CHALMERS
UNIVERSITY OF TECHNOLOGY

STRENGTHENING OF SUBMERGED PILES

Using Fibre Reinforced Polymers Materials

Master's thesis in Structural Engineering and Building Technology

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
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ABSTRACT

Submerged reinforced concrete structures exposed to harsh environment are prone to extreme deterioration and the need from maintenance of such structures is increasing. Fibre reinforced polymer (FRP) materials is an emerging method to revive structures, due to flexibility and high strength properties it is a reliable and effective repair method. Introducing Fibre reinforced polymers to submerged structures aims to reduce high porosity of concrete and act as a protective layer against the exposed harsh environment.

The aim of this thesis is to identify optimal inspection methods to improve the feasibility of repair using FRP for submerged piles. The thesis is methodically performed by conducting a comprehensive literature review, conducting interviews with the experts in the industry to understand why the conventional repair methods are used and to compare and elaborate how the use of FRP repair method could be effective.

The conclusions drawn through the interviews is that there is a demand for new methods of inspection and repair. The comprehensive literature review revealed that FRP is used for repair in the atmospheric zone and splash zone to increase the durability and extend the service life of submerged structures. Using the FRP wrap method to repair the piles have shown a reduced rate of corrosion and minimal porosity.

Key words: FRP, submerged, concrete, piles, corrosion, repair, wrapping, underwater, deterioration

STYRKNING AV SUBMERGED PILES

Använda Fibre förstärkta Polymermaterial

Magisteruppsats i konstruktionsteknik och byggteknik

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Institutionen för arkitektur och samhällsbyggnadsteknik
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SAMMANFATTNING

Sänkta armerade betongkonstruktioner som utsätts för hård miljö utsätts för extrem försämring och behovet av underhåll av sådana konstruktioner ökar. Fibre förstärkt polymer (FRP) material är en framväxande metod för att återuppliva strukturer, på grund av flexibilitet och egenskaper med hög hållfasthet är det en pålitlig och effektiv reparationsmetod. Att introducera Fibre förstärkta polymerer till nedsänkta strukturer syftar till att minska betongens höga porositet och fungera som ett skyddande skikt mot den utsatta hårda miljön.

Syftet med denna avhandling är att identifiera optimala inspektionsmetoder för att förbättra möjligheten att reparera med hjälp av FRP för nedsänkta högar. Avhandlingen utförs metodiskt genom att genomföra en omfattande litteraturgenomgång, intervjuer med experter i branschen för att förstå varför de konventionella reparationsmetoderna används och för att jämföra och utarbeta hur användningen av FRP -reparationsmetod kan vara effektiv.

Slutsatserna från intervjuerna är att det finns krav på nya metoder för inspektion och reparation. Den omfattande litteraturöversikten avslöjade att FRP används för reparation i den atmosfäriska zonen och stänkzonen för att öka hållbarheten och förlänga livslängden för nedsänkta strukturer. Genom att använda FRP - lindningsmetoden för att reparera pålarna har man visat en minskad korrosionshastighet och minimal porositet.

Nyckelord: FRP, Nedsänkt, Betong, pålar, Korrosion, Reparation, Inslagning, Under vattnet, Försämring

Contents

1 Introduction

1.1 Background

The entire life-span performance of a structure relies on the foundation, which is designed with at most care as it is not visible or accessible in shore structures, that's not the case in offshore structures, with constantly at risk due to the nature of their surroundings. This rises the need for constant inspections for proper assessment & maintenance.

The current structures of the Port of Gothenburg is resting on the substructure build before the 80's. The structures in the earlier days were built with the belief that it would be everlasting, due-to the lacking knowledge of the potential damages which lead to failure of the entire system (Röös, J., 2017).

In order to ensure a safe environment, the Port of Gothenburg as been investing tremendous amount of money to inspect and repair the damaged piles, but to fix any sort of damage it must first be identified by inspecting the structure thoroughly.

The piles is categorically divided into different zones based on its environment along with its height (Yao 2016).

The zones are classified as followed:

1. Atmospheric Zone
2. Splash Zone
3. Submerged Zone
4. Mud Zone

The zones can be seen clearly understood in the figure below

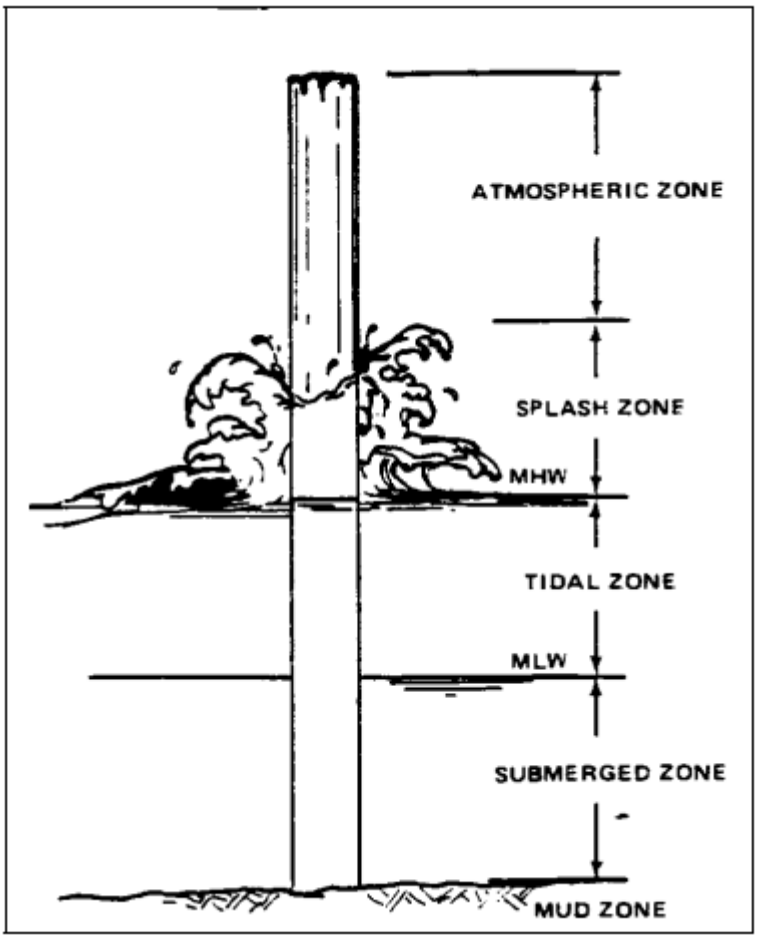


Figure 1: various zones in piling (Kelly,S. W. (1999))

The pile sustains most of its damage in the splash zone with the constant exposure to moving water this zone is undergoes a continuous loop of drying and wetting which increases the chances of scaling leading to corrosion.

To get a clear view of the sub-structure, it needs to be cleaned of the marine organ- isms to get clear visibility and access to the structure, it's time consuming but very crucial as visibility problems, but inspection, maintenance & repair of the super structure is carried at ease as working conditions are favorable. Due-to the high risk for damage rising the need for constant monitoring and maintenance. To produce a good solution to the problem the investigations need to carry out.

1.2 Aim and Objective

The aim of this master thesis is the find an effective method for investigating the submerged piles to provide a suitable repair solution, the following objectives are defined under the aim

1. Deterioration causes in submerged piles.
2. Review Current methods of inspections?
3. Review on the currently used repair methods.
4. How could restoration using FRP be beneficial?
5. How could the entire loop (START-FINISH) be optimized?

1.3 Research Approach

The aim is pursued by conducting an extensive literature review and interviewing experts in the field. The interviews are conducted with Dag Linghoff, Team Leader Marine Structures and Engineer Diving, ÅF Infrastructure AB and Ali Reza Mohammad Zadeh, Technical Manager at The Port of Gothenburg to study the cur- rent methodology involving inspection and repair to optimize the repair process the submerged piles.

1.4 Limitations

The investigation is limited to inspection of the existing submerged piles, this is carried out by studying the deterioration causes in the sub-zero climate, following the repair methods carried out.

2 Understanding Concrete

2.1 Background

When dating back to the prehistoric times, concrete has been frequently used as a building material in the world due to its immense durability which assures the survival of structures. concrete is a controlled mixture of cement, aggregates and water, in its fluid state concrete can be shaped into shape and texture (Beall, C. 2001).
The durability and strength are easily achieved by variations in materials and curing process. The wet mix of before the curing begins is known as "Fresh Concrete" which is a desired state due to its workability property making it easier to transport, handle and place without any segregation of ingredients. When the concrete is cured completely its known as "Hardened Concrete" capable of withstanding structural and service load imposed and environmental exposure (Beall, C. 2001).

2.2 Cement

Cement is only one ingredient in concrete and is not the same as concrete. Cement is a powder substance which reacts to water forming a paste, which is a binding medium that should coat each aggregate during the curing process called "Hydration" turning into a strong & hard mass (Beall, C. 2001).

The most used cement in the world is "Portland Cement" in various forms, it is vital to understand the process of manufacturing, composition, process of hydration and the end hardened fixture to make use of it effectively (Illston, J. M., 2010)

2.2.1 Manufacturing

Calcium silicates is an important component of cement which is created by heating an mixture of calcium oxide (CaO) and silicon dioxide (SiO_2) to high temperatures, these materials are available in huge quantities on the surface of the earth in various forms as calcium carbonate ($CaCO_3$). e.g. Chalk and lime stone (Illston, J. M., 2010).

The raw materials contain other components which cannot be eliminated such as magnesium, sodium, oxides of aluminum and potassium. The principle of manufacturing is simple with constant monitoring with the high temperatures and large quantities to ensure quality (Illston, J. M., 2010).

- The process begins with a controlled mixture of limestone and clay following a normal proportion of 80/20 forming a ball or roller (this mixture is known as raw meal). Sometimes it becomes necessary to add asmall amount of sand or iron oxide (Illston, J. M., 2010).
- The mixture is heated to a temperature of 1400-1500°, passed through a pre-calcining where the mixture is flash-heated to 900°eliminating 90% of car- bonate components decomposing to calcium oxide and carbon dioxide. The mixture is then passed to a heated kiln which is configured to a slope of 3°which rotates constantly (Illston, J. M., 2010).
- The mixture fed into the kiln takes about 20-30 minutes to reach the heated lower end passing out as a material known as clinker. Due-to the increasing tem- perature throughout the kiln de-carbonation is

complete at about 1100°which is known as burning zone,this process gives a mixture containing mainly of calcium silicates, calcium aluminates and calcium aluminoferrites (Illston, J. M., 2010).

- The mixture leaving the kiln emerges as clinker at 1200°, then cooled down at 60°before adding a small amount of gypsum (Calcium sulphate dehydrate, (CaSO4.H2O), limestone powder is added as a filler, usually in a ball mill to give the Portland Cement. The grinder process increases temperature of the clinker causing de- hydration, which is cooled by spraying water while spreading it out (Illston, J. M., 2010).

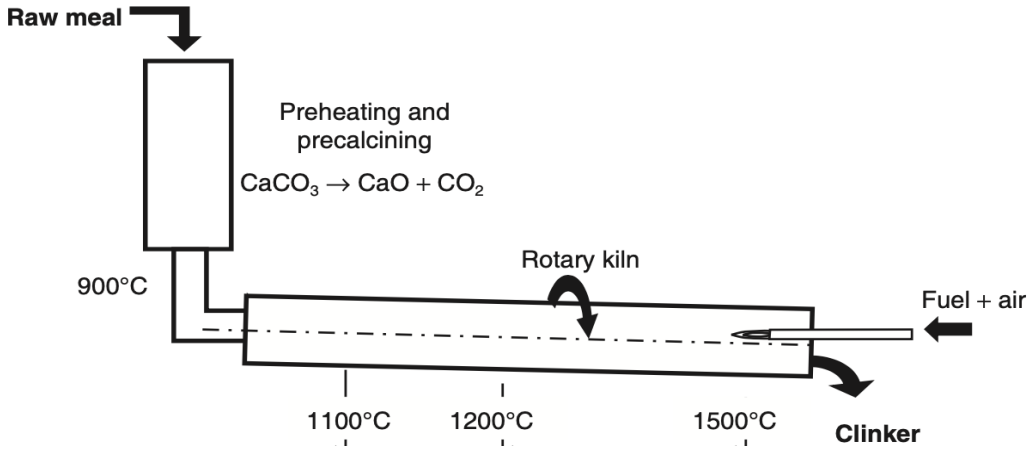


Figure 2: Process to produce Portland cement clinker (Illston, J. M., 201)

2.2.2 Physical Properties

Cement is a fine powder, having a relative density of 3.14 with a size of 2-80 microns. The size can be varied on the requirements based on mixture usage, the Blaine method is most used measure the particle size which is based on measuring the rate of flow of air under a constant pressure through a small sample (Illston, J. M., 2010).

2.2.3 Chemical Properties

There is a mixture of compound created at high temperatures in the burning zone of the kiln.

- CaO (Lime) = C; (Illston, J. M., 2010)
- SiO2(Silica) = S; (Illston, J. M., 2010)
- Al2O3(Alumina) = A; (Illston, J. M., 2010)
- Fe2o3(Iron Oxide) =F; (Illston, J. M., 2010)

The main four compounds are called as phases, in the cement:

- Tricalcium Silicate (3CaO.SiO2) = C3S (Illston, J. M., 2010)
- Dicalcium Silicate (2CaO.Sio2) = C2S (Illston, J. M., 2010)
- Tricalcium Aluminate (3CaO.Al2O3) = C3A (Illston, J. M., 2010)
- Tetracalcium Aluminoferrite (4caO.Al2o3.Fe2O3) = C3AF (Illston, J. M., 2010)

In the solid solution, tetracalcium aluminoferrite is not a true compound but makes the average composition. These compounds are formed at different temperatures as meal is passed through the kiln (Illston, J. M., 2010).

Every grain of cement consists of inmost mixture of these compound, but very com- plicated to determine the actual quantity by direct analysis instead the proportions are then determined a set of equations developed by Bogue in the year 1955 which are based on a few assumptions,

1. All the Fe2O3 is integrated with C4AF (Illston, J. M., 2010)
2. The left Al2O which is the remaining compound is combined as C3A
3. Cement is made of 71-76% C3S and C2S together making it a principal com- pound (Illston, J. M., 2010).
4. The compositions of each compound vary considerably in their relative pro- portions by orders of magnitude (Illston, J. M., 2010).
5.

2.3 Aggregates

Concrete contains both fine and coarse aggregates which are classified based on their sizes, commonly used are sand, gravel, crushed stone and pumice. In order to produce concrete, cement is mixed with water and aggregates, when cement is mixed with fine aggregates is procedures motor which is used for repairs and small works and to provide a smooth surface (Beall, C. 2001)..

Aggregates makes up to 60%-80% of the mixture providing strength and reduces the chances of shrinkage. The Characteristics of each aggregates has an direct effect on the quality of concrete produced (Beall, C. 2001).

- Coarse Aggregates: Categorized as particle size smaller than 4mm (Beall, C. 2001).
- Fine Aggregates: Categorized as particle size greater than 4mm and not exceeding 40mm in size (Beall, C. 2001).

The distribution of particle size is important to determine an optimum combination of mixture. This is carried out through sieve analysis, where the particles are dried and weighted, then passed through a stack of of sieve arranged in a descending order. The particles which are retained in the different levels are weighted (Beall, C. 2001).

