THE CONCRETE STRUCTURE REMEDIAL ASSESSMENTS IN MARINE ENVIRONMENT FROM WHOLE LIFE ASSET MANAGEMENT PERSPECTIVES

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M.Sc (Eng) INTERNATIONAL CONSTRUCTION MANAGEMENT AND ENGINEERING

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Also, for certain degrees:-

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ABSTRACT

This study makes use of a desk top review methodology to discover and understand the remedial assessment of damage concrete structures in the marine environment (sea water). Basically, the restorations of asset marine facility are done by using a correct and present repair technique to both spall concrete as well as corrode rebar and must follow the code and standards throughout construction periods. Specifically, the study undertook a comprehensive insight into the literature review of three (3) major components of research, consisting of reinforced concrete of marine structure, understanding marine environment and management of rehabilitation marine facility. The research chooses a case study of an oil refinery jetty piles terminal at Marsden Point in New Zealand. The asset facility is poorly deteriorating due to aggressive action of marine environment and need attention. The asset owners are aim to establish potential maintenance strategies in restoration of his asset facilities. The damaged marine structure will be looked at from whole life asset management perspectives; to identify various components of concrete structures that were subjected to steel corrosion and concrete deterioration. Application of whole life asset management paradigm in the case study will have significant impacts to the facilities and the owner as well. The benefits with regard to implementation of whole life asset management approaches in managing the asset marine facility correlate with risk management, accountability, service facility management and financial efficiency. The refurbishment work will make use of current repair method in assessing the restoration of damage concrete piles. This should take account of a risk management study prior selection of best procurement routes for the case studies. The case study is critically reviewed for options that suit the asset facility present condition and set up objectives to get the best approach adopted with regards to asset problem. The findings demonstrate that the adoption of the whole life asset management paradigm will promote the asset owner, to obtain best value for money concept from the investment and to gain benefits in terms of time, cost, quality and fit for purpose. It also help in promoting and prolong the asset lifespan and also to provide constant sustainable and economic service of asset facilities.

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NOMENCLATURE

Terminology	Meaning
ACI	American Concrete Institute
AM	Asset Management
ASTM	American Society for Testing and Materials
ASR	Alkali Silica Reaction
BRE	Building Research Establishment
BS	British Standards
CIDS	Concrete Island Drilling System
DBFOT	Design-Built-Finance-Operate-Transfer
EN	European Standards
Fib	Federation international du beton
GBS	Gravity Base Structure
LNG	Liquefied Nitrogen Gas
OGC	Office of Government Commerce
PMI	Project Management Institute Standards Committee
RC	Reinforced Concrete
WLAM	Whole Life Assets Management

CHAPTER 1

INTRODUCTION

1.1 Research Background

Basically, the research topics will be focus on '**The Concrete Structures Remedial Assessment in Marine Environment from Whole Life Assets Management Perspectives'.**

In particular, the research can be divided into two (2) different areas of study with the intention to cover both engineering and management topics. At first, a deep search into technical area is conducted and will include a review with regards to reinforced concrete marine structures followed by investigation of marine environments. Additionally, research on the subject of managing asset marine facility during or after rehabilitation is also conducted.

A review will also focus on the technical and managerial perspectives in the function of:

- Structural and economic appraisal
- Value culture of the asset owner
- Asset strategies and functionality
- Maintenance and repair strategies
- Adoption of whole life asset management concept to rehabilitation of marine asset in the case study.

Case studies will act as point of reference in establishing the best strategies for repair and maintenance appraisal as well as an asset management approach. A fundamental knowledge of both engineering and management functions is very important because it will significantly affect the study outcomes.

1.2 Aims and Objective

The aim of the study is to understand the assessment of remedial work of concrete structures in marine environment (sea water) using a whole life thinking approach which will result in establishing suitable method of repair assessments and managing a rehabilitate marine assets.

The objectives of the research study as follows:

- To produce a significant literature review with regards to the dissertation title.
- To make a clear understanding of the case studies' content and draw on relevant information from the literature review with the aim of adopting the necessary information with respect to case study.
- To determine the key issues throughout the project period.
- To understand and address asset owner and stakeholders value cultures from the case studies.

- To establish a risk management plan from the case study and also identify a suitable engineering approach in exercising the rehabilitation of concrete structures subjected to marine environments (sea water) accordingly.

1.3 Research Methodology

Initially this research focused on published material dealing with the research topics. The research method focused on two different fields - engineering and management - aiming at brining these same subjects together in the asset management of marine facilities.

Research outputs deal with finding, producing and later establishing a proper method of repair assessment and adoption of the best management system to rehabilitate marine assets facilities. Equally, the output contains information on how fundamental systems apply to remedial assessments and adequately cover a management methodology. In addition, examples from the literature review also demonstrated the importance of the asset owner's plan of action in managing his assets. The asset owner's prime goal towards his asset facility remedial assessment is to obtain best value for his money by investing money for restoration projects of his asset facility including utilising inadequate resources and time allocated right through the construction period of the damage asset.
As a result, the asset facility ends up with longer life span and fitting for structural purpose. The research has critiqued and reviewed the case study and marked certain reliable solutions that suited putting the whole life asset thinking and management paradigm in place.

The case studies point out the damage to marine structures and are concerned with restoration work on a number of damaged concrete piles in an oil refinery jetty terminal in New Zealand.

The desk research derived from a series of published materials downloaded from the internet and available books from the university library.

1.4 Scope and Limitations

The scope of study is broad, especially when information gained from the literature review reveals various types of recommended repair method, thus making it impossible and uneconomic to implement all aspects of repair method. A limitation on the research study is to principally concentrate on assessing **only** the aspect of critical elements in the case study.

Primarily, the scope of study will examine to 3 (three) major key sub-topics:

(i). *Reinforced concrete marine structures*

- These will cover types of RC structure used in marine such as jetty, pier, pump house for power generation etc.
- Components of concrete structures poorly affected by seawater action which result to damage on pile, beams and soffit of slab.

- Highlight literature and provide an understanding of a rehabilitation methodology which was practically exercised at some of deteriorated components of structural members.
- Repair systems that are suited well to concrete and steel reinforcement.

(ii). *Marine environment*

- Looking into the natural behaviour of marine surroundings, the seawater, its properties, tidal condition, aqua marine lives, current and much more.

(iii). *Management of rehabilitation marine facility*

- Typical asset management routes for aqua marine concrete facilities.
- Clear understanding of surrounding issues and to distinguish owner and stakeholders value cultures towards rehabilitation of asset facility.
- Review two case studies and make comparison between them.
- Review the asset strategy (service delivery, capital investment, asset maintenance, asset disposal and need) and asset framework (relationship between asset and service provided, utilisation, location, capacity, functionality)

Only applicable examples in (i) are considered for developing the literature review in Chapter 2 (two). An understanding of the marine eco-system and the properties of its main constituent's behaviour in terms of physical, chemical and biological will be the key elements in (ii). The final elements in (iii) provide an asset management perspective and structural assessments in particular and seek out trends and issues which are of values in assessing appropriate management plan for deteriorate marine structures.

1.5 Dissertation Outline

Chapter 2 - Reinforced Concrete of Marine Structures

This chapter is essentially describing the subject of the reinforced concrete structures which are built up and surrounded by the marine environment. It includes the classification of marine structure based on their characteristics and some illustrations are providing in black and white photos. An example of concrete marine structure of one type or another which have been built in some parts of the world are pictured together with an explanation about the structure's functionality. They range from submerged to floating systems of a variety of shapes and sizes: cylinders, boxes, cones, rings or doughnuts and cellular construction are among those reported in this chapter which also point up a bit about buried and immersed structure. This chapter also touches on seawater exposure and its effect to structures and some example of typical causes which relate to evaluation assessment on concrete distress and deterioration causes. Finally, some basic understanding of anode and cathode processes happening in the rebar that should be a result for corrosion is covered.

