrieved in March 1983. The outside diameter of the pile section was approximately 1.68 meters. The saw cut end of the pile exposed sound concrete and the end surface of 28 post-tensioning tendons. There was no visible deterioration of steel, concrete or aggregate at the saw cut. The remaining pile surface, inside and outside, was covered with marine growth. The other end of the pile had been preserved in its undisturbed seabed condition. The concrete surface in this area was irregular consisting of numerous broken pieces connected to the main pile section by exposed reinforcing steel. Marine growth covered the entire surface of these pieces. Reinforcing steel extended from the concrete surface at numerous locations at this end of the pile. The exposed post tensioning tendons were in good condition with surface rust and no major deterioration. The spiral bars and longitudinal bars had corroded at the exposed ends leaving long tapered points. Lengths of reinforcement that connected the broken concrete pieces to the main section of pile exhibited surface oxidation and negligible loss of steel.

Five concrete samples were taken from the exposed end of the pile. Three samples were saw cut into slices exposing embedded aggregate and reinforcement. Two samples were cored for laboratory strength testing.

Concrete adjacent to the sample surfaces contained numerous small holes and several large holes. Small clustered holes were identified as sponge attack (See Figure 7). This form of infestation was limited to aggregate in the outer concrete surface. Aggregate exposed to sponge were perforated with holes averaging 1mm in diameter and extending to 15mm. Larger mollusk boreholes were up to 15mm deep and 5mm in diameter. Generally, mollusk holes extended through both aggregate and cement, and were coated on the interior with a thin calcareous film (See Figure 8).

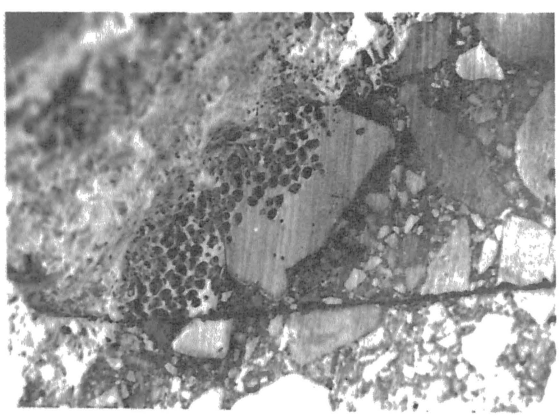

Figure 7 Sawcut Pile Section showing Sponge Infestation in Concrete Aggregate

Figure 8 Mollusk Borehole In Sawcut Pile Section

Embedded reinforcing steel, exposed in concrete slices was in good condition, with active corrosion extending about 4mm from the outer concrete surface. Steel loss was negligible.

Chemical tests performed on samples of aggregate and concrete taken 20mm from the exposed surface, indicated pH levels of 11.0 and 12.6 respectively. Considering the small highly exposed concrete samples that were tested, it is probable that intact pile concrete has maintained a higher pH, thus retarding reinforcement corrosion.

Two cores were cut from the sample pile sections and tested for compressive strength. These samples were maintained in a sea water saturated state. Test results indicated strengths of 50.7 MPa for each sample.

BORER IDENTIFICATION

Specimens of the rock borers have been identified as genus Lithophaga, rock boring mollusk, (See Figure 9) and genus Cliona, rock boring sponge. Their existence in the Arabian Gulf is well documented in marine biological literature (Vita-Finzi & Cornelius and Thomassin 1973). Both organisms are filter feeders, deriving nutrients and oxygen from surrounding water. Both bore primarily by chemical action, favoring calcareous substrates. The pattern of infestation differs markedly between the organisms. The mollusk attack is widespread and relatively deep, while the sponge attack is localized and shallow.

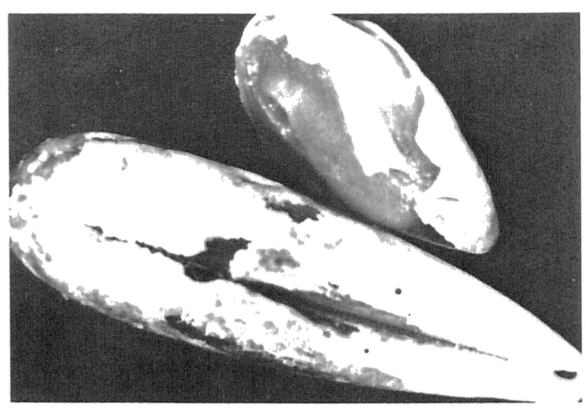

Figure 9 Rock Boring Mollusk-Genus Lithophaga

Boring Mollusks

As a filter feeder, Lithophaga requires constantly renewed clean water for survival. The chemical boring action used is most effective in breaking down the highly calcareous local sedimentary rocks and coral. Hence, the natural habitats of this bivalve are the reefs and exposed limestone bottom of the Arabian Gulf. Bored holes in rock and coral serve solely as protective enclosures for the mollusk.