The aggregates are grouped based on their source:

- Primary aggregates are manufactured for the producing concrete (Illston, J. M., 2010).
- Secondary aggregates are by-products of various manufacturing products which are not previously used in building constructions (Illston, J. M., 2010).
- Recycled aggregates are sourced from demolished structures (Illston, J. M., 2010)

2.4 Water

Water used to mix concrete is drinkable, free from harmful impurities. Many construction sites use water from supplied from the municipality, which is not contaminated, mostly the same in rural regions. The acceptable quality for mixing concrete is when water its clear, odorless and free from salty taste (Beall, C. 2001).

2.5 Formwork & Reinforcement

Formwork is medium used to provide the fluid concrete to a permanent shape till the curing process is complete, the formwork should be strong enough to endure the wet concretes pressure which is exerted till the beginning of the hardening process till the shape is held. Most commonly used materials to create a mold are lumber or plywood for straight elements and metal landscape edgings for curved elements. These materials often require a sealer to prevent the wet concrete from seeping away, if they are not pressure-treated (Beall, C. 2001).
Reinforcement is provided to concrete to increase its tensile strength and resist the natural shrinkage cracking which occurs during the curing process, the basic types of reinforcing are:

- Bars are available in different diameters and surface ridged to provided better bonding capabilities to the paste, commonly used made of several different types of steels and graded accordingly (Beall, C. 2001).
- Mesh's are made of steel wires woven or welded into a grid of squares or rectangles which are smooth surfaces, which is available in rolls and mats which is primarily used for flat work, which providing adequate strength distributing shrinkage stresses to minimize cracks (Beall, C. 2001).

2.6 Admixture

In order to produce concrete for special conditions, chemicals are added during the mixture to significantly change the fresh or hardened properties, they are acquired in aqueous form for the convenience of dispensing and dispersion into the concrete during mixture. The percentage of added to the mixture is less than 5% weight of cement, these substances are fully controlled to avoid over usage which leads to advise affects in concrete (Beall, C. 2001) (Illston, J. M., 2010)..

In the following sections several of the important admixtures are discussed making it 80% of the total quantities used in concrete which are followed after the classification of admixtures (Illston, J. M., 2010) (Beall, C. 2001).

2.6.1 Classification

Admixtures are classified on the bases of their action than their chemical constituents (Illston, J. M., 2010)

- The rate of hydration process are tempered by accelerating or delaying it.
- Increasing the plastic viscosity of the fresh concrete, by increasing the mix water (Illston, J. M., 2010).
- Increasing the protection to the embedded steel by adding chemicals to the hardened paste to repel water (Illston, J. M., 2010).
- Modifying the surface tension of the mixture to cause air entrainment (Illston, J. M., 2010).
- Increasing particle dispersion on the surface of cement (Illston, J. M., 2010). (Peter Demone)

2.6.2 Plasticisers

Concrete should be fluid and compactable, these properties combined together form a general property known as workability. Plasticisers are compounds that aids the workability of concrete, consisting of long chain polymers typically based on ligno- sulphonates obtained from processing wood for polyycarboxylate ether (Illston, J. M., 2010).

Use of plasticisers gives reduced the water: cement ratio increasing the strength, an secondary effect overlooked is that these compounds behave as a retarder decreasing the set time and early strength gain, Over use of plasticisers lead to segregation of the aggregates (Illston, J. M., 2010).

2.6.3 Superplasticisers

These compounds are more robust than the plasticisers, used to achieve increased fluidity and workability, reducing water levels drastically without notable unpleasant side-effects. Superplasticisers are a key ingredient for producing high-performance concrete, water reduction is calculated based on the type of chemical used, currently there are three chemicals used in the manufacturing industry (Illston, J. M., 2010),

- Sulphonated melamine formaldehyde SMF's (Illston, J. M., 2010)
- Sulphonated naphththalene formaldehyde SNF's (Illston, J. M., 2010)
- Polycarboxylate ethers PCL's (Illston, J. M., 2010)

The superplasticisers causes a joint repulsion and non-bonding interaction within the cement particles, but there are arguable opinions about the importance of these two effects with different chemical based superplasticisers (Illston, J. M., 2010).

- The joint repulsion is governing mechanism with the use SMf's and SNF's (Illston, J. M., 2010)
- PCL's have a high-density polymer sidechain on the block chain backbone, which leads to great efficiency with lowered dosage (Illston, J. M., 2010)
- Increase in performance can be observed for a short period when the superplasticiser is added at the beginning stages of the mixture (During the cement and water are mixed) (Illston, J. M., 2010)
- During transportation to reduce the setting period, retarders are introduced with the small doses superplasticisers at the manufacturing plant. More is introduced at the site at smaller doses to attain an optimal consistency (Illston, J. M., 2010).

2.6.4 Accelerators

To order to counter act cold weathers effect on the setting time of the concrete, accelerators are used to increase the mixtures hydration process further enhance the early strengthening after placing giving an opportunity to remove the formwork earlier and reducing the curing period by 24-48 hours. Calcium Chloride (CaCl2) is commonly used in the industry due-to its ease availability and effectiveness. These compounds accelerate both the initial and final set, but these effects vanish over time resulting with the same long-term strength as the normal concrete (Illston, J. M., 2010).

The calcium chloride compound used gets knotted in the hydra- tion process including C3A, gypsum and C4Af, the acceleration is created as the compound acts as a catalyst in the reactions, one keeps aspect to be understood is that this process increases the chances of corrosion in the embedded steel as the increase in chloride ions. This has resulted in restricting the type of compound used in reinforced and pre-stressed concrete (Illston, J. M., 2010).

2.6.5 Retarders

To delay the setting period of the concrete during the transportation or to counteract the high temperatures accelerating the hydration process or to ensure quality during large concreting work, retarders are used (Illston, J. M., 2010). The type of retarder is determined by the dosage by the weight of cement, sugar and citric acid are effective, but their effects are usually un-controllable. The working principle of this compound works by creating an early hydration product such as portlandite crystals (Illston, J. M., 2010).

2.6.6 Air-entraining agents

These are organic materials added to the mixture, to control the quantity of air which are in forms of small, microscopic bubbles placed about 0.2mm apart from each other in the paste making 4-7% by volume of concrete providing effective protection. These are not to be confused to trapped air in the concrete, present after incomplete compaction causing large irregular cavities (Illston, J. M., 2010).

These agents are powerful compounds with low surface tension changing the surface tension of the mixture, the molecules are made of hydrocarbon chain bonds. There is no effect on the hydration process at normal amount of usage on the concrete properties other the physical voids. This is used to provide concrete additional resistance to freeze&thaw, concrete contains moisture from free water in entrapped and capillary voids expanding on freezing temperatures leading to deterioration (Illston, J. M., 2010).

2.7 Mix Design

Mix design is referred as mix-proportioning as this process involves carefully selecting the ingredients in addition to the admixtures to manufacture a reasonable concrete mix (Illston, J. M., 2010). In order to obtain satisfactory results on site, and collaboration with the concrete manufacturer is important. The process involved are as followed to produce quality concrete (Illston, J. M., 2010):

- Specific Concrete properties: This section focuses on the properties such as strength, workability, and durability. The hardened properties of concrete depend on the mix design, strength at any given age is provided by the char- acteristic strength, in the European countries strength is specified as "Example:C8/10" first number being the minimum characteristic cylinder strength followed with the minimum characteristic cube strength (Illston, J. M., 2010).
- Constituent Material properties: All the properties and compositions of the ingredients are known for determining an optimal mix (Illston, J. M., 2010).
- Initial Estimate of mix Proportions: Many countries in the world follow their own methods known that result is only an estimation, an initial mix design is drawn out with providing all appropriate properties to start an laboratory trial mix before mass production (Illston, J. M., 2010).
- Laboratory Trail mix: In this stage, testing is carried out to confirm the mix proportion on a small scale. These test results will show improvements that needs to be carried out to reach a satisfactory mix, this process is carried out till an optimal mix is achieved but this process does not answer all the unknowns (Illston, J. M., 2010).
- Full Scale Trail Mix: Similar to the laboratory trials, full scale trials do not provide answers to all unknowns causing changes in the concrete properties. To achieve absolute trust new trials at full scale is carried out with altering the mix proportions followed with testing if needed (Illston, J. M., 2010).

3 Deterioration Causes

3.1 Background

Concretes has many favorable properties which is leading to its wide usage in construction industry. It can be easily mixed, transported, and placed in any desirable forms. The strength is regulated by optimizing the quantities of aggregates in the mix in order to provide long term durability against harsh exposure as discussed in the previous chapter.

When the concrete is properly mixed its performance is not affected but resilient against corrosion of steel, chemical deterioration, and structural damage. Deterioration of concrete is generally obvious if the change in appearance is originated through natural weathering, considerable deterioration is caused in the presence of water since hostile surrogates penetrate through the small pores present on the surface of the hardened concrete (Geoff, M. 2010).

Impairment caused at the beginning stages is not purely deterioration, but important as cracks gives access to harmful compounds, especially to those causing corrosion to the embedded steel (Geoff, M. 2010).

Deterioration can be caused due to mechanical and chemical or even both leading the material to failure (Geoff, M. 2010).

3.2 Chemical Causes

Generally, it is said that concrete is more likely to undergo chemical attack as its vulnerability of the hardened cement paste, for this to happen the agent of infiltration should either be in liquid or vapor form and structures that are in contact with water are likely to undergo chemical attack than structure that are not (Geoff, M. (2010).

3.2.1 Sulphate Attack

Figure 3: Concrete structure under Sulphate attack (OLUWAFEMI, L. A. (2016))

Sulphate attack arises by the dissolved ions into concrete undergoing reactions based on the exposure, resulting in expansion, cracking and loss of strength. Sulphates are available from either seawater or soil & groundwater (Dyer, T. 2014) (Gaal, G. C. M. (2004)).

- Sea water contains a sizable amount of sulphate ions, 2500-3000 (mg/L) based on the salininty of water (Dyer, T. 2014).
- Soil and groundwater damage depends on the solubility of the concrete as well as mobility, soil contains several sulphate minerals but many of these minerals have low solubility. sulphate minerals are found only in the first few meters of soil containing (Dyer, T. 2014).

The formation of ettrigite lead by the supply of gypsum with a combination of sulphate ions, aluminate phases and water (Dyer, T. 2014).

$$Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O \ldots (\ 3.1) (\text{Gaal, G. C. M. (2004)})$$

High volume of solids is formed with the poor creation of ettrigite crystals with the ample supply (Mehta 1992), this insufficient pressure created generates cracks

$3(CaSO_4 \cdot H_2O) + 3CaO \cdot Al_2O_3 + 26H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaCaSO_4 \cdot 32H_2O \ldots$ (3.2) (Gaal, G. C. M. (2004))

Delayed formation of ettrigite is another form of sulphate attack, formed during the plastic stage which does not form cracking (Dyer, T. 2014).

Cracks resulting from sulphate attacks usually starts from the corner edges of the elements moving deeper as they progress, decreasing in concrete compressive strength and stiffness which leads to accelerated deterioration. When the concentration of sulphate is moderate, it can have a beneficial influence when loaded under compression which is due to the decreased rate of entering sulphate into the element, where the entry is restricted by imposed load (Dyer, T. 2014).

3.2.2 Chloride Attack

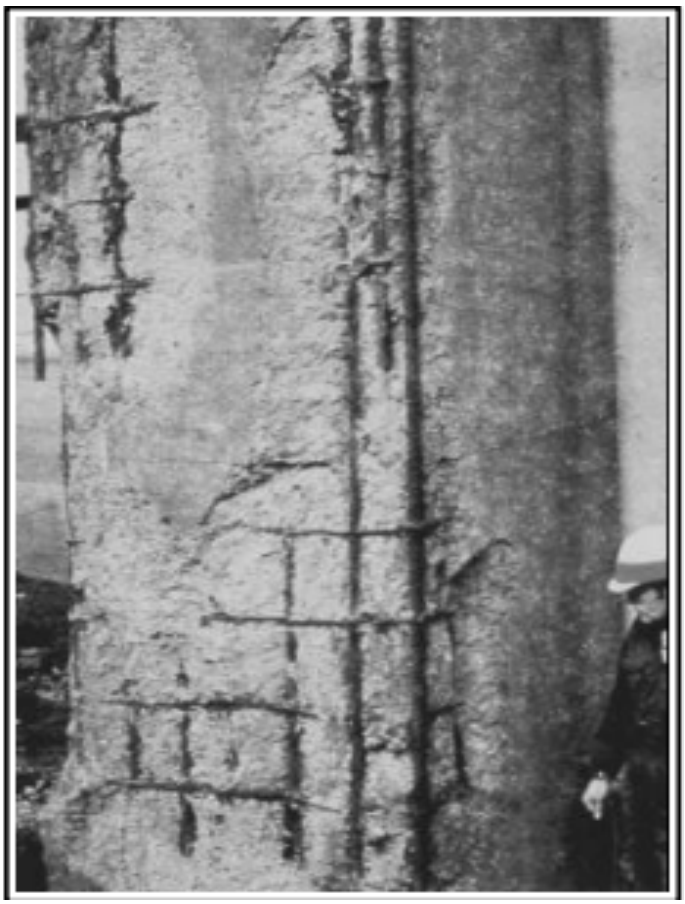


Figure 4: Concrete under chloride attack (Lampo, R., Nosker, T., Barno, D., Busel, J., Maher, A., Dutta, P., & Odello, R. (1998))

Chloride attack is a major concern to submerged structure as its exposed to both sea water and deicing caused due to the sub-zero temperatures. The concentration of chlorides is in sea water is 19,000 mg/L. Chlorides enter concrete through diffusion & capillary action (Dyer, T. 2014) (Gaal, G. C. M. (2004)).

- Diffusion: chloride entry depends on the porosity of the material, in the absence of any cracks. Chloride diffusion can be explained in terms of water/cement ratio, with lower water cement ratio the hydration increases, the volume of porosity falls reducing the diffusion coefficient. As, the porosity decreases in the outer layer of concrete, Freiedel's salts are formed within the pores. The rate of diffusion is aggravated in the presence of cracks, presenting a clear path through the concrete cover increasing the crack width and crack density. Crack width has much more influence over the diffusion rate than the crack density, but crack density has more influence on corrosion rate. Diffusion is mainly driven by the difference in the concentration levels, it is more complex when the source of chlorides is external. The diffusion decreases with the increase in concentration levels, this is due to the interaction of ions between higher concentrations which restricts their movements (Dyer, T. 2014) (Gaal, G. C. M.(2004)).
- Capillary Action: Water is drawn from the unsaturated pores present on the concrete surface, acting as a mechanism for chloride attack. this mechanism depends on the hydraulic diffusivity and volume fraction saturation in the con- crete. Capillary action is very significant in submerged structures due to the constant wetting and drying, as chloride is deposited on the concrete pores leading to excess accumulation under the surface increasing the concentration of chlorides (Dyer, T. 2014) (Gaal, G. C. M. (2004)).

When chloride reaches the reinforcement, they start to break down docile layer starting corrosion. This process forms a chloride nexus reacting to the ions from the docile layer (Gaal, G. C. M. (2004)), this occurs at a local region, initiating corrosion but the rate of corrosion is not influenced by the concentration of chlorides (Dyer, T. 2014) (Gaal, G. C. M. (2004)).