Chapter 3 – The Marine Environment

This chapter considers ocean seawater in relation to reinforced concrete in marine assets and gives answers to significant question like why concrete spall and steel corrode, how long seawater can act upon structure before deterioration can develop, how chemical reactions between seawater and concrete materials take effect. It includes but is not limited to identifying the probable causes against concrete deterioration and also how steel corrosion propagates as well as influences of the damage. Because the symptoms of concrete distress and deterioration may be caused by more than one mechanism acting on the concrete, it is necessary to have an understanding of the basic underlying causes of damage and deterioration.

Chapter 4 – Rehabilitation of Concrete Structures

This chapter is essentially concerned with the methodology in assessing the rehabilitation of deteriorated asset marine facilities. However, it does take into consideration determining the primary cause or causes of the damage seen on a particular structure and to make intelligent choices concerning selection of repair materials and methods.

The objectives of structural appraisal in chapter four (4) is to know the present asset condition and discovering the cause or causes of the structural problem which may include addressing a series of question which can only define during investigation or inspection of the structures and also to mark out for possible repair option.

Chapter 5 - Management of Deteriorating Concrete Structures

The objective of this chapter is to provide a perspective on asset management and structural assessments in particular and also to seek out trends and issues which are of value in assessment of deteriorating concrete structures. This will, as a matter of course engage with some form of critical argument against input of preceding researcher that is realistic and representative and also essential to be conscious and thinking optimistically in engineering terminology.

Chapter 6 – Case Study of Deterioration Reinforced Concrete Structures Subjected to Marine Exposure.

This chapter shows one case study which briefly discuss about deterioration scenario of marine asset facility. The case study shows the asset owner efforts in establishing the best repair strategies of his asset facility. A factual critique and review on case studies will designate a reliable solution that suite the case studies scenarios. It also takes into account certain important matters that should be understood and taking necessary action to find the best solution of the problems that arise during the commencement of the project. In general, the assessments of Whole Life Asset Management (WLAM) strategy will primarily aim on four (4) **key points** as follows:

(i). The WLAM issues and analysis of the case study.
(ii). Establish the asset strategy for the case study.
(iii). Establish the maintenance strategies for the case study.
(iv). Highlight the potential risk and establish of risk management studies.

Identification of the cause or causes of the case studies issues are so important as the first move towards finding a significant solution to those issues. it might be helpful to visualised a damaged structure and relate it with the aspects behaviour of the sea. Emphasis to the relationship between structures and sea is prime concern for example; case study is about terminal oil jetty so it is important to establish the function of the jetty i.e. what it is intended to provide

Chapter 7 – Discussion

This chapter considers the impacts of whole life asset management on the asset marine facilities case studies by establishing key drivers with regards to the engineering and management fields, which should result in increased the asset life span and contribute benefits to asset owner in terms of time, cost, quality and in addition fit for purpose of asset functionality.

Exploration of the case studies and implementation of appropriate remedial work as well as embracing the whole life thinking concept should induce positive reaction in the minds of asset owners and these have to be encouraged in the future._A series of question are posed such as; Will asset function increase? And shall it behave as it intended to? Or are they sure that asset life span prolong once restoration work completed? Are we maintaining the strength properties or will it be greater than before?

Chapter 8 - Conclusions & Recommendations

This chapter will conclude the overall research study with reference to the aims and objectives. There will be a focus on remedial work of concrete structures in marine environment (sea water) and adoption of the whole life asset management thinking approach will result in establishing a suitable repair method and management of rehabilitate marine assets.

CHAPTER 2

REINFORCED CONCRETE OF MARINE STRUCTURES

2.1 Introduction

The purpose of this chapter is to describe on reinforced concrete marine structures which build up and are surrounded by the marine environment. It will cover the following topics;

- Marine Structures Classification
- Concrete in the Marine Environment
- Concrete Exposed to Seawater
- Cause of Concrete Deterioration in Marine Environment
- Evaluation of Causes of Concrete Distress and Deterioration
- Effect of Ice Impact and Abrasion to Marine Concrete
- Structures Buried in Seawater
- Structures Immerse in Seawater

These topics are considered important topics for dissertation because it highlights the key points of the chapter and will provide basic understanding on the typical concrete structure behaviour when it's surrounded by marine ecosystem. The classification of marine structure will be based on their group and some of it is illustrated in black and white photo. Examples of concrete marine structures of one type or another which have been built in some parts of the world were pictured together with explanation about structure's functionality. They ranged from submerged to floating systems of a variety of shapes and sizes: cylinders, boxes, cones, rings or doughnuts and cellular construction are among those reported in this chapter. This chapter also touch on seawater exposure and its effect to structures and some example of typical causes which relate to evaluation assessment on concrete distress and deterioration causes. Finally, highlight a bit about buried and immersed structures which demonstrate some basic understanding of anode and cathode processes experience in rebar that result to corrosion.

2.2 Marine Structures Classification

The word, 'marine structures' as suggested by **Mehta P.K., (1991),** typically applies to costal berthing and mooring amenities, breakwaters and tidal barriers, dry docks and jetties, container terminals, and offshore floating docks and drilling platforms. Such as report of marine structures is based on their function, and is not useful for design purposes. **Mehta P.K (1991)** has grouped the wide diversity of marine structures into five general categories: piled platforms, flexible bulkheads, gravity structures, rubble mounds, and floating structures. **Maxwell-Cook, (1973)** has notified of the FIP Symposium I which hold in USSR. Proposals described included a floating airport, LNG carriers and floating immersed tunnels. Among implemented project were immersed tunnels, bridge caisson, lighthouses, oil storage, a tidal power station and floating dry-docking.

As illustrates in Fig. **2.1** below, 5 varieties of groups containing different structural types, each group were differentiated in a way they behaved when resisting the main loads. Again, there are several fabrication options for each of these structural types, for instance, cast-in-place, precast, cellular, and prestressed concrete, which represent another level of classification. According to **Buslov (1990)**, the classified level only indentifies the primary types of a structure. Various hybrids and combinations are also possible, such as rigid anchored walls, sheet-pile cells (filled-shell gravity structures retained by flexible bulkheads), composite steel-concrete sandwich structures, etc.

