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A Study of Pile Fatigue Failures in the Arabian Gulf

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ABSTRACT

In the summer of 1974, construction commenced for an oil tanker terminal in the Arabian Gulf. The following winter, a particularly strong tropical storm hit after the piles were driven, prior to installation of the superstructure. Without the superstructure, the piles were lacking in lateral support and, as a result, two of the piles failed at the mudline due to fatigue. After further investigation, two other piles were determined to have suffered through-thickness fatigue cracks. These events triggered studies to ensure that further fatigue issues would not follow in the replacement piles, as well as to explain the fatigue failure mechanism.

The studies outlined the following two topics. First, the motion response of cantilever piles in the ocean. As the piles were not yet supported by the superstructure, they were subjected to additional forces and the freedom to bend in ways that may have caused overstressing at the mudline. The next area of study was the fatigue damage due to cyclic stress associated with motion response. Essentially, the repetitive motions of the waves may produce a cyclic motion in the piles, causing repetitive stress at the same point, namely the mudline in this case.

This report will utilize this situation as a case study to discuss the failure that occurred in the piles and why. An introduction to pile design and the various construction methods will be outlined, as well as an overview of the studies performed and their results.

1 INTRODUCTION

Many studies were done surrounding the 1974 construction of an oil tanker loading terminal located in the Northern Arabian Gulf (Figure 1). These studies were developed based on an incident that occurred during the construction of the pile foundation support structure. Failures observed in the piles following strong seasonal storm waves were analysed to determine whether they would occur again, the cause of the failure and, in general, the causes of fatigue based failures.

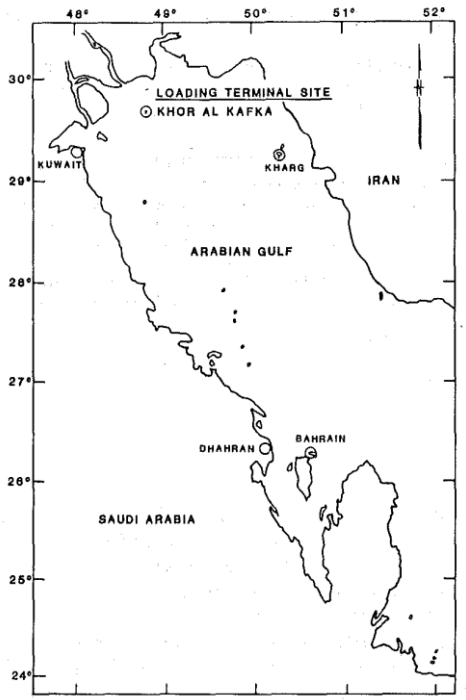

Figure 1 – Project Location

Construction for the terminal commenced in August of 1974. The terminal, comprised of several structures, contained four (4) berths designed to accommodate tankers of varying size. The structures making up the terminal were connected by bridges, which were supported by a pile foundation. The piles were tubular steel, driven as foundation support for the pre-fabricated superstructure. There were 167 piles driven from August through to the following December, as weather and waves got rougher. Both vertical and battered piles were driven, some in groups and some standing alone. The battered piles were in an inverted "V" formation. They were tied together using structural angles and capped to prevent in-plane motion (Figure 2). During construction, it was decided that the single standing piles would be tied in to the battered piles to make use of the extra stability, reducing motion during construction prior to the installation of the superstructure. These ties were developed using ¾ in. wire rope and turnbuckles (for tension).

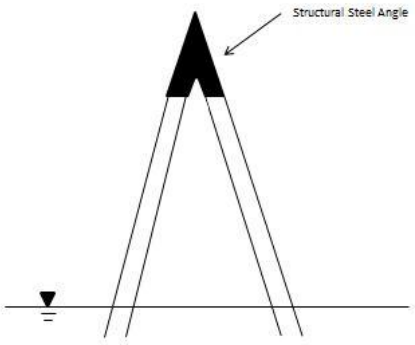

Figure 2 – Batter Piles

The force on the free piles due to the wave loading caused significant moments at the mudline. In December of 1974, a particularly large storm hit, and two days later it was discovered that two of the

piles had failed and cracked at the mudline girth butt weld. A butt weld is a weld between two parallel objects that are pushed together but do not overlap, i.e. no additional components are used. Essentially, the girth butt weld connects two lengths of hallow steel pipe pile together around the circumference. The cracked piles were removed and larger diameter piles were fitted over the existing bases.