3.2.3 Carbonation

Figure 5: Effect of carbonation (OLUWAFEMI, L. A. (2016))

There is about 0.03% of carbon dioxide present in normal air (Geoff, M. 2010), concrete exposed to the normal environment is prone to enter of carbon dioxide, upon enter the reaction caused brings down the pH level below the carbonation depth, when sufficient oxygen / moisture is present the passive state of reinforcement is lost resulting in start of corrosion (Gaal, G. C. M. (2004)).

At the point when the profundity of carbonation reaches the steel the paste in contact with the metal will have a lot of decreased alkalinity and the securing layer will presently will not frame with the presence of oxygen (Geoff, M. 2010).

The pace of carbonation relies on the following:

- Concrete used (Gaal, G. C. M. (2004)).
- Size of aggregate (Gaal, G. C. M. (2004)).
- Dampness conditions and convergence of carbon dioxide in surrounding air (Gaal, G. C. M. (2004)).

3.2.4 Alkali-Aggregate

(a) (b)

Figure 6: Alkali-aggregate seen on a pillar (a) Picture from a far (b) Picture up close (Costa, F. L., Torres, A. S., & Neves, R. A. (2016))

The alkali in various aggregates causes expansive reactions, the most prevalent of which is the alkali-silica reaction, which occurs at the particles' surface and produces a non-expansive reactional product causing chemical shrinkage, as moisture is absorbed silica gel created in this reaction swells, this swelling increases the pressure in the concrete leading to cracks (Gaal, G. C. M. (2004)).

$$2NaOH + SiO_2 + H_2O \rightarrow Na_2SiO_3 \cdot 2H_2O \ldots\ldots \text{ (3.3) (Gaal, G. C. M. (2004))}$$

Every concrete is subjected to alkali reaction, but happens under certain conditions:

- Water is needed for the expansion (Gaal, G. C. M. (2004).
- The rate of transportation of ions is required to be high (Gaal, G. C. M. (2004).
- Availability of alkali ions (Gaal, G. C. M. (2004)).

3.3 Mechanical Causes

Concrete elements that undergo mechanical damage tend to lose they're load carrying capabilities and stiffness these changes in behavior makes the element very brittle from ductile. (Carpinteri, A., & Ingraffea, A. R. (Eds.). (2012)).

3.3.1 Abrasion

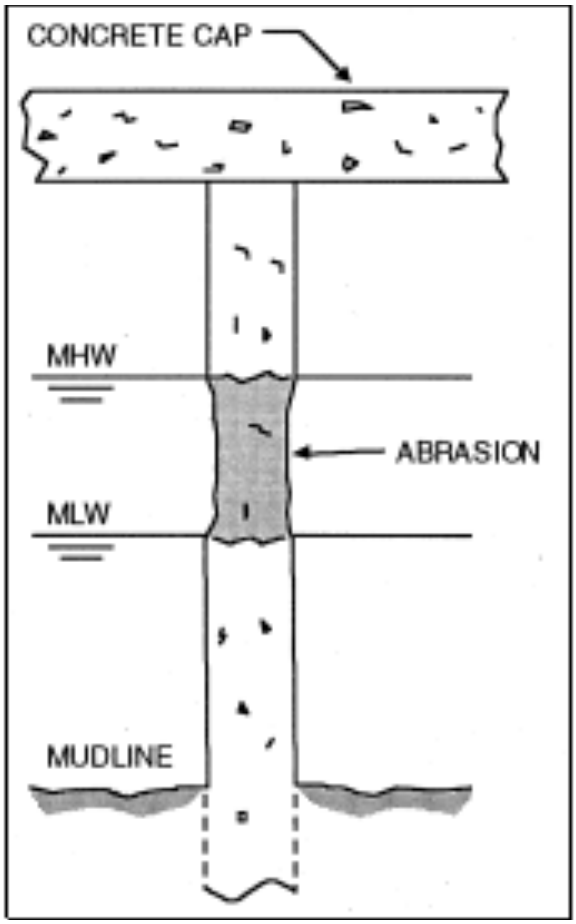


Figure 7: Abrasion effect on the pile (Kelly,S. W. (1999))

As mentioned in the in previous chapter, the splash zone is very vulnerable to sources like waves, sediments and ice causing a wear and tear on the surface of the pile.

Concrete goes through scraped spot in an exceptionally sluggish cycle, until exposed to different components bringing about lopsided surfaces diminishing the front of support. These lopsided surfaces permit gathering of water which speeds up the interaction causing broad surface degradation.

The damageable source being the ice which can strip through the substantial cover uncovering the supporting steel (Bengtsson, A., & Thornström, G. (2011)). Since, the greater part of the base at the port of Gothenburg were worked before the 80's, the heaps are built with heap defenders, But the recently introduced heaps are given insurance.

3.3.2 Accidental Loads

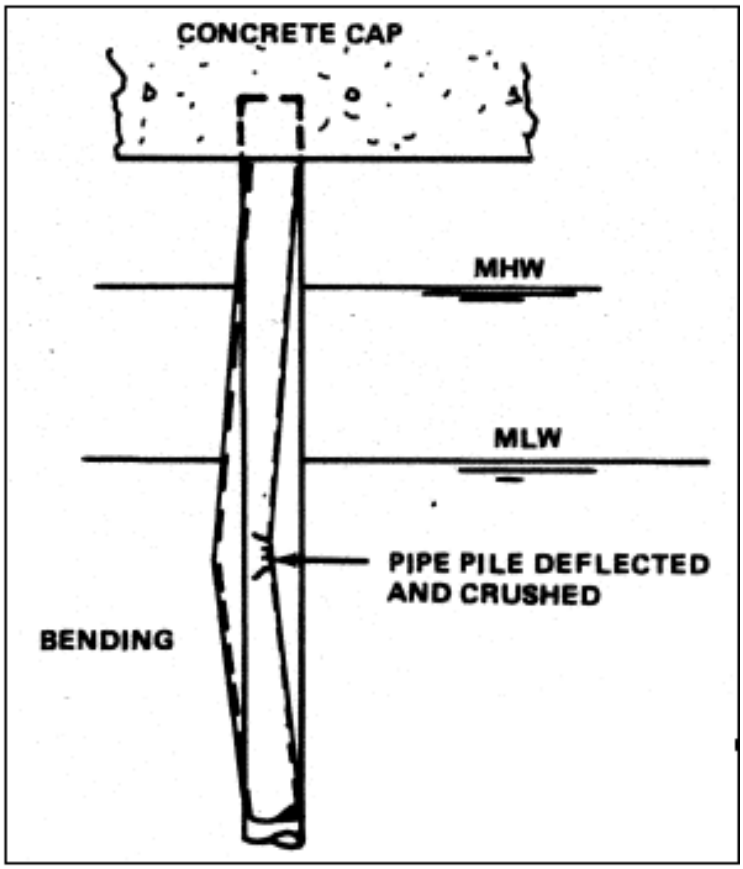


Figure 8: Effect of accidental loading (Kelly,S. W. (1999))

Accidental loading are man-made, probability of this occurring is lower as construction process is carried out carefully, A wide range of potential accidents are possible, but mainly focused on the ones effecting the structural performance such as ship collision, object, fire, and blast hazards (Röös, J., 2017).
When the vessel strikes the deck the impact damage causes structural deformations to the members (Röös, J., 2017).

3.3.3 Production Damage

Damages before and during the installation are considered as initial imperfections leading to reduction in service life. This could occur during transportation or placement of the pile, damage by collusion is a possibility when the piles are driven in an angle, any such damage can affect the surface of the concrete (loss of concrete cover) (Röös, J., 2017).

3.3.4 Cavitation

At the point when fluid pressing factor dips under fume pressure making bubbles, when coming in touch to the substantial surface they breakdown making shockwaves bringing about disintegration. As the construction presented to water waves ceaselessly prompting forceful scraped area (Lambert, P., Brueckner, R., & Atkins, C. (2010)).

3.3.5 Scouring

Figure 9: souring under the structure (Rossow, M. (2012))

Scour is caused quick water getting top layer free from the seabed of the settlements around the construction. As, the layer is taken out the bearing limit of the heap is diminished as the flows eliminate the base layer of the material too. Scouring brings about expanding the compelling length just as the clasping length of the submerged pile (Röös, J., 2017).

3.3.6 Freeze & Thaw

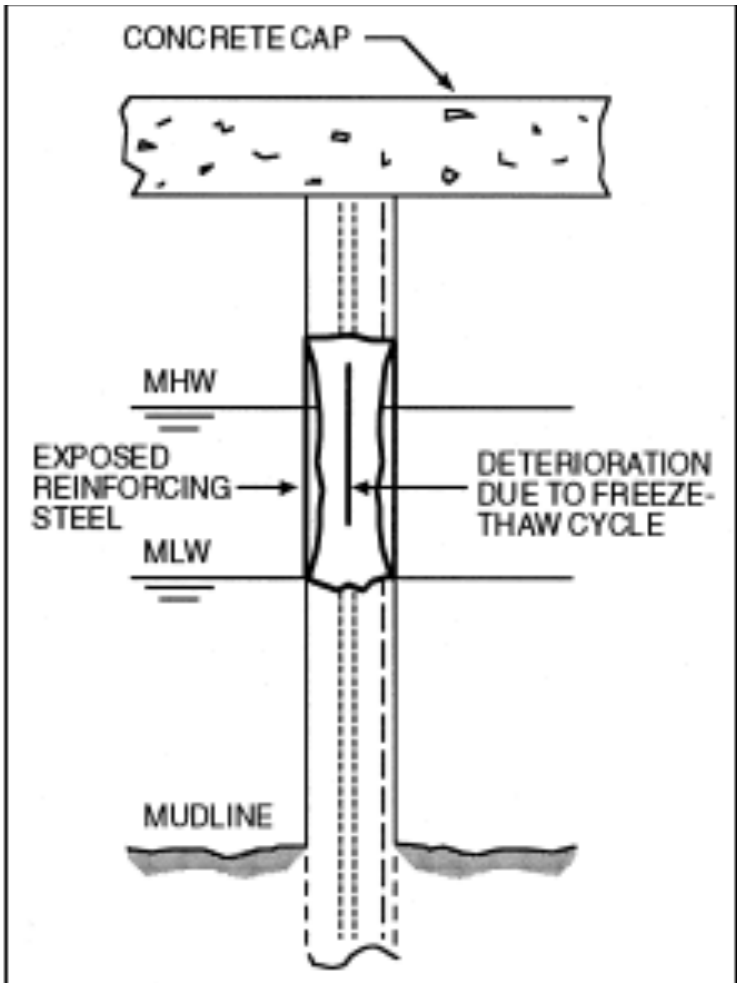


Figure 10: Loss of concrete by freeze & thaw (Kelly,S. W. (1999))

Deterioration is brought about by pore water development, water builds volume by 8-9%, when arriving at its edge of freezing over 0°, as referenced ice being a primary driver of harm in the sprinkle, As the temperature drops slowly the water present in the pores of the substantial extend (Domone and ILlston 2010) , as they change to ice, with the limitations on space an inner pressing factor is made, with no space to assuage this extensive pressing factor the substantial breaks from within to bring down this pressing factor, this is a consistent cycle during the freeze/thaw cycle (Thoresen 2014). If the pores on the external surface are around filled a greater amount of 92% containing basic immersion, the construction will go through crumbling in the colder time of year duration (Lambert, P., Brueckner, R., & Atkins, C. (2010)).

3.3.7 Exfoliation

Similarly, to freeze & thaw, the pores in concrete are filled with moisture and entrapped water, undergoing expansion. As the wetting and drying cycles are continuous formation of crystals is inevitable causing an increase in the tensile stresses which is imparted into the concrete reducing the concrete cover (P. Lambert, R. Brueckner and C. Atkins).

3.3.8 Scaling

With the continuous wetting and drying in the splash zone, the salts crystals are formed as the water evaporates from the surface, these crystals will continue to grow in size with the wetting and drying cycles. These crystals create a pressure on the surface disrupting the concrete. This can be avoided through using concrete with low permeability and with addition of admixtures (Röös, J., 2017) ,.

3.4 Indirect Deterioration

The main culprit of indirect deterioration is caused by corrosion of reinforcement, as irons react with oxygen their volume increases causing cracks and spalling. The rust formation is dependent on the pressure, moisture, temperature and oxygen (Liu 1988).

Corrosion is an electrochemical process which requires anode and cathode reactions, as the metal dissolution happens it is an anodic reaction, which loses electrons.

$$2Fe^{2+} \rightarrow 2Fe^{2+} + 4e^{-}$$

Pore water plays an essential role in the oxygen reduction. Hydroxyl ions are formed as anode releases free electron which react with the oxygen and the water.

$$4e^{-} + 2H_2O + O_2 \rightarrow 4OH^{-}$$

The following reaction shows the reaction procedure involved in the production on hydroxyl ions.

$$2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2$$

The hydroxyl ions formed are of low solubility, precipitating around the reinforcement, in the presence of oxygen hematite irons are formed which are also known as hydrated forms of rust (Lambert, P., Brueckner, R., & Atkins, C. (2010)).

$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 + 4H_2O$$

3.5 Concluding Remarks

On studying the causes of deterioration in piles it is clear that the exposure to hash environment is the main reason that the structure is undergoing these phenomenon's and they are summarized in the flow-chart below, mechanical and chemical.

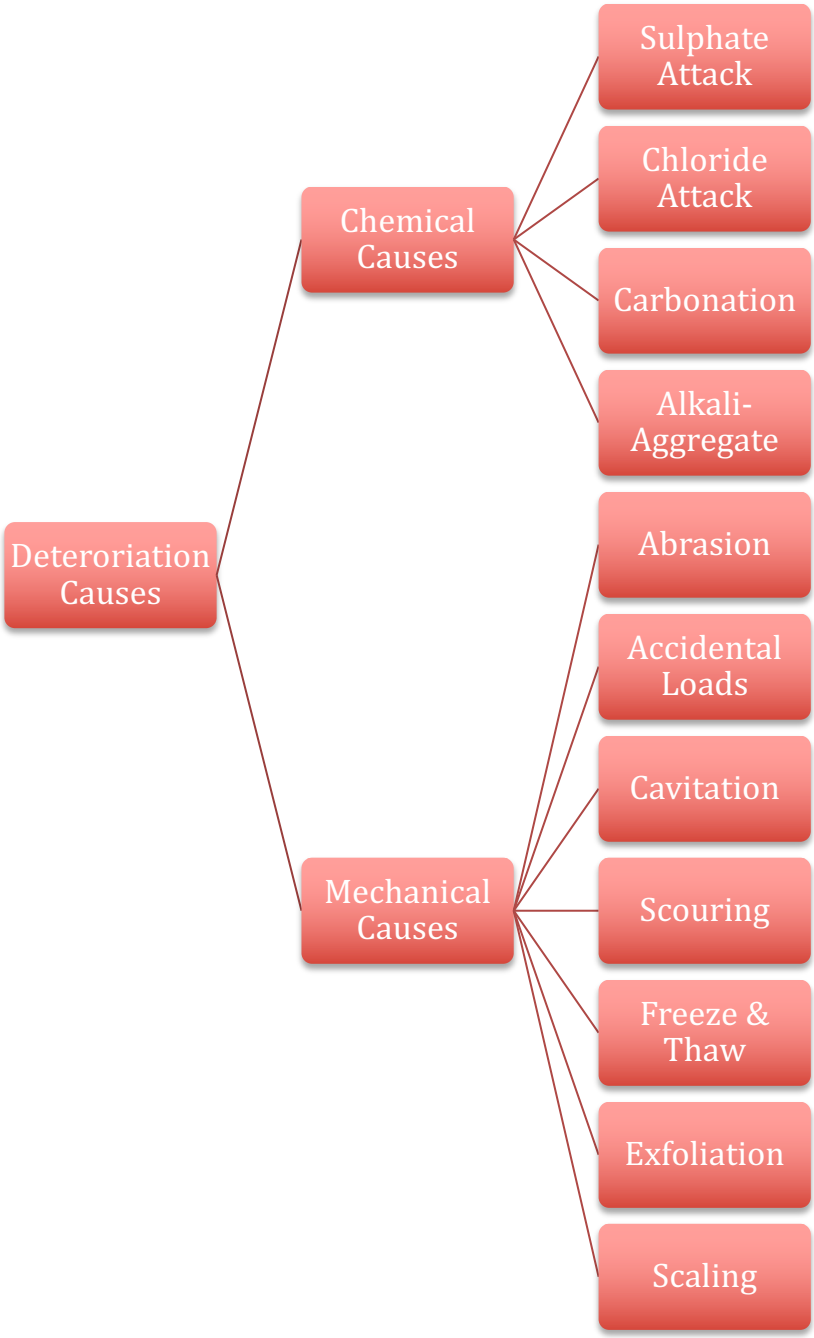


Figure 12: Overview of the deterioration causes

Figure 13: Indication of either one can influence the other

By interviewing Mr. Ali Reza Mohammad Zadeh(Port of Gothenburg) and Mr. Dag Linghoff it can be concluded that the most commonly seen deterioration is chloride attack which may have been caused with or without the initial physical damage. The initial production damages are caused as the piles are driven and the chloride attack through the chlorides swiping into the concrete.