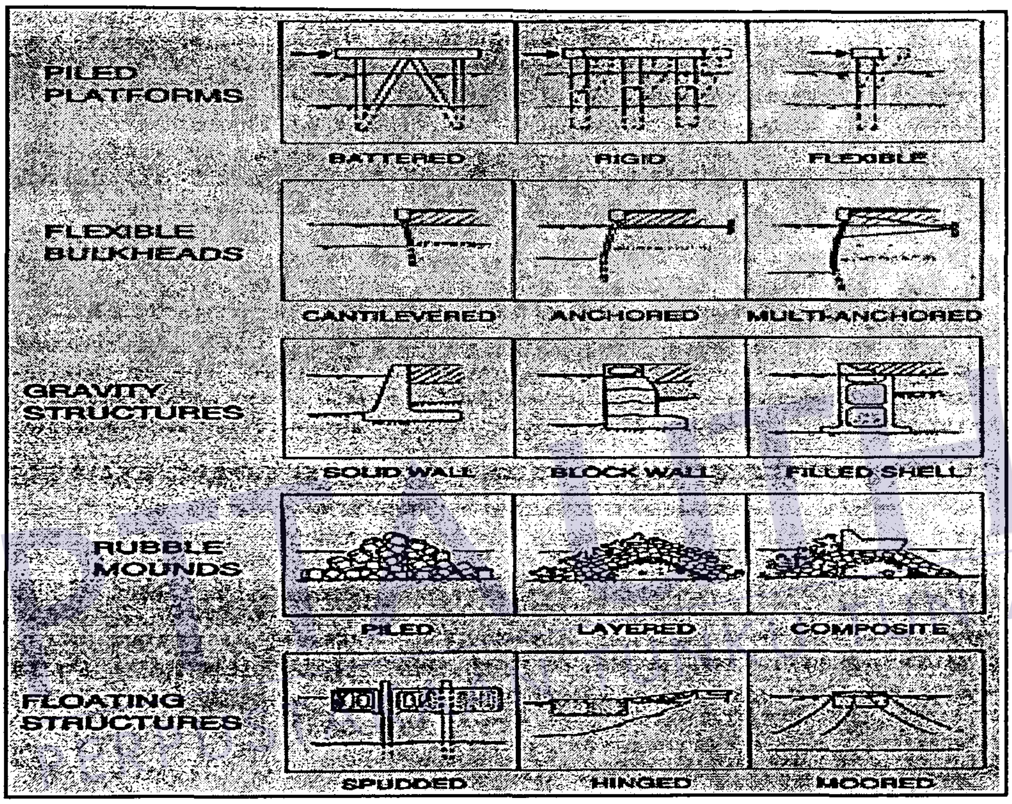

Fig. 2.1 Classification of Typical Marine Structures (after **Mehta P.K, 1991**)

2.3 Concrete in the Marine Environment

Mehta P.K (1991) had claimed that reinforced concrete has become the most frequently used material for building of marine structures whilst distinguished among three basic structural materials, specifically timber, steel, and concrete. Reinforced Portland cement concrete was invented approximately one hundred years ago, and it has become one of the most broadly used industrial materials in the world. According to **him**, there are certain number of reasons for that, such as the superb resistance of the concrete to water, the ease with which structural concrete elements can be formed into a variety of shapes and sizes, and also the low cost and easy availability of concrete-making materials that can almost find anywhere in the world. **He** compared to other building materials, concrete also happens to show better resistance to the action of salt water; the vast numbers of wharfs, docks, bridge piers and beams, breakwaters, and subsea tunnels bear a clear testimony to its general acceptance as a suitable material of construction for structures exposed to the marine environment. The use of concrete as the primary structural material in the last two decades has been extended to so many spectacular marine projects that **Gerwick (1989)** foresees the world of concrete is to be increasingly ocean-oriented and **Mehta. P.K (1991),** have suggested that the twenty-first century will be the century of concrete in the oceans.

The forecasting of the use of the concrete in both offshore and inshore sea structures are not easy to justify. A human history record in the past revealed that oceans have been used for fishing, business-related navigation and waste disposal. While world population gradually rise, approaching 6.7 billion peoples today, an equivalent grow in coastal and offshore construction were attained. The most important thing is that the rise in human expectations for a better standard of living has provided key momentum for the use of undersea energy and mineral resources. The oceans itself has cover twice as much surface as the combined area of the seven continents of the earth, which is more than 25% of the world's hydrocarbons in the form of oil and gas are being extracted from coastal and offshore deposits. The world's first offshore concrete platform named Ekofisk was constructed in 1973 in the North Sea, and nowadays there are more than 20 oil and gas production platforms containing heavily reinforced and prestressed concrete elements has been constructed **(Mehta P.K 1991)**.

Many marine construction projects concerning complex structures, such as superspan bridges, undersea tunnels, breakwaters, and man-made islands, have been built and these made known that concrete is now widely established as the preferred material of construction in the marine environment will be evident from some of the recently constructed or under-construction projects described below.

2.3.1. Offshore Concrete Platforms in North Sea

The oil industry has in the past been steel-oriented as observed by **Moksnes (1989)**. Therefore, in 1972, a daring decision was made by Phillips Petroleum Company to go for concrete as the principal structural material for the Ekofisk oilfield in the North Sea. Afterwards, a total of 20 concrete platforms containing approximately 2 million m^3 of high-quality concrete have been built in North Sea, with water depths ranging from 70 to 206m. The Condeep type platform, invented by the Norwegian Contractors, was a concrete gravity base structure (GBS) consists of several shafts supporting the upper deck as viewed in **Fig. 2.2.** The size of the caisson structure is ruled by basic need of oil storage facility. The foundation area provides structural stability during normal operation and buoyancy as floating-stability requirements during transportation and installation at the offshore location. A picture of Gullfaks C, the world's largest offshore concrete platform, is shown in **Fig. 2.3** that was fabricated in a dry dock at Hinna, near Stavanger. The concrete substructure was standing at the height of 262 m tall consist of 24 oil-storage cells and four shafts and tie in by a 50 000-tonne steel deck. In early 1989 the assembly was towed out to the installation site. The mixtures are mix up with a high-performance concrete with a range of 70-80 MPa compressive strength, a similar valued that was used for the caisson elements construction.

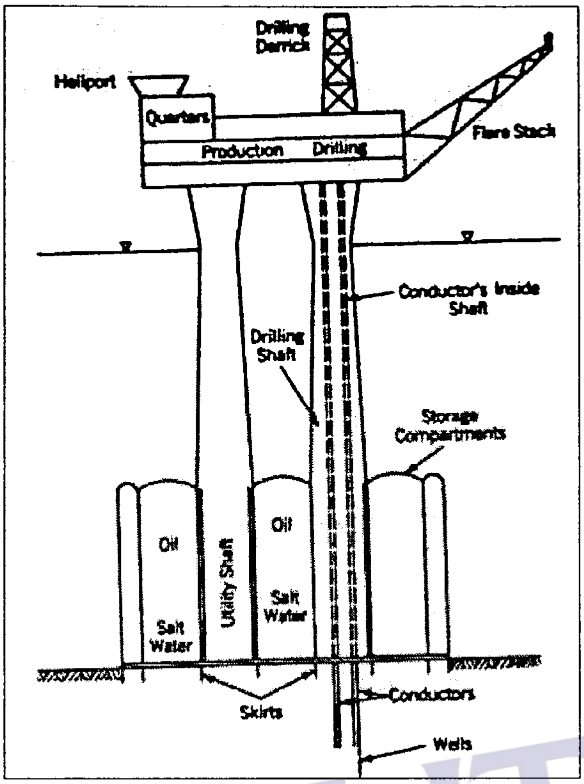

Fig 2.2. Concrete Gravity Platform – Condeep type (**B.C. Gerwick, 1988**)