After some observation, it was determined that the excessive moments exerted at the mudline during the storm resulted in fatigue failure of those two piles at the mudline. Further investigation showed that several other piles showed cracks at the mudline, some larger than others. This discovery triggered a more in-depth study to determine whether the piles would fail in the future and why the fatigue occurred in the first place.

The following section discusses the basics of steel pipe pile design. The discussion will then carry into the outcomes and results of the studies, including why the fatigue failure occurred in this case, as well as other general discoveries about fatigue in steel piles due to dynamic loading.

2 BACKGROUND – STEEL PILE DESIGN

The function of a pile foundation is to transmit the applied load to the bearing ground, as well as to resist lateral and uplift loading. The structure consists of pile caps and piles. Piles can be made of wood, concrete, or steel, and can be driven or bored. Each material and method combination has its strengths and weaknesses.

Pile design requires several different considerations. The acting forces include the lateral and uplift forces of the submerged/soil zone (both water and soil) and the downward normal forces transmitted through the cap. The forces must be transmitted to solid bearing ground. Failure can occur due to pile failure or due to soil block failure. It should be noted that the capacity of an individual pile in a closely spaced group may be lower than that of an identical pile that is isolated. The result is that the block capacity of a group may be less than the sum of the individual piles.

Steel piles require a relatively small cross sectional area relative to their strength. As a result, they are easier to drive into the ground, and therefore can be manufactured to the full desired length. Steel piles can be cut and welded. They are often capped at the bottom with a cone shaped point welded to the member. Corrosion is a concern with the use of steel, however methods can be employed to prevent corrosion, such as tar coating or cathodic protection.

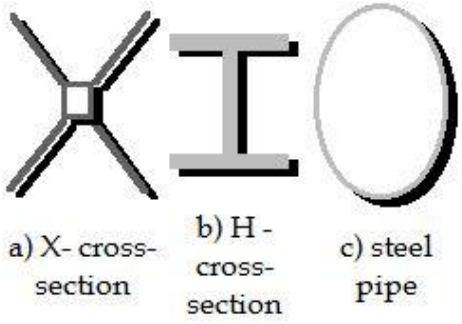

Figure 3 – Steel Pile Cross-Section Options

Piles are usually the chosen or required option in deep water conditions or when the soft soils extend relatively deep beneath the sea floor. The depth to bedrock or competent ground requires a long structure to transfer the loading through the soft soil. Piles can be used at shallow locations but the cost to anchor the piles to the bedrock usually exceeds the cost of a suitable fill type structure. Piles can

also be used to resist horizontal loading in normal ground conditions. Piles are a common choice in marine structures, such as jetties or bridge piers.

Figure 4 – Wharf Supported by Steel Piles

2.1 Required Materials

The materials required in the construction of a pile structure include the following:

- Steel piles (several lengths welded as one member)
- If utilizing the driving method, a hammer
- If utilizing the boring method, an auger or other equipment, as well as grout, bentonite, cloth, casing or other form of support required in soils
- Cap material and construction/placement equipment

2.2 Methods of Construction

There are two methods of installing piles. These methods can be displacement methods or non-displacement methods. Displacement methods essentially cause the soil to move radially or vertically as the pile is inserted. A large pile driver, which is essentially a big hammer, drives the pile into the ground. When pile driving, there are several factors to be considered, such as head room, size and weight of the pile, driving resistance, and noise restrictions.

Non-displacement methods (i.e. boring) require a hole be dug/drilled through the use of an auger or other equipment, and the pile to then be inserted. The pre-dug hole often requires some form of support to prevent caving; for stiff clays, this may only be a cloth or screen, but for granular soils one may require casings, bentonite or grout supports.

2.3 Advantages and Disadvantages

The use of piles boasts strong advantages. For one, as previously mentioned, they provide support in areas where solid ground is deep below the surface. In these cases, they are highly cost effective when compared with other alternatives that do not provide the same benefit. Piles are relatively easy to design and manufacture, and are easy to install.