4 Inspection Methodology

4.1 Background

Structure failure endangers the lives and causing substantial property damage, to prevent such events from occurring constant evaluation needs to carried out to establish adequate structural safety.
This evaluation is carried out by performing thorough inspections acquiring the necessary information to assess the current and predict the condition of a structure to determine the service life and repair procedures (Stowe, R. L., & Thornton, H. J. T. (1984)).

Inspections are scheduled when the conditions are favorable to obtain clear visibility of the structure and can be of categorized into three types:

1. Routine Inspection: This inspection is visual / feel also known as "swim by" inspection carried out to detect damages or problems, mostly carried out once a year. Any damage identified in this process leads to a detailed inspection. Also known as Level One Inspection.
2. Detail Inspection: This inspection is more detailed and driven towards measuring the damage hidden behind marine vegetation, Before the detailed inspection is carried out the structure needs to the cleaned of the vegetation to obtain clear access, inspection is only carried out on only the damaged elements which were identified during the routine inspection. This level of inspection is carried on once every five years or depending on the details obtained in routine investigation. Also known as Level Two Inspection
3. Highly Detailed Inspection: This is a unscheduled inspection carried out on catastrophic events as floods, vessel impact and evidence of excessive souring. Mostly carried out to determine the extent of damage by conducting several non-destructive tests depending on the severity of the damage. (Guidelines on underwater inspection of bridges 2008)

4.2 Cleaning

Figure 14: Pile cleaning carried out by water-gun (Rossow, M. (2012))

Cleaning is a strenuous and labor-intensive process which is very necessary for initial inspection of the structure, which employs tools such as wire brush and chipping hammers in shallow waters and in deep waters hydraulic powered water jets and grit blasting are employed. Before any NDT methods are conducted, the structure has to be cleaned depending on the level of cleaning. The process involves removal of marine organisms such as algae, mussels...etc most of the tools are depended on humans for operations.

Inspection methods are categorized into two sub-categories

- Destructive Testing
- Non-Destructive Testing (NDT)

4.3 Destructive Testing

The aim of this type of testing is to investigate the service life and to detect any possible weakness or problems which might not be seen in normal conditions. (Gupta, S. (2018))

4.3.1 Coring

Figure 15: Under-water coring (Rossow, M. (2012))

This type of investigation is carried out, when there is question about interior deterioration. This process requires an underwater hydraulic drill to extract a core of predetermined size and length from the specimen, the extracted core sample provides an opportunity to conduct Laboratory experiments to measure the strength, density, chloride permeability and extent of carbonation which gives an overview of the structure's performance and capabilities.

This destructive process causes pressure on the surface leading to minor crack in the region, progressing to loss of concrete cover. (Sandor popvics and Willie E mcDonald 1989).

As,an general rule destructive testing is not suggested, but needs to carried out when reasons are reasonable doubt arises about the integrity of the structure.

4.4 Non-Destructive Testing

The aim of this type of test is to investigate the flaws in the concrete in terms like cracks which lead to lose of strength. (Gupta, S. (2018))

4.4.1 Divers

Figure 16: Fully equipped diver holding a scale (Rossow, M. (2012))

Divers are and still be a traditional primary investigator for any visual documentation. The investigation includes cleaning which is a time consuming than the investigation itself, making this a very demanding job (R.Frank Busby)

Divers can follow self-contained diving, who operates independently from the surface carrying breathing air required for the intended time he/she would spend underwater "or" follow surface supplied diving, who's breathing air is supplied from the surface through a flexible tube which is attached to the diver (Rossow, M. (2012)).

In the current moment due-to the lack of availability commercial/Scuba and construction divers haven been employed from time-to-time to carry out inspections provided them with specific knowledge about the task that needs to be carried out.

4.4.2 Sonar

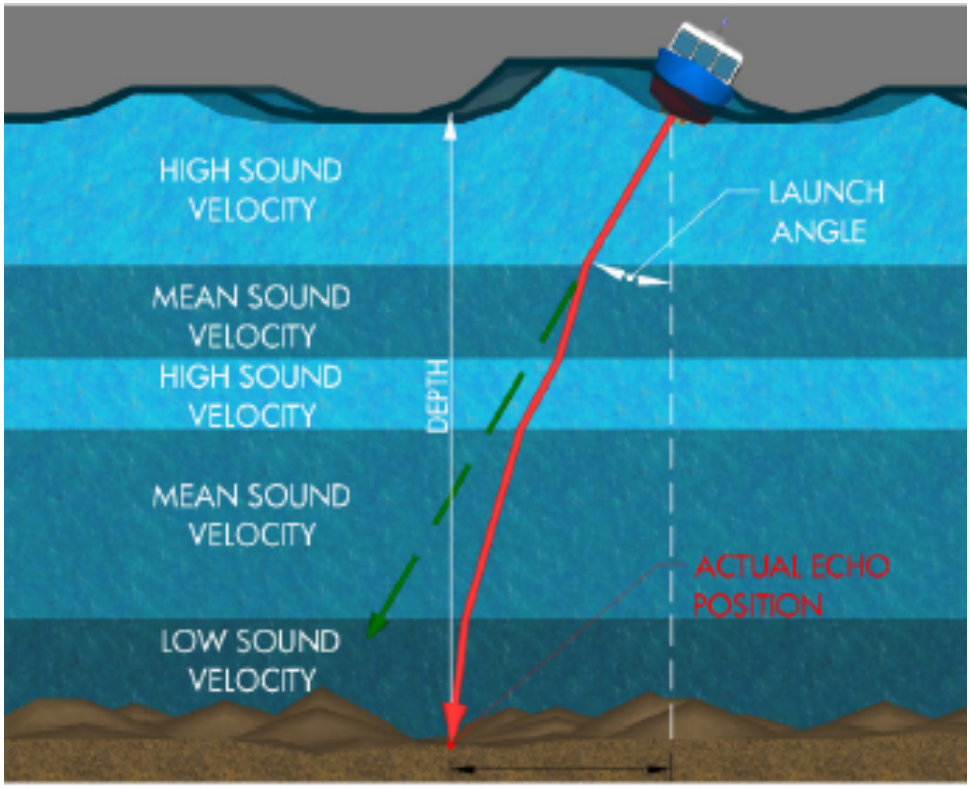


Figure 17: Pictographic representation of sonar waves travelling through the water (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

Sonar is a part of underwater imaging technology that shown a lot of potential for developments, this technology can produce two-dimensional and three-dimensional images and water depth data. This technology works by emitting a acoustic pulse which travels through the medium inverted dome pattern in all directions moving towards the member and measures the time it takes to bounce back to the source transducer (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The transducer behaves both like an emitter, receiver and upon on emitting the transducer converts the electrical signal into sound waves, upon on receiving the sound waves is converted back to electrical waves behaving as a hydrophone.
The waves travel in an inverted dome pattern in all direction, the waves are strongest directly under the transducer and weakest as the angle from the central axis increases. The transducer cone angle is the measure of a wave central focus, as the distance from the central axis to the half point. The cone angle is desired to be smallest for the required inspection of a bridge (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The sound waves are assumed to travel at a constant speed through the environment. However, with the varying density, depth, temperature the waves are affected but the frequency remains constant (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The following figure shows the path of sound waves as it travels through varying layers in the water.

This Technology is categorized on the bases of the data that is produced, explained in the following subsections.

4.4.2.1 Three-Dimensional System

Three-dimensional system is made of several beams with several data points with unique x, y & z coordinates, these points are interpolated to generate a rendered sonar image, this system works well when the angle of incidence is low (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The detail's obtained from this inspection depends on

- Area on which the beam is to be focused in order to get a reading
- Number of points obtained

The points obtained is known as the data density, if the system has more beams, it increases the density of data with lesser time. 3D systems include Echo-sounders, Geophysical sub-bottom profilers and real-time multibeam sonar (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.1.1 Fathometer

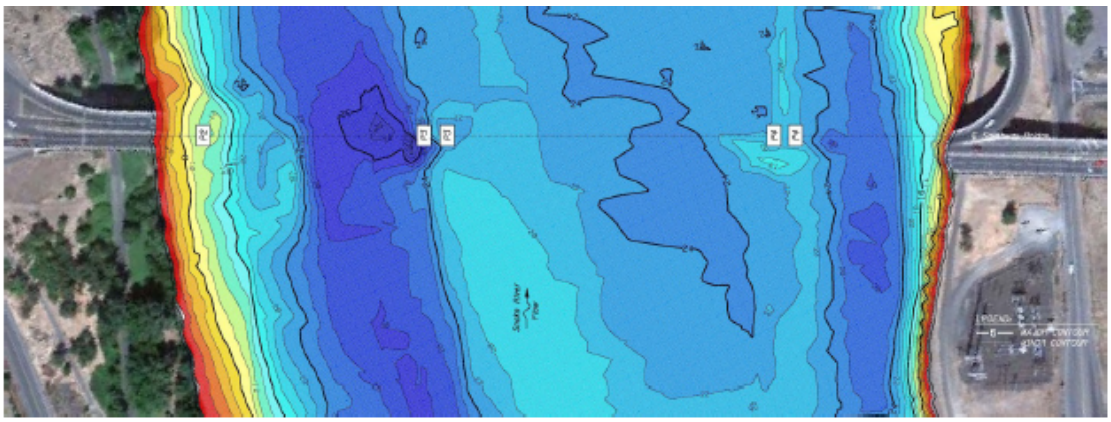


Figure 18: Results obtained from the fathometer of a bridge (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

These are single beam sonar systems gathering 3D data with frequencies ranging from 24 to 340 kHz, high resolution image is yielded with high frequency. A single beam sonar beam is quite large at the depth and return of the echo's is not always accurate (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

Most of these systems are capable to connect with GPS receiver allowing geographic coordinate locating allowing accurate channel survey which can be used to study past data or refereed to future studies carried out. Data obtained is relatively low while comparing other methods limiting the detection of irregularities unless the vessel holding the transducer moves over the section as the beams are narrow (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The preliminary benefit of this method is the ability to generate georeferencing bottom profiles used to locate scour and area of infills. The limitation faced by this system is acquiring large data as the beam is narrow and any objects not in the path of the vessel is not scanned (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.1.2 Geophysical Sub-Bottom Profiles

Introduced in the mid-1960s still used till date for detecting bedrocks, this system generates images of the embedded objects, bedrock via a digital device. Either an electromagnetic or acoustic radar are employed and also known as ground penetrating radar (GPR) (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

These profilers can locate the position and depth of buried cables and other objects under the movable bridges before any repair, they can also be employed to detect scour holes (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The preliminary limitation is the interference that results in the images that can be difficult to interpret, the interference faced are the waves bouncing off objects before returning. This system cannot be used in saline water or depth greater than 9.1m (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.1.3 Multibeam Swath and Mechanical Scanning Sonar

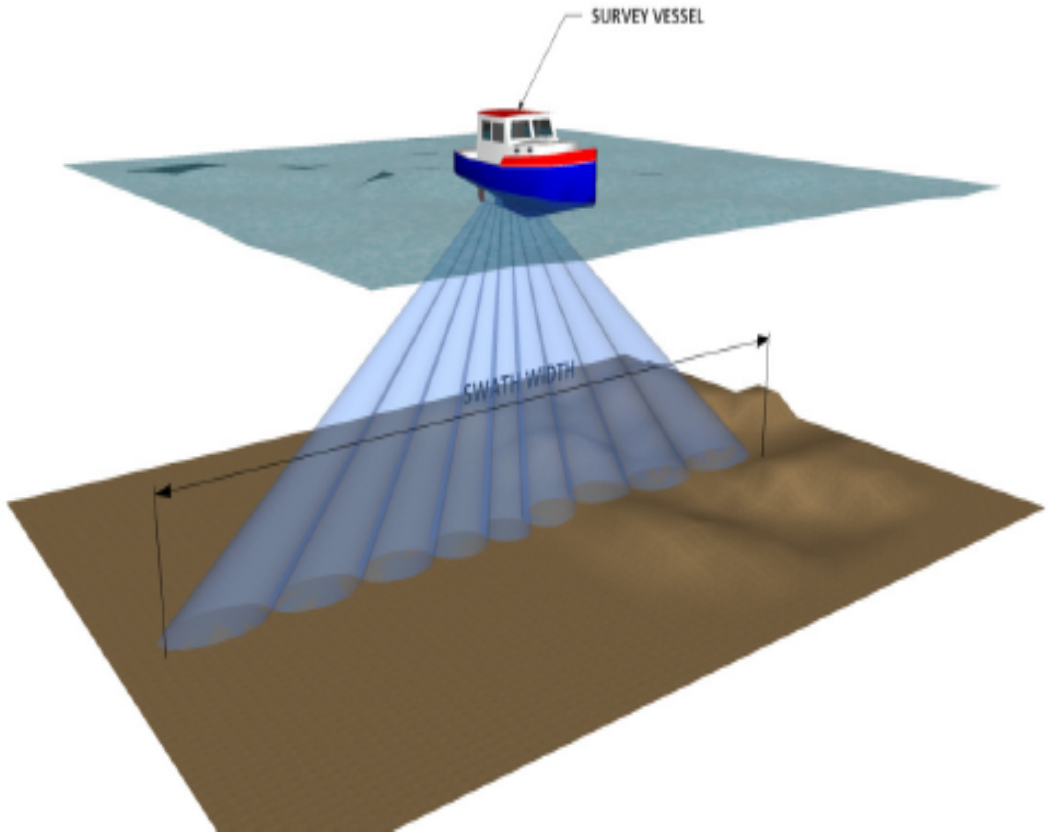


Figure 19: Swath beam pattern (Shen, J., Forsyth, R., & Kilgore, R. (2018))