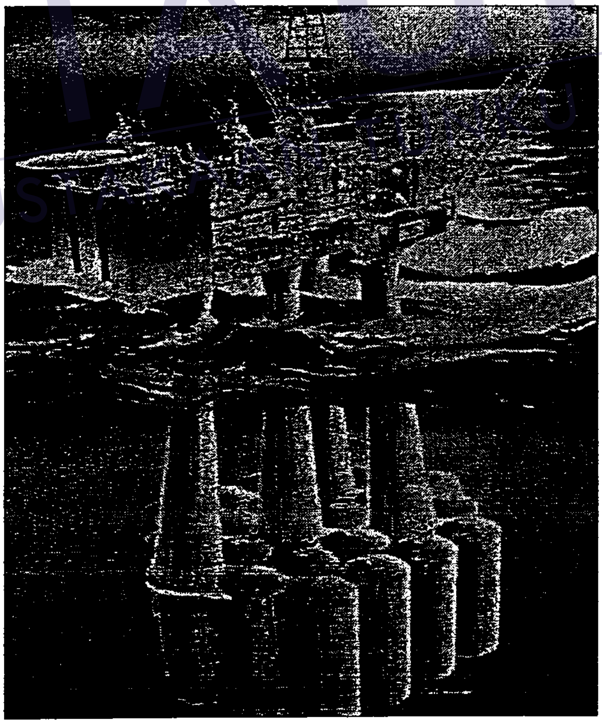

Fig 2.3. Gullfaks C – The World's Largest Offshore Concrete Platform (**J. Moksnes, Norwegian Contractors**). Key data: water depth 216 m; production capacity 245 000

bbls/day; concrete volume 240 000 m^3 (C65-70); reinforcement 70 000 tons; prestressing 3500 tons; deck weight during towing 49 500 tons.

2.3.2. Concrete Island Drilling System

A concrete island drilling system (CIDS) lead the way in 1984 by American and Japanese consortium companies to considered drilling in shallow waters of the Beaufort Sea Alaska, United States. **Yee *et al.* (1984)** reported on three basic components of the system, based on exploitation of correct materials for altering environmental conditions; consist of a mud base, a concrete module, and a storage deck. According to him, the fully submerged mud base and the storage barges are not subjected to ice forces and thus constructed of structural steel. The 71 x 71 x 13 m reinforced and prestressed concrete module, which is located in the splashing zone, is designed to resist bending, shear, and torsional forces from ice floes. Since the platform was constructed at a dry dock in Japan and then towed to the installation site in the Beaufort Sea, structural strength and buoyancy were optimized by using two types of concrete mixtures for the module. A high-strength (55MPa) normal-weight concrete mixture was used for the interior, but in the other hand a high-strength (45MPa) lightweight concrete mixture was used for the top and bottom of the slabs and for exterior walls. Finished shale, sealed-pore type, lightweight aggregate was engaged to produce the high-strength lightweight concrete.

2.3.3. Super span Cantilever Concrete Bridges

Generally, a steel bridges span measuring between 120 to 200 m in length is an example of economical prestressed concrete beam bridges used in construction. In Norway, 16 numbers of post-tensioned box-girder bridges with 150 m or more main spans were built during 1973-83, and the number of prestressed concrete bridges, with 100 to 150 m main spans built during the same period was considerably higher. In 1987, a 230 m long main-span bridge, the Norddalsfjorden Bridge, was constructed at a cost of only 4 million US dollars. The technology to produce even longer-span bridges is readily available. For such bridges, the dead load of the superstructure represents over 85% of the total load. Considerable reduction in dead load can be achieved by make use of high-strength lightweight concrete mixtures to the above said type. Practical methods effectively use to reduce the overall dimensions, weight and cost. A first-of-its-kind superspan bridge, the Helgeland Bridge, possessing as longest main span with a 390 m long, was successfully built in 1990 **(Mehta P.K, 1991)**.

T.Y. Lin (1989) bravely expressed his belief that it may be possible for people to travel using surface transportation facilities from Alaska to Siberia across the Bering Strait by mean use of future bridges that potentially link six continents for travel, trade, and cultural exchange. Since this East-West linkage is visualized to promote commerce and understanding between the people of the United States and the Soviet Union, the proposed bridge is called the Intercontinental Peace Bridge. The design suggested by Lin is made up of 220 spans, 200 m long and approximately 23 m vertical clearance. Each of the 220 concrete gravity piers is expected to require about 20 000m normal-weight concrete; the superstructure will require 2.6 million m^3 of lightweight concrete.

2.3.4. Undersea Tunnels

An undersea tunnel was a unique example of marine structures that has been successfully built by human in 21st Century. The structure are surrounded by salt water even though sited in soils well beneath the seafloor, with an inside environment that supplies oxygen and heat are controlled by advanced system. Leakage ensures that there is a humid saline atmosphere in the interior as well as outside, with alternate wetting and drying due to ventilation and vehicle movement. However, a serious leakage has been reported from the Kanmon tunnels (between Honshu and Kyushu in Japan), the Hong Kong tunnels, the Al-Shindagha tunnel (under the estuary of the Dubai Creek), and the Suez tunnel. High-quality concrete is essential for construction of tunnel lining for the reason that structures are severely exposed to aggressive marine condition **(Mehta P.K, 1991)**.

Fig. 2.4 exhibits the cross-section and longitudinal grade of world's largest undersea tunnel measuring 54 km long. Construction of Seikan Railway Tunnel in Japan was ingeniously completed in 1988 which took 24 years for construction work to complete. The concrete-lined tunnel is approximately 100 m beneath the sea bottom at its midpoint and has both wide tracks for *Shinkansen* (Bullet) trains and narrow tracks for conventional trains. Since it provides an all-weather link between the overpopulated Honshu Island and the under populated Hokkaido Island, it is expected to play a vital role in the regional economic development of Hokkaido, wealthy island rich with natural resources.

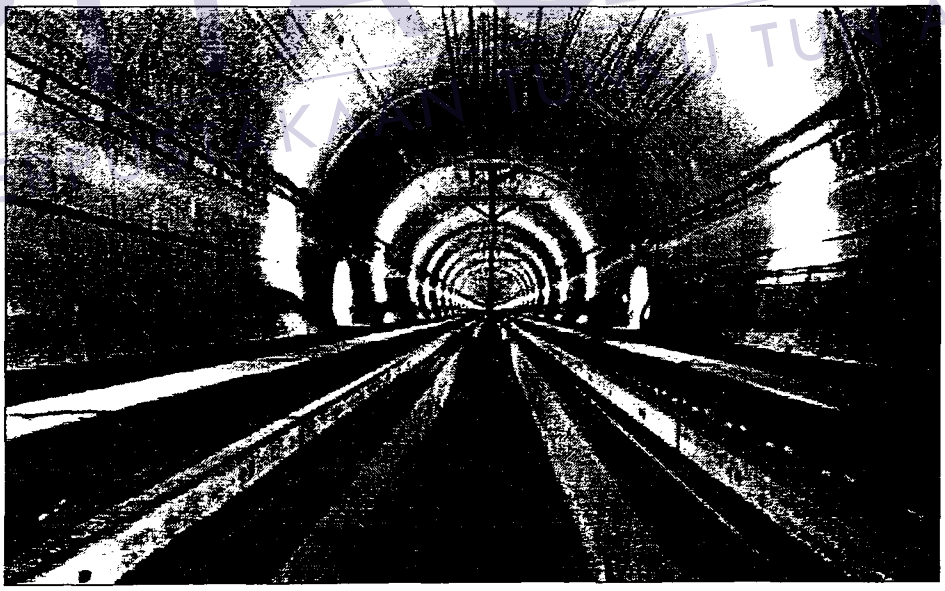

Fig 2.4. Seikan Tunnel-The World's Largest Undersea Tunnel Shows the Cross-section and Longitudinal Grade (**Japan Railway Construction Public Corp.**)

Eurotunnel, also called the Channel Tunnel, was a 50 km undersea link between France and Great Britain is reportedly the biggest infrastructure job to be privately financed in this century. The tunnel was designed for a service

life of 120 years and scheduled for completion in 1992, this 9.2 billion US dollars project contains two 7.5 m internal diameter of rail tunnels, and 4.8 m internal diameter of service tunnel, which are bored in chalk deposits 20 to 50 m below the seabed of the English Channel.
Because of the poor rock quality, prefabricated reinforced concrete liners are used to line the rail tunnels. High-quality, relatively impermeable concrete mixtures were developed for the fabrication of these concrete liners **(Mehta P.K, 1991)**.