One of the disadvantages to utilizing steel pile supports includes corrosion. Corrosion of steel pilings in sea water is mostly due to the establishment of localized corrosion cells and the effects of the tidal changes. Typically, a loss of 0.2-0.5 mm can be expected due to corrosion. There are, however, several frequently used and highly effective methods of preventing this, such as tar coatings or cathodic

protections. It should also be noted that the lifetime requirements of a marine structure are typically much shorter than a land structure, around 15-25 years. After the expected loss due to corrosion, the piles should be sufficient for approximately 50 years.

Other disadvantages to the use of piles are that open type structures generally require more maintenance than massive concrete or stone structures, and that piles provide less horizontal and vertical load capacity and impact resistance than closed, solid fill construction.

3 STUDY RESULTS

As previously mentioned, after the storm two piles were discovered to be cracked at the mudline due to fatigue. These were removed and replaced, as other piles were investigated. Several piles were determined to have cracks, which triggered an in-depth investigation to determine which piles may have been damaged, as well as how the fatigue failure came to be.

One possible cause of failure could be attributed to manufacture faults. The piles are formed by rolling sheets of steel into "cans" and welded longitudinally. These sections are then welded together using girth butt welds to achieve the desired length. Sometimes, a mismatch occurs where the longitudinal welds do not line up.

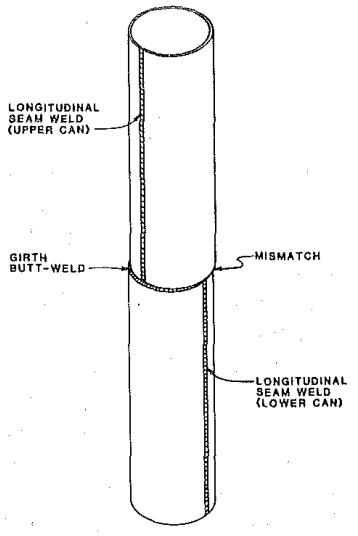

Figure 5 – Weld Mismatch

This mismatch creates a discontinuity, which interrupts bending stress patterns. As a result, it cannot deliver full curvature.

Welding quality could also have been a cause for failure. The welding procedure was changed after the first 40 piles, therefore it was a concern that the quality was poor. Loading platform A was the first constructed, therefore these piles were tested for weld quality. The testing included a radiograph scan of the girth weld to identify possible cracks. Cracks were observed, however the location of the cracks with respect to regions of lack of fusion indicated that weld quality was not a critical factor.

Fatigue had been determined; it was now necessary to prove the soundness of the existing piles and whether or not they would succumb to fatigue during the life of the structure. Radiography was used to check all uncapped piles. Mudline welds were located and cleared by a diver, and a film placed on the outside. The inside of the pile was dewatered and cleared of mud; then an x-ray source was lowered inside opposite to the weld. A 10 in. long defect was detected in on pile, and was considered

an unacceptable crack. Several others had possible defects. See Table 1 for defects detected in battered piles only.

Table 1 – Detected Cracks

Location (1)	Pile (2)	Driven (3)	Comment (4)
LPA	B-5	8/06/74	Failed 12/15/74
LPA	B-3	8/14/74	Reported down 12/20/74
LPA	C-1	8/20/74	Through thickness crack 1/25/75
LPA	D-6	9/27/74	Through thickness crack 2/03/75
LPA	C-9	10/03/74	5-in. defect in laboratory test specimen
MD5	A-1NE	10/29/74	14-in. crack, 5/8-in. deep
MD5	A-3NW	10/29/74	15-in. flaw, 1/10-in. deep

Note: 1 in. = 25.4 mm.

It then had to be determined whether a pile deemed suitable by radiography would, in fact, be suitable for the life of the structure. This was completed through uniaxial cyclic loading, applied on lengths of welded pile stubs from the mudline, both on vertical and battered piles. Of the 26 tested, 2 failed prior to reaching the number of cycles expected from the American Welding Society (AMS) X-Curve. One of the piles that failed had a large mismatch, one had a pre-existing flaw in the corner. These results indicate that a normal quality weld would be adequate for the required fatigue life.

The next concern that had to be addressed and studied was that an undetected isolated defect could grow into a through-thickness crack. For this concern, it was required that crack propogation studies must be completed to analyse the situation. This involved the estimation of design, stresses, shear resistance, and operating conditions with the superstructure installed. With this, the expected bending stresses at the mudline could be calculated (Figure 5).