Developed in the mid-1960s for the U.S. Navy is also called an echo sounding system, similarly to the single beam they project fanned arrays covering a wider range. These allow for a dense data collection in a short period of time, a typical survey can swath width of several times the depth of water. Mechanical scanning is an multibeam unit fitted with a stepping motor which remains stationary during inspection (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The operational range is about 0.7 to 1.8 MHz, a preliminary benefit of the swarth system is the ability to acquire large amount of 3D data producing an 3D still image which is offered to a point of cloud. The limitation faced by this system is vast amount of data requires time to process and additional sensors are needed to be placed in between sensors to get an accurate reading (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.1.4 Real-Time Multibeam Sonar

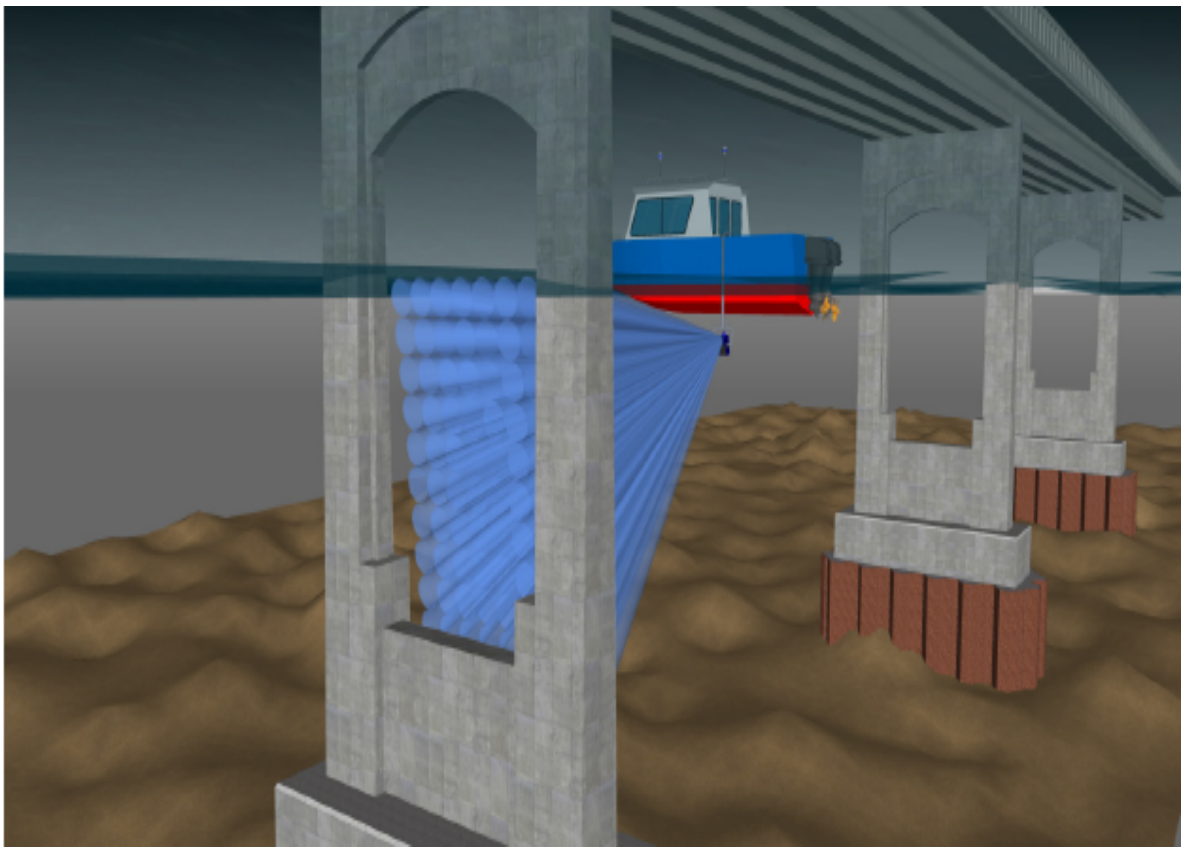


Figure 20: Real-time sonar pattern (Shen, J., Forsyth, R., & Kilgore, R. (2018))

This is a volumetric system consisting of various rows and columns of narrow beams, the matrix of beams allows for a dense data coverage able to create thousands of points with every cycle. This system creates a three-dimensional image which is updated in real time as similar to watching a video. Employment of this system requires less skilled operators, with the large number of data created large structures can be inspected quickly without losing time (Shen, J., Forsyth, R., & Kilgore, R. (2018)).
The limitation faced by this system is the vast data produced can obtain much time in the post processing (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.2 Two-Dimensional System

Two-dimensional system is made of a fan-shaped beam, recording in full range of returns from wider dimensions of the cone angle and plotting them in a 2D drawing, it cannot differentiate from which portion of the cone angle it came from but can determine if an echo returns from more than one object (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

2D systemns include side-scan sonar, sector-scanning sonar and lens-based multi- beam sonar (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

when the site conditions are adverse to divers like extreme depths, low visibility and high velocity currents, sonar technology is preferred due to its accelerated advance- ments by providing an outstanding quality of non-optical image even during turbid water with no visibility conditions (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.2.1 Side-Scan Sonar

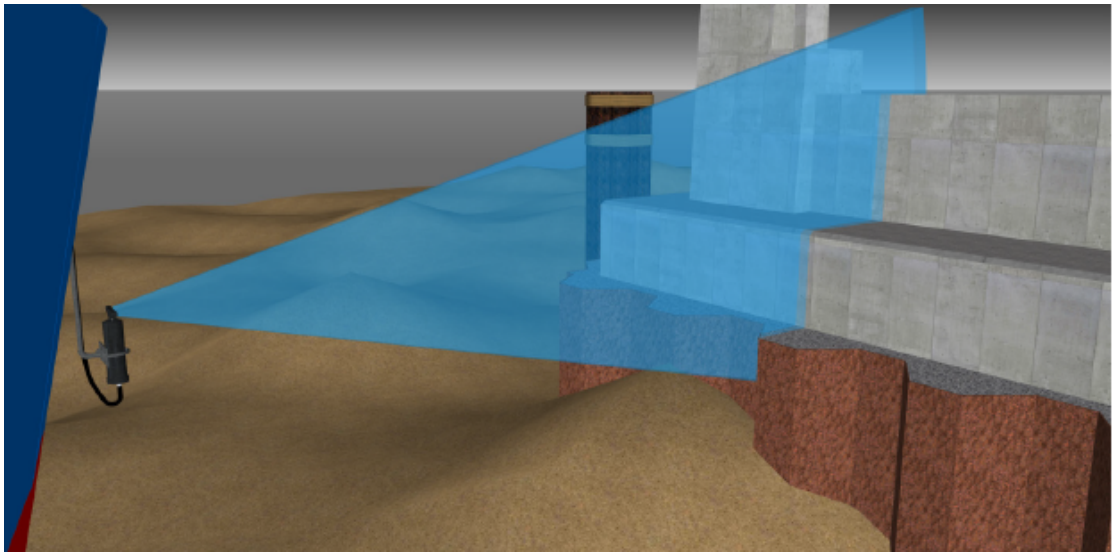


Figure 21: Side-scan pattern (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

Introduced in the beginning of 1960s for recoding underwater findings, this system works by emitting a fan-shaped wave through the water column with an operating range of 83 to 800 kHz. The beams are completely narrow in one directional and wide in the other direction (Shen, J., Forsyth, R., & Kilgore, R. (2018)).
The transducer is dragged behind the boat or mounted on the hull of the boat, the image is creating as the transducer is dragged forward and backward. The images are stitched together along the travel (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The preliminary benefit of this method is the quick and effective generation of image of large areas typically suitable for large operation inspections, but the limitation are faced while inspecting vertical submerged structures and linear targets (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.2.2 Sector-Scanning Sonar

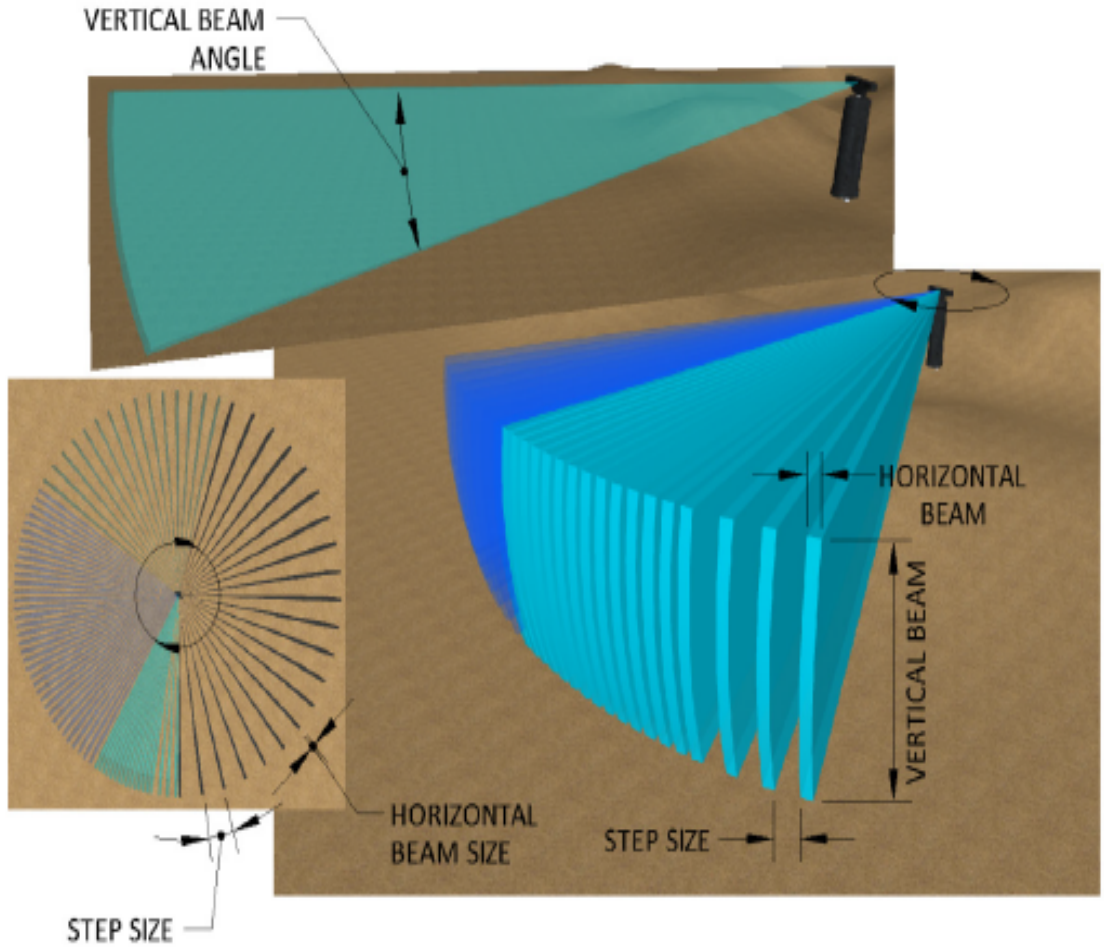


Figure 22: Sector scan sonar patter (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

First used to inspect the location and resting position of a sunken bridge deck in the year 1990, this system emits beam in a fan-shaped through the water requiring the carrying vessel to move in order to develop an image (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

This system works best if the transducer remains constant while only rotating the head mechanically. The images are recorded in a series of slices generated after every rotation of the transducer. The operation range is about 330kHz to 2.25 MHz using a common frequency of 675 kHz for structural imaging (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The preliminary benefit of this system is obtaining a detailed image of submerged structures that are extended from the bottom of the channel to the surface giving more information to the diving inspector of potential defects. Limitation faced during the employment of this system is that limited range as the transducer is mounted in a fixed position increasing the time to obtain an image and also the stability of the transducers (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.2.2.3 Lens-Based Multibeam Sonar

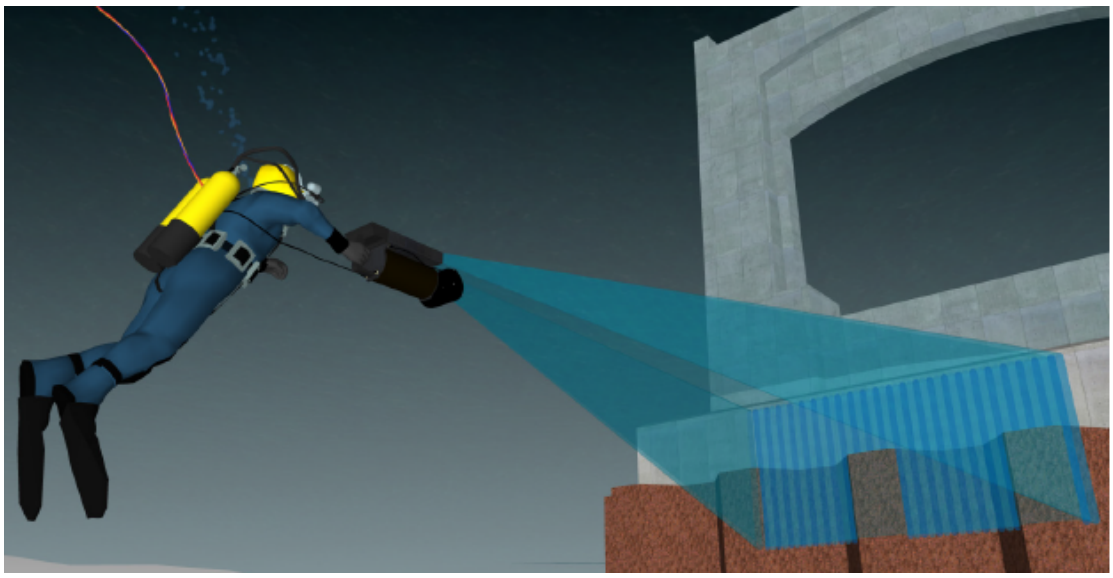


Figure 23: Lens based sonar pattern (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

This system was introduced through a funding provided by the U.S Navy in late 1990s at the University of Washington department of applied physics to identify swimming intruders, later adopted by offshore oil industry for structural inspections (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

It is essential for sector-scanning that does not rotate, this system consists of multiple elliptical beams which are placed side by side helping to create an image in one transmit and receive cycle, the operational range is 0.7 to 1.8MHz (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

The preliminary benefit of this system is to provide a quality as video, as the show real-time it is much easier to track and provide direction to the diver. The only limitation faced by this system is obtaining complete images of a vertical surfaces, because the image is obtained in two-dimensional it is not possible to obtain the depth of scaling or penetration information (Shen, J., Forsyth, R., & Kilgore, R. (2018)).

4.4.3 Optics

In this type of visual investigation, the use of instruments with the capabilities to capture pictures and record videos for documentation purposes are preferred when other methods are facing limitations.

4.4.3.1 Photographic Cameras and Video-Graphic Cameras

Figure 23: Typical camera capable of taking picture and vidoe used during inspection (Rossow, M. (2012))

This method is depended on the divers inspecting the submerged structures to record data. These mechanical instruments are waterproofed having the ability to capture image and videos, most of the modern instruments come with both features of capturing image as-well as videos. When it comes to their application underwater, they are distinguished as two different instruments.