Two subsea road tunnels, each length approximately 4 km long has been built at Aalesund on the west coast of Norway in 1987. The tunnels fall on to a depth approximately 140 m below sea level, but because of the good rock quality, extensive concrete lining was unnecessary. However, where the rock quality was poor, application of shotcreting repaired method was all set with primed wet concrete mixture containing silica fume and steel fibres put into practice. The 'wet' shotcreting techniques were also discover extensive application for repair of coastal structures. **(Mehta P.K, 1991)**

2.3.5. Storm Barriers and Breakwaters

Other example of marine structures is storm barriers and breakwaters. Breakwaters were specially designed structures purposely construct by meant of protection from aggressive waves action and usually accomplished by construction of bottom-founded vertical face breakwaters of miscellaneous constructions, rubble mound breakwaters, floating breakwaters, fixed and floating wave attenuators of miscellaneous designs (**Gregory P.T 1995**).

Storm surge barriers and breakwaters are typical example of easily found coastal structures essentially construct to guard significant coastal and offshore structures from high ocean waves (**Leenderste and Oud, 1989**).

Examples of the storm surge barriers highlighted by **Leenderste** are the Oostershelde Storm Surge Barrier located in the south western part of Netherlands. It was built in 1986 and strategically located at the meeting delta of three rivers, the Rhine, the Maas, and the Schelde. The barrier was part of Delta Project which includes the shutting of the main tidal estuaries and inlets in the south western part of the country. This has decreased the country's coastline by hundreds of kilometres, and keeping out of saline water from a large area and was expected to exhibit a significant improvement to freshwater management.

Leenderste and Oud (1989) also noticed the storm surge barrier which length approximately 3000 m long was built in three tidal channels. It made of 65 numbers of prefabricated concrete piers, between which 62 sliding steel gates are installed. With the gates in a raised position, the differences between the high and low tides behind the barrier are maintained at two-thirds of their original range, which sufficient to preserve the natural environment of the Osterschelde basin. When storms and dangerously high water levels are forecast, the gates can be closed in order to safeguard the population of the area from the ravages of the North Sea.

Gregory P.T (1995) also notes the type of wave protection structure used in marina construction is largely dictated by wave climate outside the marina water area, the allowable height of waves inside the marina perimeter, bottom conditions and availability of suitable materials at or near the site of construction. He classified bottom-founded breakwaters into two types: the impermeable vertical solid type construction breakwaters and the sloping mound-type structures, but combination of both types is also common in use.

Sarpkaya and Issacson, (1981) have notified the general classification of breaking waves is as spilling, plunging, collapsing and surging.

Another significant example of the concrete wall breakwaters was The Ekofisk concrete platform in the North Sea, built in 1973 and was standing in 70 m water depth located at 170 km off Norwegian coast. It was protected with a breakwater to withstand up to 60 t/m pressure from the 100-year high design wave. As shown in **Fig. 2.5**, the breakwater consists of a perforated concrete wall which is designed to dampen the wave energy. Unreinforced elements of precast, high-strength (60-70 MPa compressive strength) and erosion resistant concrete were used to construct the breakwater **(B.C. Gerwick, Jr & E. Hognestad, 1973)**.

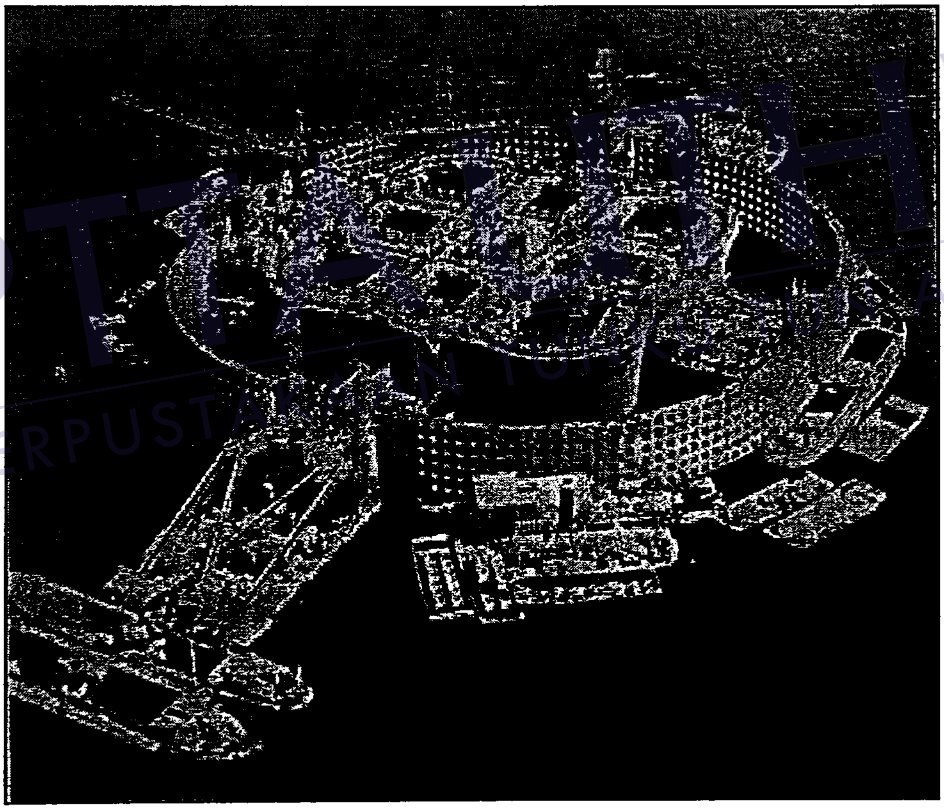

Fig.2.5. Ekofisk Oil Storage Tanks and Breakwater (**B.C. Gerwick, Jr & E. Hognestad,** ASCE Environmental Design / Eng Construction. August 1973)

During the oil and gas extraction, it was discovered that the local seabed had sunk significantly more than expected. As a result, the platform had to jack up and a special protective ring was necessary to protect the entire installation. A concrete ring, 108 m high and 140 m in diameter was constructed in a dry dock in

Rotterdam, the Netherlands, and successfully installed in 1989. The failure evidence of the seabed where the oil rigs platform seated is only a secondary point to view because it's very rare to happened in modern construction of the offshore structures, but the principal is to look on the effect of a long term waves action perform to the structure. As quoted by **Hallam et al, (1977)**; while it might therefore be expected to affect inshore and coastal structures, offshore structures are not immune from it since wave can often reach their limiting steepness under storm conditions.

2.4 Concrete Exposed to Seawater.

Regourd (1980) summarised her study of the physio-chemical effects of seawater on hydrated cements as follows:

(i). Chemical attack by seawater on cement only occurs in the case of permeable concretes

(ii). C_4AF in contrast to C_3A has no deleterious effect

(iii). Portland cement with C_3A contents lower than 10 per cent resist chemical attack in seawater

(iv). Cements containing more than 65 per cent slag are most resistant to sea water attack

(v). The effects of pozzolan depend on their mineralogical composition and reactivity

(vi). Compressive or flexural strengths are not a good basis for assessing durability once reaction commence, a much better basis is the measurement of expansions as they continue.