Historically these borers have been found in water depths up to 90 meters. However, they favor shallow depths during the larval stage. Existing colonies produce an almost constant stream of larvae, which are released to drift with the currents.

The microscopic larvae are planktonic and photoattic. They migrate to the near surface area where sunlight, oxygen and food are abundant. Eventually the organisms descend through the water in search of a host. Metamorphosis is initiated when suitable conditions are encountered, i.e. calcareous substrate, low energy environment, abundant clean water and nutrients.

Mature mollusks can grow to 100mm long (Vita-Finzi & Cornelius 1973, Warme & Marshall, 1969 and Kleeman, 1969). The typical mature borehole is 10mm inside diameter. Growth measurements indicate a rate of 10mm per year in most natural material. Borer penetration into the substrate is generally perpendicular to the outer surface. However, where high concentrations of borers exist, it is common for holes to interconnect.

In light of the mollusks reproductive and development cycle, it is probable that if left unchecked, infestation would culminate in near surface borer saturation spreading down the full exposed pile length. It is also notable that secondary attack by less formidable boring organisms that inhabit abandoned mollusk boreholes will result in continued concrete deterioration, subsequent to the disappearance of the mollusk (Warme & Marshal, 1969).

Boring Sponges

Cliona is a filter feeding organism that bores and scarifies by chemical action, similar to the mollusks. It also bores effectively in highly calcareous materials, but differs from the mollusk in that the sponge uses bored holes to fasten itself to a fixed substrate with its mass exposed. This type of sponge is common in the Arabian Gulf, but it does not proliforate as does the mollusk. Cliona is apparently insensitive to water depth and generally reproduces sexually or asexually.

This sponge bores shallow, closely spaced small diameter holes, which often interconnect. The attack is generally concentrated in small areas. As the degree of honeycomb increases, surface material crumbles away and new substrate is exposed. In hard substrate, such as the Juaymah piles, deterioration is relatively slow.

PILE DETERIORATION

Underwater inspections and analysis of concrete samples recovered from a damaged trestle pile show no evidence of usual pile deterioration, such as surface spalling and corrosion of reinforcement. Recorded damage consists primarily of mollusk and sponge boreholes. It is clear however, that mollusk infestation is more serious, since these borers multiply rapidly, and penetrate both aggregate and cement paste to depths greater than the thickness of concrete reinforcement cover.

To date concrete loss due to borer attack is relatively small with little impact on the structural integrity of the piles. It is expected that the rate of future borer infestation, especially mollusks, will remain constant as a result of the near proximity of heavily infested coral reefs immediately upstream of the trestle (See Figure 1).

Concrete loss due to boring activity will increase at an almost constant rate. Boreholes will expose additional concrete surface to seawater infiltration. As a result, cement paste may be leached from the concrete, resulting in spalling.

Deeper penetration of mollusk boreholes, will reduce concrete cover on reinforcing steel, allowing seawater to penetrate the concrete, supplying oxygen and chlorides to the steel surface and initiating corrosion. The active warm water environment of the Arabian Gulf provides the conditions necessary to perpetuate borer initiated concrete deterioration and steel corrosion.

Thus far the consistent high density concrete used in these piles has shown excellent resistance to seawater infiltration. In addition, centrifugal casting has provided an exceptional steel/cement bond. Hence, pile deterioration has been retarded by the durable nature of these piles. It is therefore, concluded that although pile deterioration is immenent, the resistant nature of the centrifugal cast concrete cylinder piles will allow them to withstand future exposure during the performance of repairs without loss of structural integrity.

PILE REPAIR ALTERNATIVES

Several repair alternatives were studied for use on the trestle piles:

1) Impermeable plastic surface wrap
2) Underwater epoxy paints
3) Impressed current
4) Polyester bags with cement grout
5) Molded fiberglass jackets with epoxy grout

The molded fiberglass jacket with epoxy grouted annulus was selected on the basis of borer, impact and abrasion resistance, low exposure profile, extended services life, rapid curing characteristics and general suitability for open sea installations.

CONCLUSIONS

Based on the foregoing it is concluded that:

1) Comprehensive study of potential biodeterioration should be included in the design of all major structures.

2) Rock boring organisms favor the highly caleareous concrete used in the trestle piles.

3) Sources of rock borers are the coral reefs and exposed limestone bottom immediately surrounding the trestle.

4) Borer attack impacts the entire wetted pile surface, and is concentrated near the water surface on the down current side of the piles.

5) Pile cleaning exposes additional concrete surface area to concentrated borer attack, accelerating infestation.

6) Mollusk boreholes are the more serious form of infestation, accelerating concrete and steel deterioration.

7) Concrete loss resulting from reinforcing steel corrosion presents the most serious threat of pile damage.

8) Serious pile damage has been delayed by the excellent durability of the cylinder piles.

9) Molded fiberglass jackets with epoxy grout have been selected to repair the structure and provide the desired pile protection.

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