4.4.3.2 Remotely Operated Vehicles

Figure 24: ROV used for inspection (Bogue, R. (2018))

These are tethered underwater instruments which are equipped with a high-resolution camera mount with wide-range flash to capture images or videos giving a live feed to the visual controller allowing the users a clear view of the structure, with divers facing limitations with depth, weather conditions and visibility issues these instruments are employed.

This instrument is categorized based on their size, power consumption and weight giving the user a range of options to choose depending on the need.

4.4.3.3 Autonomous Underwater Vehicles

Figure 25: A typical AUV being deployed into the ocean (Zhang, H., 2021)

These instruments are pre-programmed to follow a set path of trajectory before being deployed requiring no input for operations, these are not tethered or controlled from the surface but are docked underwater mainly used for military purposes and research, they are not yet common in commercial use.

4.4.4 Testing Equipment's

Small testing methods employed to conduct non-destructive testing in order to check the concrete

4.4.4.1 Acoustic Ringing

This investigation is carried out by striking the surface with a underwater hammer to find loose internal areas of the structure exfoliating the cover caused by freezing and thawing (Busby, R. F.,1978).

4.4.4.2 R-Meter

This instrument is used to measure the cover thickness of concrete and the size of the reinforcing steel through induced magnetic field which is produced through the rechargeable batteries. The accuracy of this instrument depends on the initial configuration settings (Busby, R. F.,1978).

4.4.4.3 Schmidt Hammer Test

Figure 26: Schmidt hammer (Browne, T. M., 2010)

This test is conducted to determine compressive strength of concrete and penetration resistance of the material, the instrument is held right angled to the sample's surface and pushed into the surface with an energy, the instruments spring recoils inwards measuring the surface hardness which can be co-related to concrete's compressive strength (Busby, R. F.,1978).

4.4.4.4 Parallel Seismic Testing

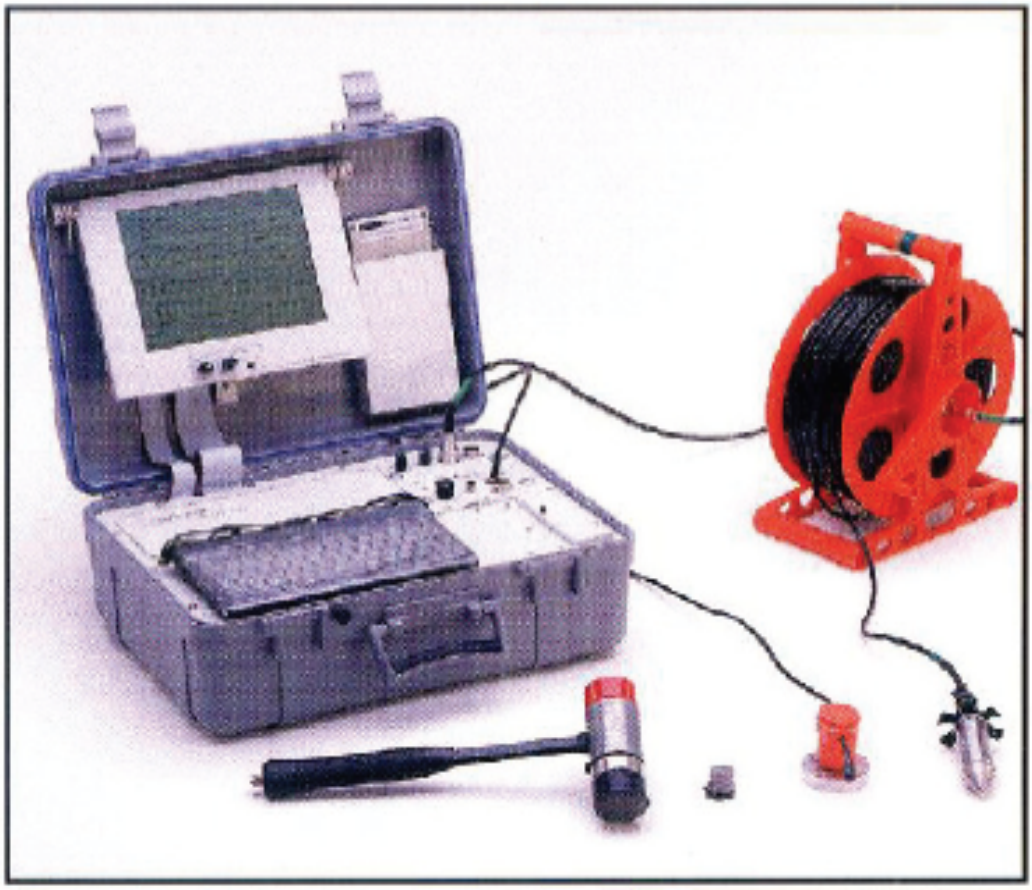


Figure 27: Parallel seismic testing equipment (Rossow, M. (2012))

This investigation is carried out to check the piles embedment length, this information is very valuable to know susceptibility of the structure to scouring (Busby, R. F.,1978).

4.4.4.5 Ultrasonic Pulse Velocity Test

Figure 28: Ultrasonic pulse velocity meter (Browne, T. M., 2010)

This test is designed to find voids, crack and forms of deterioration, this method depends on compressional waves having a frequency ranging from 50 to 150hz. The device is made of a vibrating transducer on the left side placed on side of the concrete member and the receiver on the other end. The waves travel through the member, where the waves are disrupted by the density of concrete, steel and voids. This method is commonly used to study the quality estimation (Busby, R. F.,1978).

4.5 Review on Studies Conducted

The case studies were conducted to find a way to reduce the entire inspection duration.

4.5.1 Development of ROV for Visual Inspection of harbour Structures

(Choi, J., 2017) This literature paper is published by Jinwoo Choi of the Ocean system engineering research division of the Korea Research Institute of Ships and Ocean Engineering (KRISO), keeping mind the limitations faced by the conventional method of inspection an underwater robotics system was developed. The developed system is equipped with navigation sensors and visual inspection systems helped to reach the structure acquiring and transmitting image. The system is operated from the shore connected by a tether cable through which the image is transmitted.

The system has been equipped with four horizontal thrusters for two-dimensional planar motion, both in omi-directional and precise motion control required to acquire a high-quality image. For navigation purposes the system is fitted with AHRS, DVL and depth sensors, where AHRS and DVL are used to stabilize the vehicle in horizontal plane and the depth sensor to take depth information of the vehicle.

For the inspection task, the system is equipped with a forward-looking HD camcorder and a halogen lighting system to tackle the low visibility, in addition an imaging sonar is fitted to help the system move towards the structure

Figure 29: The developed system is about 60cm by 60cm and about 40cm in height (Choi, J., 2017)

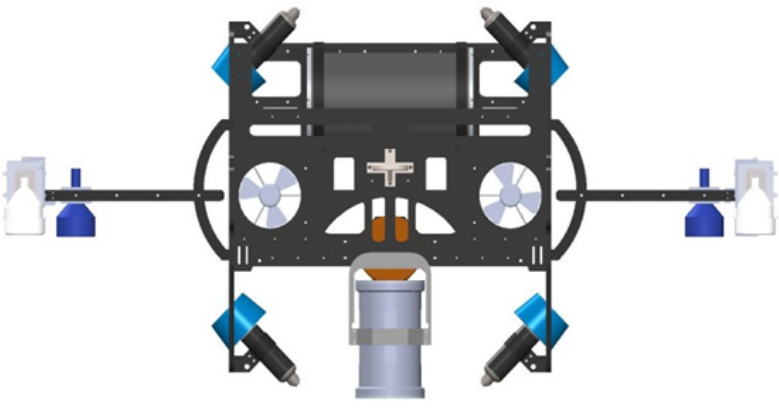


Figure 30: 3D CAD model of the ROV (Choi, J., 2017)

The developed system is backed with evidenced by conducting basin and a sea trial, the basin test is created by simulating planar and columns, first the system is moved closer to initial position manually followed by moving it closer to the targeted area.
The rover carries out the inspection by horizontal and vertical motion through controlled heading.

Figure 31: column type structure (Choi, J., 2017)

The sea trail is carried out in the harbor of the southern sea research institute in Korea, the system performed inspection task of a column by moving around them. The inspection is carried out by moving the rover up and down in several directions to obtain a high-quality image.

Figure 32: Environment of a sea trail (Choi, J., 2017)

4.5.2 Damage detection of underwater foundation of a ancient Chinese stone arch bridge via sonar-based techniques

(Chen, B., 2021) emphasize the need for routine inspection of bridges as they collapse due to sourcing. These papers presented sonar-based techniques that have been used to inspect an arch bridge in china called Gongchen Bridge in Hangzhou, the used equipment's in inspection procedure are a multi-beam echo sounder employed to measure the bottom profile of the bridge and a side-scan sonar for understanding the wooden stake that has been exposed. The scour of the foundation has been analyzed using multi-beam sounding techniques, in find the geological condition holes were drilled 2 meters away from the foundation.

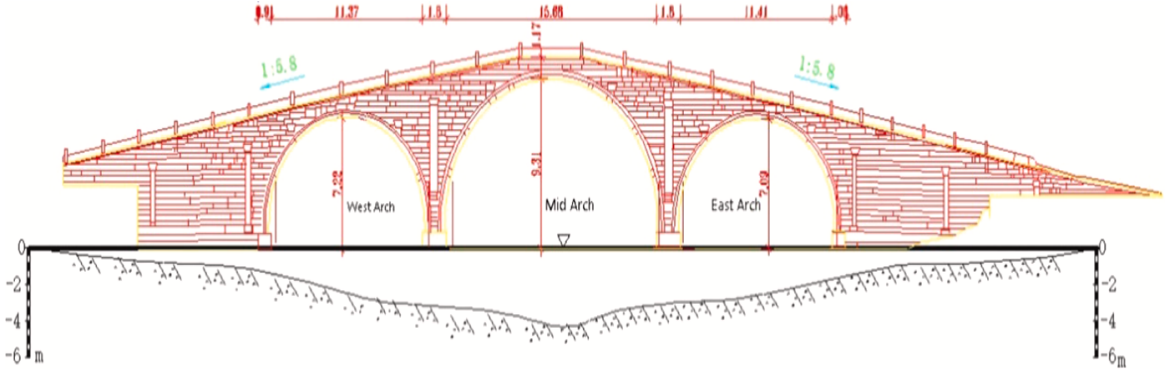


Figure 33: Longitudinal section view of the arch bridge (Chen, B., 2021)

The bridge is located at the north of Dengyun bridge in Zhejiang Province, built in 1963 and has been termed as key cultural relic in 2013. The foundation has been damaged by several years of river erosion, weathering, and numerous ship collisions leading to serious safety hazard.

The bottom profile of the river is examined through employing multi-beam sounding using sensors based on satellite positioning system calculating the spatial position to obtain the features of the bottom terrain. The Scour condition is inspected through the side-scan sonar which sends the echo signal images using the principle of sound wave reflection. The Figure below show the principle of side scan sonar

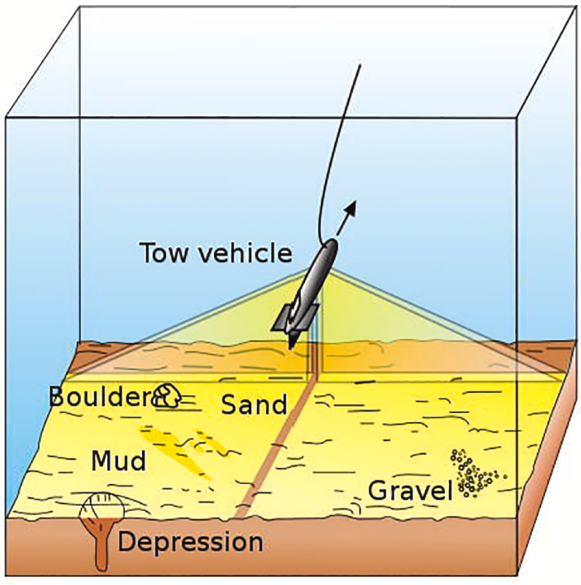


Figure 34: Schematic presentation of the principal side scan sonar (Chen, B., 2021)

The sonar is used for inspecting the bottom of the bridge and other obstacles to see the appearance of the wooden pile and the stone foundation.

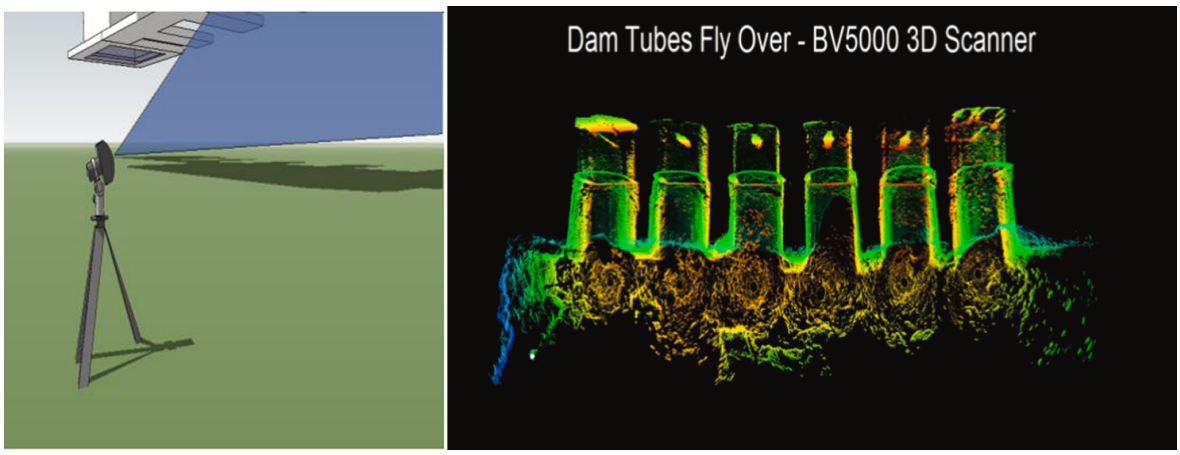


Figure 35: Underwater panoramic sonar scanning imaging inspection schematic diagram (Chen, B., 2021)

The foundation has been inspected using the BV5000 3D sonar for panoramic sonar scanning and imaging, the sonar penetrates the surface to produce a high-quality 3D image of the abutments as shown in the Figure…. Above, the instrument is placed by the diver at the bottom.

Geological drilling is carried out to estimate the bridge condition and to conduct acoustic CT which is based on the theory of acoustic rays measuring the time to travel, the ray is retrieved to reconstruct an acoustic model.

From the analysis of the results, it was seen that the wooden piles have undergone erosion caused by river erosion and ship scraping, leading to instability of the upper strip stone foundation, it was concluded by the author that reinforce and repair the stone strip and seal the exposed piles, finally to remove the obstacles in the river near the bridge.

4.5.3 Polar Map: A Digital Representation of closed structures for underwater Robotic Inspection

(Sandøy, S. S., 2020) of the Norwegian University of Science and Technology have worked on this project to improve the production in aquaculture industry which has been affected by the economic losses and negative attention from the users.

The maintenance and repair of sea-based fish farms are inspected by divers and remotely-operated vehicles (ROV's), divers are exposed to hazards and repercussions are expensive, hence using UUV' s for its cost-effective operation.