Processes such as the corrosion of steel, freeze thaw erosion and cavitations of concrete occur at the same time as concrete attack and always weaken the concrete.

Mehta P.K (1980, 1988) stressed in his two papers on durability of concrete exposed to seawater that of all chemical and physical properties, permeability of concrete is the most important factor influencing performance. **He** notes that concrete containing even high tri-calcium aluminates cements have excellent service lives if the permeability is sufficiently low. Such concretes are achieved by using mixes having high cements contents and low water: cement ratios, through consolidation and control of thermal and shrinkage cracking and also limiting cracks due to mechanical loadings. Pozzolanic materials, particularly high proportions of blast furnace slag improve the impermeability of the concrete by reducing the volume of large pores in the paste fraction of concretes. **Popovics (1987)** notes that sulphate attack from sea water is less than would be expected from its ion concentration. He proposed that chloride reacting with the tri-calcium aluminates, inhibit the expansive phenomena associated with sulphate reactions. He also notes the advantage of the formation of tri-calcium chloro-aluminates hydrates which act as absorbers of some of the chlorides which would otherwise be free to attack the reinforcing steel.

A large quantity of reinforced concrete has been used for marine applications. However, significant problems may occur because of carbonation attack against concrete structures. Without a doubt it clearly showed evidence of chemical degradation of Ca $(OH)_2$, resulting a pH decreasing and presence of chloride ions (**The Institute of Metals, 1990**). Equally, both cases demonstrate as carbonation (exhibit as chemically induced of concrete) and chloride attack on steel bar (an internal action of ion Cl) as it penetrate deep inside a homogenous concrete and caused pitted rust to steel bar. As ions reach the steel, rate of diffusion can be determined. Thus, the best remedies to apply on deteriorated concrete are the application of high density concrete.

2.5 Cause of Concrete Deterioration in Marine Environment.

Tsinker G.P., (1995) notes that concrete deterioration is an extremely complex subject to look at but recommend for possible effort to identify a specific, single cause of deterioration for every symptom detected during an evaluation of a structure. **Tsinker** believed that the damage detected in most cases will be the results of more than one mechanism. For example, corrosion of reinforcing steel may open cracks that allow moisture greater access to their interior of the concrete. This moisture **he** said could lead to additional damage by freezing and thawing.

While **Fjeld and Roland, (1982)** have attributed to only four causes degradation of concrete such as chemical attack, freeze thaw damage, fatigue and abrasion, the **US Army Corps of Engineers EM 1110-2-2002, (1986)** has classified general causes of distress and deterioration of concrete as follows:

- Chemical reactions
- Construction errors
- Corrosion of embedded metals
- Design errors
- Erosion
- Freezing and thawing
- Settlement and movement
- Shrinkage
- Temperature changes

2.5.1. Chemical Reactions

This category exhibits a wide variety of symptoms. In general, deleterious chemical reactions may be classified as those that occur as the result of external chemicals attacking the concrete (acid attack, aggressive water attack, miscellaneous chemical attack, and sulphate attack) or those that occur as a result of internal chemical reactions between the constituents of the concrete (alkali-silica and alkali-carbonate rock reactions).

2.5.1.1. Acid Attack

Tsinker G.P (1995) reported that the deterioration of concrete by acids is primarily the result of a reaction between the acid and the result of a reaction between the acid and the products of the hydration of cement. If the acid is able to reach the reinforcing steel through cracks or pores in the concrete, corrosion of the reinforcing steel will result, which in turn will result in further deterioration of the concrete. If reinforcing steel is reached by the acid, rust staining, cracking, and spalling may be seen.

2.5.1.2. Aggressive Water Attack

Some waters have been reported to have extremely low concentrations of dissolved minerals. These soft or aggressive waters will leach calcium from cement paste or aggregates. This phenomenon has been infrequently reported in the United States **(Holland et al., 1980).**
For aggressive water attack to have a serious effect on marine structures, the attack must occur in flowing water, which contains a constant supply of aggressive water in contact with the concrete and which washes away aggregate particles that become loosened as a result of leaching of the paste. Visual examination will show concrete surfaces that are very rough in areas where the paste has been leached.

2.5.1.3. Alkali-Carbonate Rock Reaction

Certain aggregates of carbonate rock have been found to be reactive in concrete. The results of these reactions have been characterized as ranging from beneficial to destructive. The destructive category is apparently limited to reactions with impure dolomitic aggregates and are a results of either dedolomitization or rim-silicification reactions. The mechanism of alkali-carbonate rock reaction is covered in detail in **US Army Corps of Engineers EM 1110-2-2000 (1985)**.

Experts have found that chlorides can amplify the adverse effects of alkali-aggregate reactions and significantly increase concrete expansion. Chloride salts react with the products of cement hydration to generate additional or secondary alkalis. Oddly enough, alkali-aggregate reactions do not decrease compressive strength of concrete appreciably. Because structural adequacy of concrete in situ is often determined based on compressive core strength, the data obtained from cores can be misleading. Therefore, when evaluating the structural adequacy of concrete affected by alkali-aggregate reactions, it is advisable to determine compressive and tensile strength, as well as the modulus of concrete elasticity.
Visual examination of those reactions that are serious enough to disrupt the concrete in a structure will generally show map or pattern cracking and a general appearance that indicates that the concrete is swelling. A distinguishing feature that differentiates an alkali-carbonate rock reaction from an alkali-silica reaction is the lack of silica gel exudations at cracks **(American Concrete Institute ACI 201.2R, 1985c)**.

2.5.1.4. Alkali-Silica Reaction

Some aggregates containing silica that is soluble in highly alkaline solutions may react to form either a solid nonresponsive calcium-alkali-silica complex or an alkali-silica complex that can imbibe considerable amounts of water and expansion, disrupting the concrete. Visual examination of those concrete structures that are affected will generally show map or pattern cracking and a general appearance that indicates that the concrete is swelling. Petrography examination may be used to confirm the presence of alkali-silica reaction. A detail on alkali-silica reaction is referred to **Hobbs (1988), Okada et al. (1989), and Acres International Ltd. (1989)**.

2.5.1.5. Miscellaneous Chemical Attack

Concrete will resist chemical attack to varying degrees depending on the exact nature of the chemical. **American Concrete Institute ACI 515.1R (1985d)** includes an extensive listing of the degrees of resistance of concrete to various chemicals. Most chemicals, in order to produce a significant attack on concrete, must be in solution form and must be above a certain minimum concentration. Concrete is seldom attacked by solid dry chemicals. Also, for maximum effect, the chemical solution needs to be circulated in contact with the concrete. Concrete subjected to aggressive solutions under positive differential pressure is particularly vulnerable. The pressure gradients tend to force the aggressive solutions into the matrix. If the low-pressure face of the concrete is exposed to evaporation, a concentration of salts tends to accumulate at that face, resulting in increased attack. In addition to the specific nature of the chemical involved, the degree to which concrete resists attack depends on: the temperature of the aggressive solution, the water/cement ratio of the concrete, the type of cement used (in some circumstances), the degree of consolidation of the concrete, the permeability of the concrete, the degree of wetting and drying of the chemical on the concrete, and the extent of chemically induced corrosion of the reinforcing steel **(American Concrete Institute ACI 201.IR, 1985b)**.