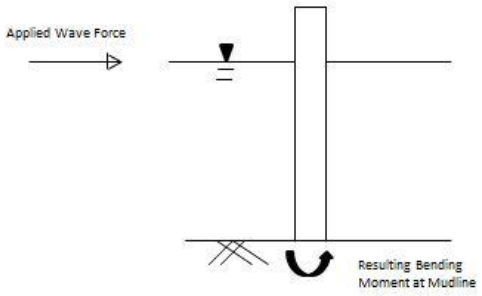

Figure 6 – Bending Stress

The bending stresses, based on all assumptions and estimations, were determined to be low in this case.

Analysts were then able to utilize crack propagation rates to determine that any crack less than 0.25 in. would not propagate to a through thickness crack during the life of the structure. It was then estimated that based on the radiograph results and the possibility that cracks were missed there was a 4% chance that a crack of this size could have been missed. Therefore, it can be assumed that all piles would withstand fatigue throughout the life of the structure and would therefore sustain the forces applied and resist failure.

4 FATIGUE DUE TO DYNAMIC LOADING

Fatigue cracks occur in situations with dynamic loading, such as wave loads. The cracks occur due to the cyclic nature of the vibrational dynamic loading. The cracks continue to open and close in a "breathing" like fashion, according to the vibration amplitude, adding continuous stresses on the area. The problem with fatigue cracks is that they are harder to detect. They open when they "breath" at the peak of a vibration due to dynamic loading, otherwise they are closed. Various studies have shown that several fatigue cracks are more of a problem than several open cracks of the same size due to the nature of the issue and the difficulties in identifying the problem. If undetected, a fatigue crack may lead to failure of the structure.

In this case, dynamic loading was considered based on the possibility that tie-backs may not have been fully effective at all times. The period of motion, for both batter and vertical piles (without tie-backs) was found to be approximately 3 seconds. The natural wave period was determined to be about the same. As a result, dynamic loading must be considered as a possible issue.

Dynamic loading is an incredibly complicated study concept with several complex physical mechanisms involved. There are many aspects that must be considered when performing an analysis of fatigue damage due to dynamic loading.

First, the wave energies vary over a wide range of frequencies and directions and are difficult to predict. In addition, the flow field and fluid pressures exist in components both in and perpendicular to the direction of the main wave propagation.

Another consideration is that the stresses vary around the diameter of the pipe due to the fact that the wave attack and resulting pile response are non-uniform. The stresses in the welds tend to be non-uniform based on the possibility of mismatch during manufacture.

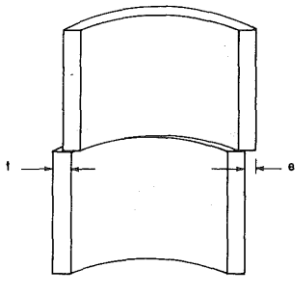

Figure 7

Due to these uncertainties, as well as others, experimental methods provide a wide range of outcomes when it comes to fatigue in dynamic loading.

Should fatigue be suspected, there are ways of detecting the resulting cracks. As discussed, methods of detecting fatigue cracks at the time of the incident in this study included radiography by inserting an x-ray source into a pile. As indicated, sometimes cracks could be missed using this method.

As with anything else, the past few decades have provided substantial additions to the technology in this area. Now, detection methods include lamb waves and laser ultrasounds, as well as acoustic emission techniques. All have been explored extensively, and have been proven to be accurate, however all require a lengthy inspection process due to the small area over which analysis occurs.

5 CONCLUSION

After a December storm in 1974 in the Arabian Gulf, several broken piles triggered an in-depth investigation into what caused the failure. When it was determined that fatigue was the ultimate cause

of failure, radiography was used to determine whether other piles had been damaged. This result required testing to determine whether the remaining piles would succumb to fatigue damage throughout the life of the structure. In addition, an in-depth study was undertaken to analyse the different aspects of dynamic loading.

The results of this situation were that the pile failures were, in fact, found to be due to fatigue damage in the welds near the mudline, and that the remaining piles would not succumb to through thickness cracks and fail during the life of the structure. In addition, it was determined that this was due to dynamic loading due to the natural period of the piles and the waves.

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