This paper gives a mapping approach has it's a highly memory efficient, low runtime and online applications, this method is applicable to dynamic and static environments. This method is scalable which is beneficial for its minimal system memory and computational efforts.

The cylindrical fish cage is discretized using cylindrical coordinates with respect to angle, depth and each model section is modelled with Gaussian distribution, 3D mapping of the cells is carried out in Cartesian grid which includes free cells too. This mapping approach is fulfilled by these following assumptions:

1. The range of sections are statistically independent
2. Each point in the structure is defined from a vertical line along Z-axis which provides angle and range

The online mapping approach for a flexible structure requires a model which reflects any change in structure position in any time, these changes can be periodically and slowly varying. The slowly varying is modelled in a random walk process which is carried out on an assumption- The change in range of each section can be modelled in a random walk process

To update, the 2.5D map all measurements are required which is acquired from a vehicle with pose in relation to the NED frame, pose does not include roll and pitch angle of the vehicle. The measured model range is fulfilled through an assumption- The sensor noise is Gaussian distributed. The range measurement is computed through Euclidean norm at the endpoint.

Gaussian distributed model does not take outliers in the sensor measurement which is a weakness and therefore another separate outlier detection step is included to smoothing for each measurement before Kalman filter which is used for each section, where initial conditions can be specified. When no initial conditions are specified, sensors are used to update the process, where an information filter would be advantageous has it will define covariance matrix as infinite which avoids the need for initial condition and runtime.

There are two different sensors used setup scenarios for localization and mapping of aquaculture, the robot localization is carried out for orientation and positioning for a certain time relative to a local environment providing an reference frame. To acquire pose of the UUV, positioning system is needed for acoustic needs. One type of positioning system is short-based line (SBL), using the flight time from the transponder in the UUV to transponder fixed outside at a known location and UUV's location is found through the speed of sound based on time-of-flight signals. To find direction of flight an magnetic compass is necessary but the compass is exposed and prone to electromagnetic noise.

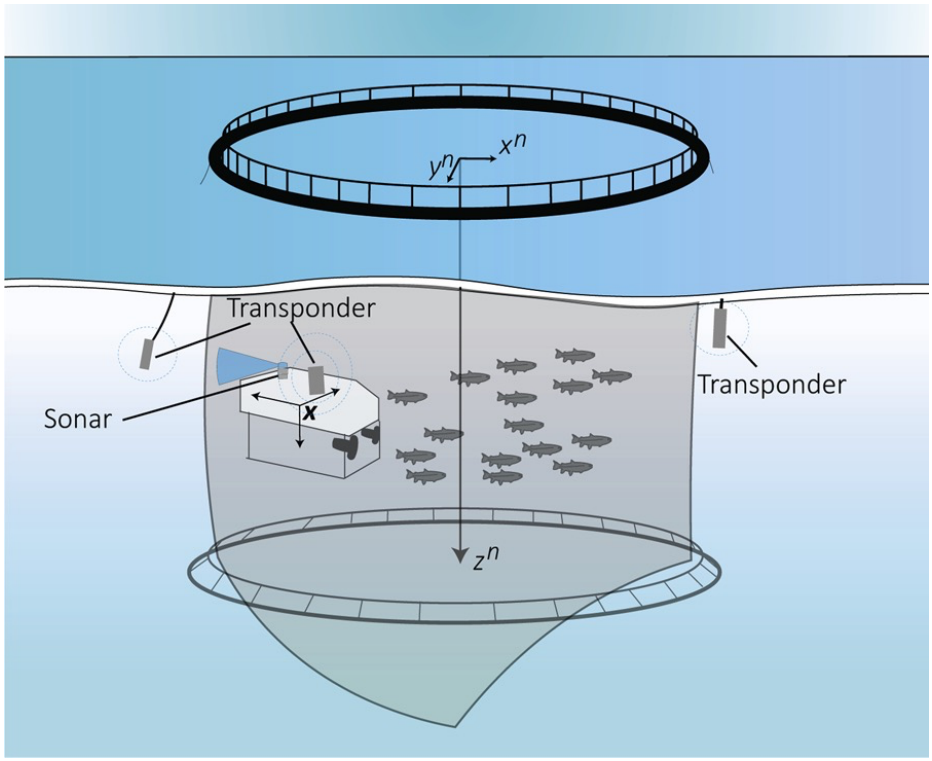


Figure 36: Mapping scenario illustration (Sandøy, S. S., 2020)

Simultaneous localization and mapping (SLAM) method performs operation of finding the location of the robot at the same time providing an map of the environment. To localize the map needs to be known and vise-versa, advantages of this method is that no compass is required avoiding heading errors caused by magnetic noise. The first sensor is an Doppler Velocity log(DVL) scanning obstacles in the systems path and second being gyro which measuring the rate of heading angle, apart from these sensors an pressure sensor is installed to estimate the depth of the sea.

Two cases studies were carried out to check the mapping and localization using a UUV of the fish cages, (1) Cage mapping with known pose; (2) Mapping with unknown pose. The UUV used for these case studies have been shown in the figure below

Figure 37: UUV Tri-Dog 1 (Sandøy, S. S., 2020)

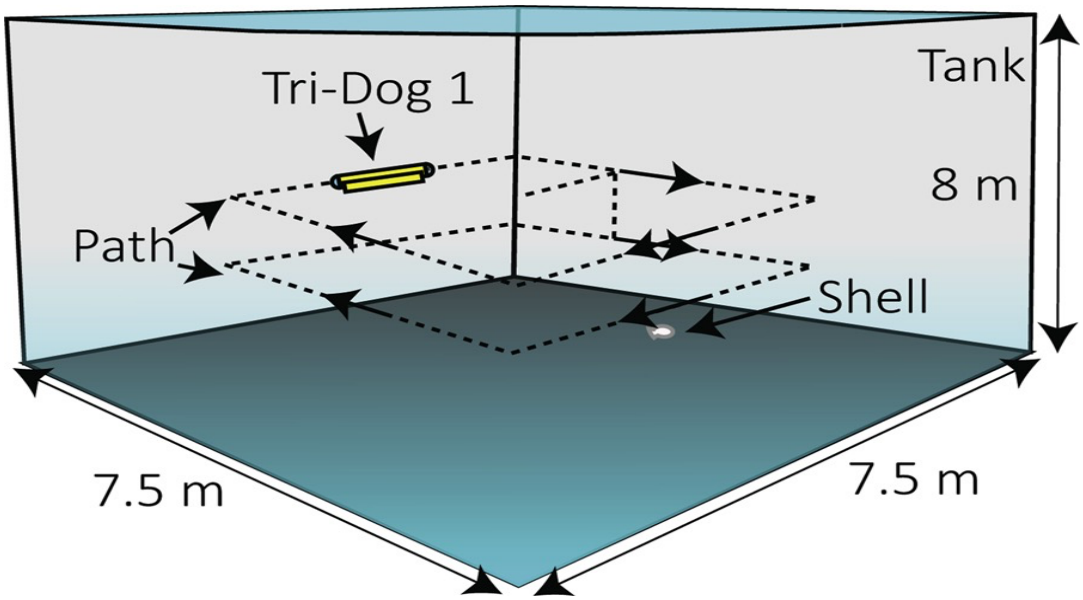


Figure 38: The path of the vehicle (Sandøy, S. S., 2020)

In the first case study, 28,800 range and bearing were obtained after processing. The results showed the surface plot interpolates the estimated ranges in each section and the errors vs true range have been shown on the color scale, an root mean square error (RMSE) was compared to the fish cage position which has been computed by estimating the error between error and true ranges for each section in the polar map. It was noted that the map limits the assumption 2 due to large deformation in the cage but an center line can be adjusted to deal with the tilt in depth. The RMSE computation has been carried out using the nearest-neighbor transform, the error is evaluated by the true maps position which is generated. The produced map is discrete map and does not generate a continuous surface. When comparing the usage of memory, the polar method uses very less space. The results of the first case study is presented below figure shows the polar map and figure shows the data point and octomap

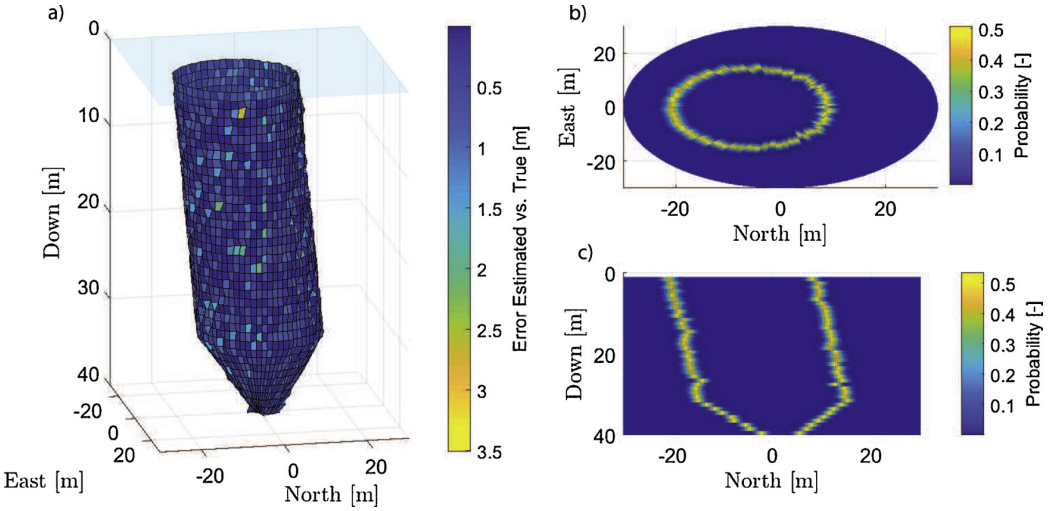
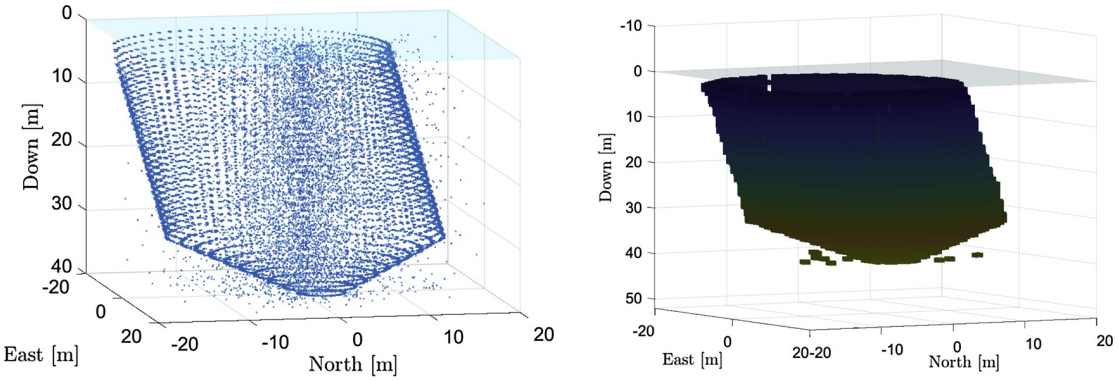


Figure 39: Case study 1 polar map (Sandøy, S. S., 2020)



(a) Case study 1: Raw data point cloud

(b) Case Study 1: Octomap

Figure 40: Data points and Octomap (Sandøy, S. S., 2020)

The second case study did not use the process model has the cage is an static structure, performance of polar map and octomap are similar with respect to position accuracy and consistency of the shell position estimates but some differences in vehicle trajectory, The covariance is increases drastically due to accuracy of the sonar system. The low complexity computational depends on constant updating of the map with range and bearing measurements which relies completely on range of measurements as insertion of range to map needs traversal of each cell on the range of measurements and the differences are very evident after map update time. Polar maps use less time in computational time in comparison with the octomap which is found in the resampling operation in both the approaches. The complexity of octomap increases with change in depth which also increases the runtime with increase in iterations and the polar map computational time remains same. The results of this study is shown below in the figure showing the polar map particle filter-based SLAM in the tank and figure shows octomap particle filter-based SLAM in the tank

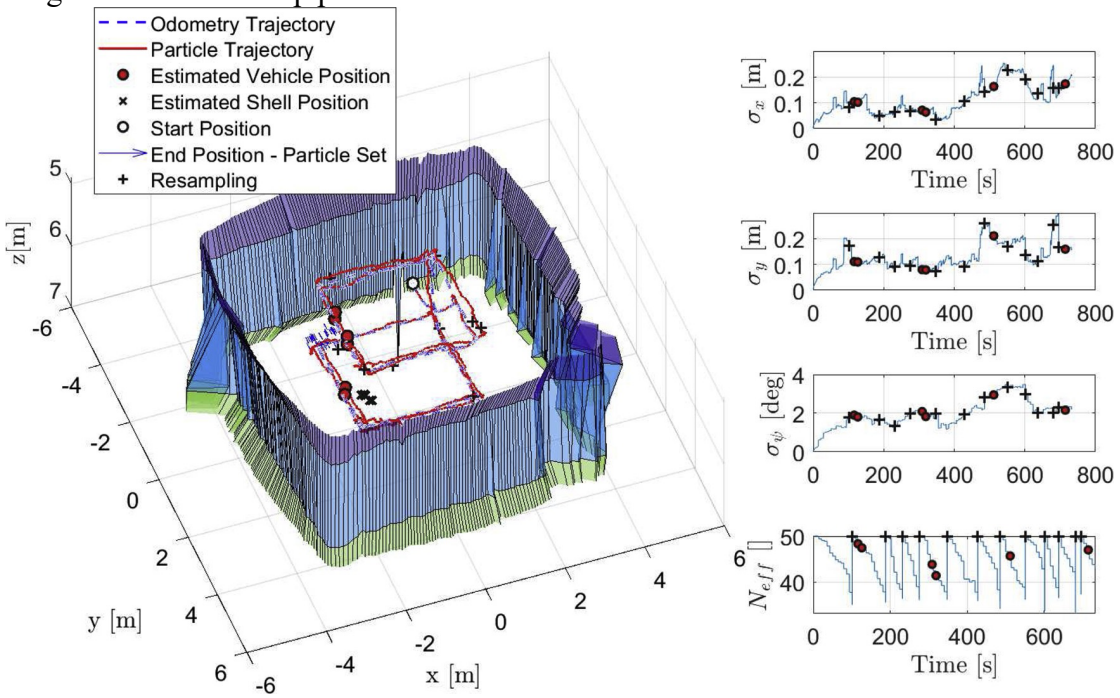


Figure 41: Polar map particle filter-based SLAM (Sandøy, S. S., 2020)

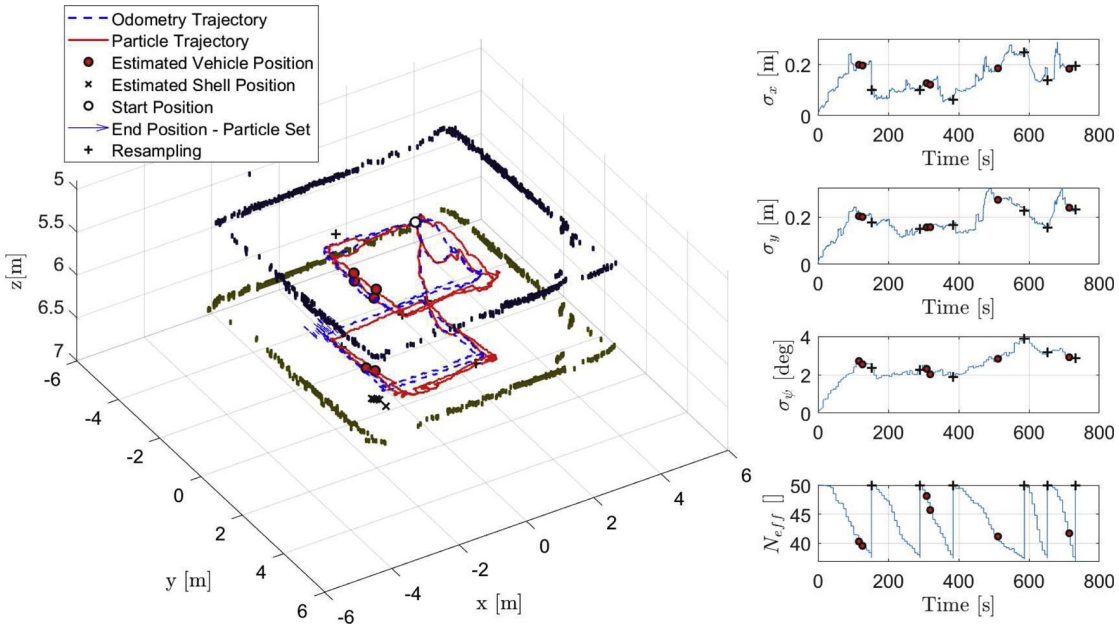


Figure 42: Octomap particle filter-based SLAM (Sandøy, S. S., 2020)

In conclusion of the experiments, it was seen that Polar maps uses less memory and computational time in comparison with the octomap which requires huge amount of sensor readings. In order to improve the aquaculture industry polar map are more suitable as it enables automation of inspection which has the ability to reduce the cost and risks related to environments

4.5.4 Model-based underwater inspection via Viewpoint Planning using Octomap

(Floriani, B. L., 2017) explained the importance of underwater inspection and its role in different fields. This project shows the abilities to reconstruct an environment using the gathered data, the reconstruction is carried out after the inspection is carried out from multiply views, knowing the number of viewpoints required to construct an environment is called view planning problem.