2.5.1.6. Sulphate Attack

Naturally occurring sulphates of sodium, potassium, calcium, or magnesium are sometimes found in soil or in solution in groundwater adjacent to marine structures. The sulphate ions in solution will attack the concrete. There are apparently two chemical reactions involved in sulphate attack on concrete. First, the sulphate reacts with free calcium hydroxide which is liberated during the hydration of the cement to form calcium sulphate (gypsum). Next, the gypsum combines with hydrated calcium aluminates to form calcium sulphatealuminate. Both of these reactions results in an increase in volume. The second reaction is responsible for most of the disruption due to volume increase of the concrete **(American Concrete Institute, ACI 201.2R, 1985c)**.

2.5.2. Construction Errors

Tsinker G.P (1995) stated that failure to follow specified procedures and good practice or outright carelessness may lead to a number of conditions that may be grouped together as construction errors. Typically, most of these errors do not lead directly to failure or deterioration of concrete. Instead, they enhance the adverse impacts of other mechanisms previously identified. **He** suggests the types are likely to occur during repair or rehabilitation projects as during new construction as follow:

2.5.2.1. Adding Water to Freshly Mixed Concrete

This practice will generally lead to concrete with lowered strength and reduced durability. As the water/cement ratio of the concrete increases, the strength and durability will decrease and shrinkage and permeability will increase.

2.5.2.2. Improper Consolidation

Improper consolidation of concrete may result in a variety of defects, the most common being bug holes, honeycombing, and cold joints.

2.5.2.3. Improper Curing

Curing is probably the most abused aspect of the concrete construction process. Unless concrete is given adequate time to cure at a proper humidity and temperature, it will not develop the characteristics that are expected and that are necessary to provide durability. Symptoms of improperly cured concrete can include various types of cracking and surface disintegration. In extreme cases where poor curing leads to failure to achieve anticipated concrete strengths, structural cracking may occur.

2.5.2.4. Improper Location of Reinforcing Steel

This may result in reinforcing steel that is either improperly located or is not adequately secured in the proper location. Either of these faults may lead to two general types of problems. First, the steel may not function structurally as intended, resulting I structural cracking or failure. Second, the concrete cover over steel is reduced which makes it much easier for corrosion to begin.

2.5.2.5. Movement of Formwork

Movement of formwork during the period while the concrete is going from a fluid to a rigid material may induce cracking and separation within the concrete.

2.5.2.6. Premature Removal of Shores or Re-shores

If shores or re-shores are removed too soon, the concrete affected may become over-stressed and cracked. In extreme cases there may be major failures.

2.5.2.7. Setting of the Sub-grade

If there is any settling of the sub-grade during the period after the concrete begins to become rigid but before it gains enough strength to support its own weight, cracking may occur.

2.5.2.8. Vibration of Freshly Placed Concrete

Most construction sites are subjected to vibration from various sources, such as blasting, pile driving, and from the operation of construction equipment. Freshly placed concrete is vulnerable to weakening of its properties of subjected to forces that disrupt the concrete matrix during setting.

Work carried out by **Building Research Establishment (BRE), UK** encompass of construction errors at site has suggested that most of the errors in structures are caused by design mistake and poor workmanship on site, with only 10 per cent being due to inadequate materials. Analysis of data done by **Campbell-Allen (1979)** in Australia showed similar findings with **Paterson (1984)** survey data which was done in France where less than 5 per cent of defects could be considered as principally caused by materials problems. They addressed various causes of design faults as below.

The **design errors** may possibly because of:

(i). misapprehension of client's needs
(ii). Poor communication between design team members
(iii). Inadequate and inaccurate specification of design
(iv). incorrectly use of design standards and/or code of practice
(v). Outdated and incorrect data employed
(vi). Failure to appreciate the influence of construction procedures and tolerances on the product at various stages of construction.

The **construction errors** may possibly because of:

(i). misapprehension of design drawing or specification
(ii). Poor communication with suppliers and sub-contractors
(iii). Less site supervision
(iv). Poor workmanship due to inadequate skills and experience of labour force or lack of satisfactory instruction.
(v). Failed to understand the design principle or how this involved in construction procedure or sequence.

Six major factors were acknowledged and be part of the cause most significantly to the occurrence of structural failure by **House Committee on Science and Technology of the US Government** based on their report legally recognized ***Structural Failures in Public Facilities*** and these include:

(i). Communication and organization in construction industry.
(ii). Construction inspection by structural engineer.
(iii). General quality of design.
(iv). Structural connection design details and shop drawings.
(v). The selection of architects and engineers.
(vi). Timely dissemination of technical data.

2.5.3. Corrosion of Embedded Metals

Experts studying the effects of chlorides of concrete noted a marked increase in corrosion when cement contained as little as 0.2% $CaCl_2$. However, $CaCl_2$ doses below that amount appeared to have no appreciable effect. Based on the results of this study, it was recommended that chlorides should not be added to concrete if the structure is likely to be subjected to electric currents **(Novokshchenov, 1988).**

Numerous subsequent studies have confirmed these early findings. As described by **Uhlig (1971), Mehta (1986, 1988), Holmes and Brundle (1987), American Concrete Institute ACI 222R-85 (1985a)** and many other experts, corrosion of metals in concrete is an electrochemical process during which the iron can corrode by chemical attack. When carbon steel reinforcement is embedded in concrete the surface of the steel oxidizes to form a very thin surface film of ferric oxide (Fe_2O_3). This film is known as the passive film because it is extremely stable when embedded in the highly alkaline cement matrix (pH normally greater than 11). Provided the alkaline environment is sustained and the passive film remains intact the reinforcement will undergo virtually no further oxidation over an indefinite period and the reinforced concrete structure will therefore exhibit none of the problems associated with corrosion of the reinforcement. However, if chloride ions are present in sufficiently high volumes at a reinforcing bar within the concrete they cause the passive film at that point to breakdown. This breakdown causes a difference in electrode potential between the exposed steel at the point at which depassivation has occurred and the oxide-coated steel on either side.

In an acid medium, the reaction taking place at the cathode is the reduction of hydrogen ions to hydrogen. As summarized by **Holmes and Brundle (1987)**, the factors affecting the corrosion rate are as follows:

1. The chloride concentration at the surface of the reinforcing bar
2. The initial integrity of the passive layer on the surface of the reinforcement
3. The electrical resistance of the concrete
4. The availability of oxygen to complete the cathodic reaction.

They said that deterioration of many marine structures over the past few years, to some extent, has been attributed to introduction of salts in the concrete mix used in the past. However, the external supply of chloride ions from the marine environment is mainly responsible for deterioration of concrete. The concentration of chlorides on concrete surfaces due to effects of the external (marine) environment can vary significantly from one part of the structure to another. For example, in the splash zone solar radiation and drying winds can produce rapid evaporation, which could lead to the deposition of salt crystals. Gradual build-up of these crystals can increase the chloride concentration in this zone.

Referred to what **they** discovered in tidal zone, salts are built up on the concrete surface during a falling tide and as the tide level increases the concrete surface is washed and the surface salt concentration is reduced. In the submerged zone the chloride concentration at the surface of the concrete is relatively constant and the maximum concentration approximates the concentration of salts in seawater.

They commented that high concentrations of salts in contact with the concrete surface have only a limited effect on the integrity of the concrete matrix itself. Salt crystals can cause disruptive pressures within the surface layer of concrete which often results in a minor loss of cement paste or aggregate from the concrete surface; the expected long-term result can be loss of cover to the reinforcement.

According to **them**, depassivation of the reinforcing steel is affected mainly by the rate of chloride penetration. Penetration of the salts into the concrete and concentration of chlorides at the level of reinforcing steel depend on concrete cover permeability, which in turn is dependent on concrete matrix density, and degree of cracking present in the concrete cover. **They** also believed that concrete density is the most important factor affecting the rate of chloride penetration into concrete. Dense concrete with a relatively low porosity is less permeable to moisture-containing dissolved salts than a less dense concrete with a high porosity.

However, **they** suggest that cracks within the concrete cover can have a significant bearing on the effective permeability of the concrete despite the presence of a highly dense and impervious concrete matrix. Cracks also play major role in permitting an abundant supply of oxygen to come into contact with the reinforcement. The availability of a supply of free oxygen is essential to the corrosion process and any limitation to this supply will restrict the corrosion rate. The fact that marine structures seldom exhibit signs of serious reinforcement corrosion in the submerged zone is believed to be largely due to the limited amount of free oxygen in the seawater. Once the passivity of the steel is destroyed, the electrical resistivity of the system controls the rate of corrosion. The electrical resistance of the concrete and the consequent rate of ionic transfer are governed to a large extent by the moisture content. Moist concrete is a good conductor of electrons between the anode and the cathode. Because the corrosion process is a chemical reaction, the rate of reaction is affected by changes in temperature. This means, **they** said that the higher ambient temperatures in countries with warm climates result in a much higher rate of corrosion of steel than in more temperate climates.

In the context of the above described fundamental principles underlying the process of corrosion of steel in concrete done by previous researcher, it may be concluded that corrosion of the reinforcing steel can occur when the passive oxide film on the steel is destroyed by chlorides ions, the excess of oxygen to this area is available, and an abundance of moisture is present there. Accordingly, different parts of marine structures within the maritime environment are at higher risk than others.

Reviews of the relevant case histories **(Mehta and Gerwick, 1982; Buslov and Rojansky, 1983; Gilbride et al., 1988; Ingram and Morgan's, 1986; and many others)** clearly indicate that the parts of concrete structures most susceptible to steel corrosion are those that are most saturated and/or exposed to intermittent wetting and drying. The saturated tidal zone of marine structures has more potential than other parts of the structure for cracking due to cyclic wetting/drying conditions, freeze and thaw attack, and other factors described in this chapter. It is also the most vulnerable to corrosion of reinforcing steel. In many cases the splash zone has been reported as being vulnerable to corrosion of reinforcing steel.

In addition to the development of an electrolytic cell, corrosion may develop under several other conditions. The first of these is corrosion produced by the presence of a stray electrical current. In the case, the current necessary for the corrosion reaction is provided from an outside source. A second additional source of corrosion is chemicals that may be able to act directly on the reinforcing steel. In the case of embedded metal corrosion visual examination of the existing marine structure will typically reveal rust staining of concrete. This staining will be followed by cracking. Cracks produced by corrosion generally run in straight, parallel lines at uniform intervals corresponding to the spacing of the reinforcement. As deterioration continues, spalling of the concrete over the reinforcing steel will occur with the reinforcing bars becoming visible. One area where laboratory analysis may be beneficial is the determination of the chloride content in the concrete. This procedure may be used to determine the amount of concrete to be removed during a rehabilitation project.

2.5.4. Design Errors

Tsinker G.P (1995) has divided design errors into two general types: those resulting from inadequate structural design, and those resulting from lack of attention to relatively minor design details. In the case of inadequate structure design the failure mechanism is simple-the concrete is exposed to greater stress than it is capable of carrying, or it sustains greater strain than its strain capacity.

He stated that visual examinations of failures resulting from inadequate structural design will usually show spalling and/or cracking. To identify inadequate design as a cause of damage, the locations of damage should be compared to the types of stresses that should be present in the concrete. If the type and location of the damage and the probable stress are in agreement, a detailed stress analysis will be required to determine whether inadequate design is the cause.

He said, although structure may be adequately designed to meet loadings and other overall requirements, poor detailing may result in localized concentrations of high stresses in otherwise satisfactory concrete. These high stresses may result in cracking that allows water or chemicals to get access to the concrete. In general, poor detailing does not lead directly to concrete failure; rather, it contributes to the action of one of the other causes of concrete deterioration described in this chapter. Abrupt changes in section may cause stress concentrations that may result in cracking. A typical example is the use of relatively thin sections such as pier **Approach Bridge** decks rigidly tied into massive abutments. Insufficient reinforcement at openings tends to cause stress concentrations that may cause cracking. Poor attention to the details of draining a structure may result in the ponding of water. This ponding may lead to leakage or saturation of concrete and may result in severely damaged concrete if the area is subjected to freezing and thawing. Inadequately designed expansion joints may result in spalling of concrete adjacent to the joints.

He added that the use of materials with different properties (modules of elasticity or coefficient of thermal expansion) adjacent to one another may result in cracking or spalling as the structure is loaded or as it is subject to daily or annual temperature variations.

2.5.5. Erosion

Erosion damage to a marine structure is usually caused by the action of ice, sediments, or miscellaneous floating debris that are rolling and grinding against a concrete surface. Ice is typically the principal source of concrete erosion. Moving ice, which can have compressive strength as great as 20MPa, has been known to remove all the concrete cover and near-surface layers of reinforcement in marine structures **(Hoff, 1988).**
Ice abrasion at or near a waterline is a typical result of the combined effects of ice impact (or repeated impacts) and sliding of ice floes along the structure which create friction or drag on the concrete surface.

Wind-and/or current-driven ice floes can possess significant kinetic energy, much of which is dissipated into the concrete during collision with the structure. Some kinetic energy is lost in the crushing of ice. As driving forces continue to drag the ice floe against and along the structure a local failure occurs in both ice and concrete. The degree of failure of the ice/concrete system depends on ice and concrete characteristics, as well as on the dynamic response of the structure to the repetitive ice dynamic loading. With time this repetitive loading can affect the aggregate bond near the surface of the concrete, and cause or propagate microcracks in the concrete matrix. When eventually the integrity of the surface of the concrete has become impaired, the ice dynamic/abrasion action may cause particles of the surface to be removed. Oblique impact forces on exposed aggregates can be especially damaging. Some ice floes may contain grit which provides more abrasive impact on exposed concrete. **Gjorv et al., (1987)** suggested that wet concrete abrades more rapidly than dry concrete.

Environmental effects such as cyclic freezing and thawing and saturation of concrete in the splash zone and below the waterline can also be a contributing factor to weakening of the concrete matrix and aggregate bond weakening.
At any point in time, the degree to which each of the above factors has contributed to the overall deterioration and loss of concrete due to ice action is difficult to quantify. Recent field and laboratory studies of ice abrasion provided some useful information **(Hoff, 1988)**. One useful (and quite obvious) conclusion of the above studies is that normal weight concrete is more abrasion resistant if hard and tough aggregate are used. The general perception of structural light-weight aggregates is that basically they do satisfy this requirement.
Visual examination of a concrete surface exposed to any kind of abrasion typically will reveal local scratches and a surface that looks worn and sometimes polished.

2.5.6. Freezing and Thawing

As the temperature of critically saturated concrete is lowered during cold weather, the freezable water held in the capillary pores of the cement paste and aggregates expands on freezing. Is subsequent thawing is followed by refreezing, the concrete is further expanded, so that repeated cycles of freezing and thawing have a cumulative effect. By their very nature, concrete marine structures are particularly vulnerable to freezing and thawing simply because there is ample opportunity for portions of these structures to become critically

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