This project discusses the two main methods used to tackle the viewpoint problem:

- Non-model-based methods- System determines the number of viewpoints based on the analysis carried out on the previous views
- Model based methods – Suitable viewpoint is selected based on previous view

The authors have suggested the model-based method, the AUV used in this project is equipped with an multibeam sonar with an overall pan with tilt to achieve the goal of getting a sequence of viewpoints. The vehicle experiences some limitations such as navigation drift which effects the consistency of scans, this project presents results of an experiment where the path as been planned and executed with the help of Gazebo simulator.

The algorithm proposed focuses on finding the smallest amount of viewpoint with wider visibility and lost cost path connecting all the points avoiding all obstacles. The approach is sub-divided to four steps

1. Environment Representation

   The environment is presented in a set of nodes known as octrees; each node represented a cubic volume which is further sub-divided till an defined size is achieved. The environment is implemented using Octomap due to its advantages of compact size, fast computation algorithm, well supported library.

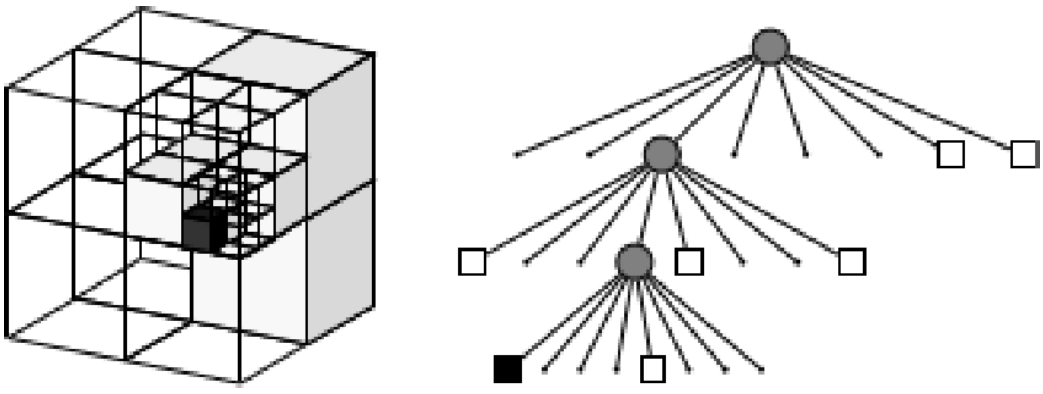


Figure 43: An octree model (Floriani, B. L., 2017)

The above figure represents an octree of an sunken boat as a test experiment, followed with an Figure of the simulated sunken boat

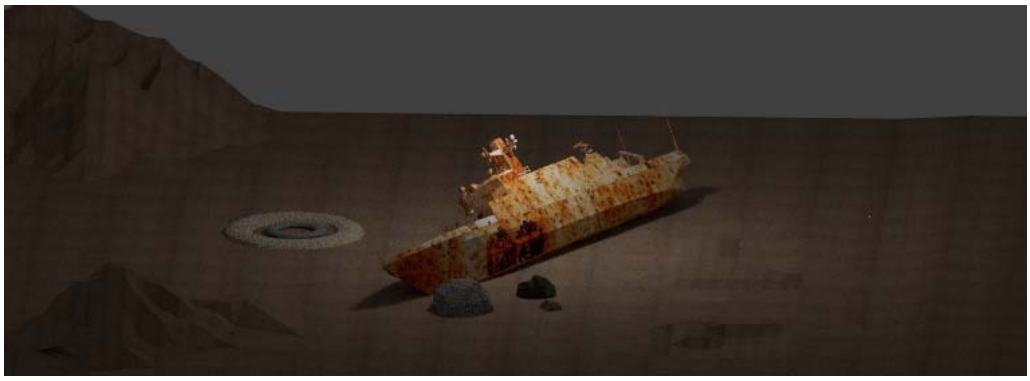


Figure 44: Simulation of the test experiment (Floriani, B. L., 2017)

2. View-point selection

   The viewpoint is selected after the working area that needs inspection is selected which is done by the user shown in the Figure , the user defined working area restricts possible viewpoint position as viewpoints are generated randomly inside the area. The following evaluation have considered for each viewpoint (a) Viewpoint should be inside a free cell (b) Occupied cells should be visible from the point under sensors range (c) The selected point is at a saver distance from an occupied cell. The resolution of the viewpoint is depended on sensors used, if the sensor has a 5m range then the ray is separated into 2 degrees

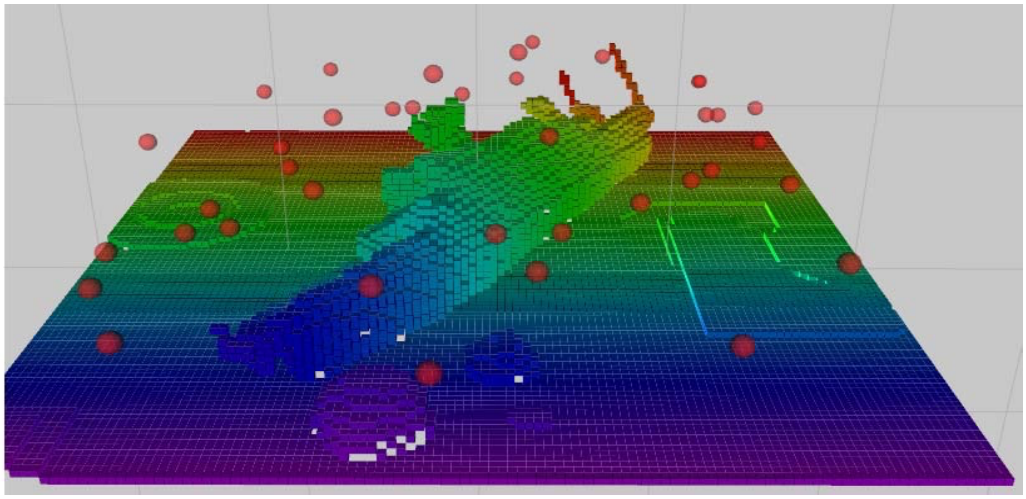


Figure 45: Selected viewpoints and visible area (Floriani, B. L., 2017)

   After all the viewpoints have been generated, the more visible cells are selected which are removed from the octomap of all other viewpoints, this process is repeated till no more points are below the threshold defined by the user

3. View-point sequence

   To connect all viewpoints an traveling salesman problem (TSP) needs to be solved, which is an NP-complete, well understood problem leading to several fast solver algorithms in a quite short interval. The problem can be considered as a city and the cost estimate to travel between them is known as pair, we need to find the shortest path to travel from the original city and back.

We are dealing with viewpoints; hence the neighboring approach is used in the algorithm, TSP solver is used after the obtaining a matrix from connecting viewpoints. The alternatives that could be used here are computing the free path between using a standard path planning or the Euclidean distance between each pair of viewpoints, both these methods can be employed by using rapidly exploring random tree (RRT).

4. Final path computation

   The path created from the connected viewpoint sequence by using the neighbor approach using RRT algorithm see in figure, obstacles are defined using an priori environment. An open motion planning library is used has it has many planning algorithms already implemented.

   The output from proposed view planning algorithm is an list of viewpoint x, y, z, min_yaw, max_yaw and the paths connecting them are min_yaw and max_yaw and which also define the arc

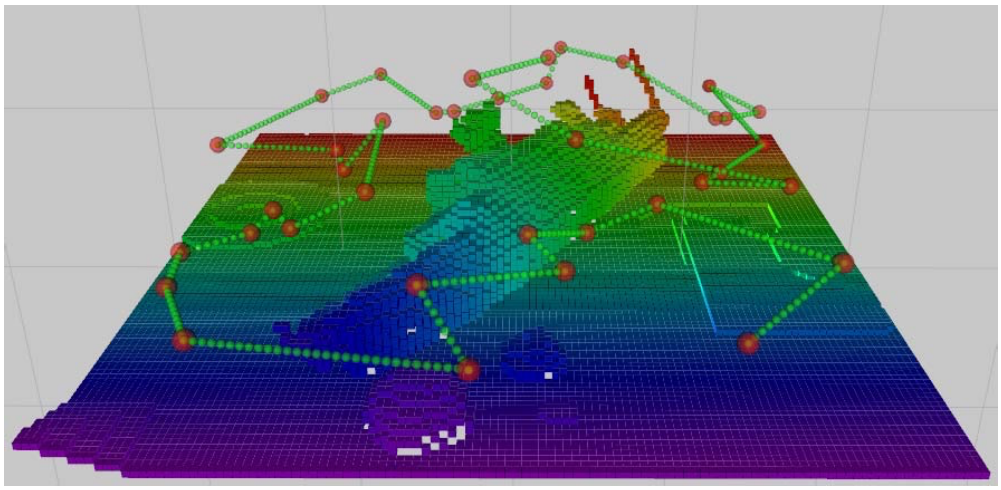


Figure 46: Visible cell and the final path (Floriani, B. L., 2017)

The evaluation is carried out through performing several tests with two different models in real challenging scenarios, with the vehicle kept 2-5m with respect to the priori model. After the inspection path is evaluated by the algorithm, a high-level controller is required to command the vehicle from a viewpoint to a follow a free path which is defined by the RRT. When viewpoint is reached the vehicle needs to be static to acquire the environment, this process is repeated till all orientations are covered. To execute the paths created in a real environment two issues need to be addressed (1) Obtain accurate a priori model (2) Improve navigation of the AUV

4.5.5 Subsea Pipeline Leak Inspection by Autonomous underwater vehicle

(Zhang, H., 2021) explained the complexity and uncertainties of marine environment in inspection and maintenance of pipelines transporting oil and natural gases. In general, the inspection is carried out working ships one section at a time and daily constant inspection has become extremely uneconomical which has led to dependency on AUV's due to stability and autonomy for daily inspection to identity of leaks.

AUV's have become more popular in underwater mission has they are flexible, dependence on a mothership is eliminated, it is cost efficient as the systems are equipped with acoustic and optical sensors for gas leakage detection for its back scattering properties of gas filled bubbles.

The pipeline inspection autonomous underwater vehicle (PIAVU) is 533m in diameter and weighs 650 kilograms, adopting a streamline, slender having low resistance with an cross-type tail. Drag coefficient and other attachments are calculated using CFD methods, the system reaches a speed of 4knots including an turning radius of 34m in an trial that was conducted. The sensors are placed in the front and including back cabin for navigation, communication and propulsion reasons. Both these cabins are equipped with high strength Fibre reinforced plastic, but middle section cabin is made of aluminum which integrates an dry structure helps in providing large buoyancy and volume utilization rate. The overview of the system used is shown in the Figure below

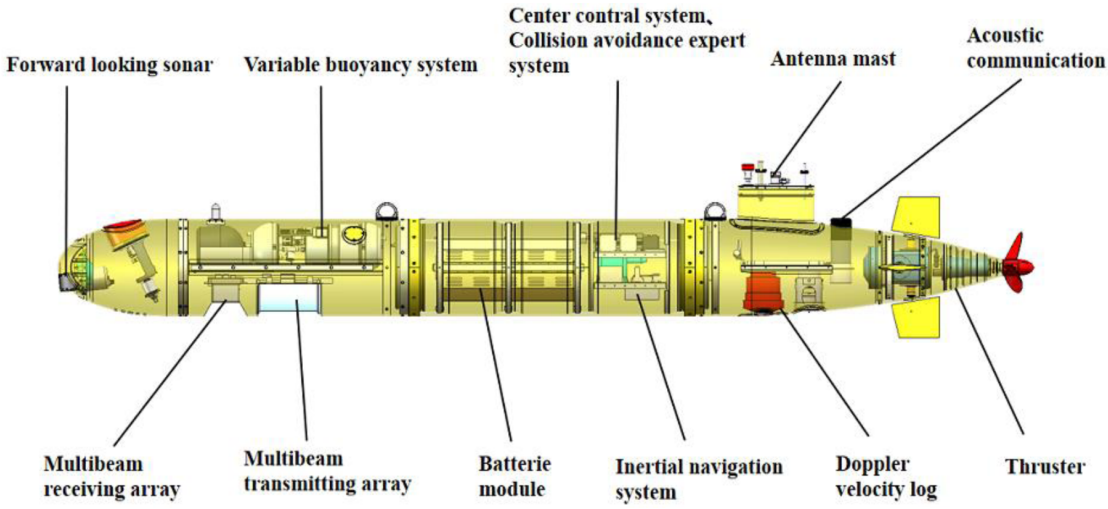


Figure 47: Overview of the system module (Zhang, H., 2021)

The overall control system includes the following:

1. Communication system
2. Navigation system
3. Central control system
4. Collision avoidance expert system
5. Multi-beam echo sounder Data-processing system

The central system is an embedded system consisting of various series of chips, used for receiving and analyzing instructions from the surface deck unit helping the propellers for navigation. Collision avoidance system is programmed with C^{++}, initially this system obtains real time scene of the environment helping to

improve an Ostu algorithm implemented for obstacles known as location information function. Finally, Kalman filtering is employed to estimate and predict real-time location of the obstacles and arrange a new route of inspection.

As the dependence on mothership is eliminated, the system emerges ever 10kms to get DGPS data and correction of positioning, this decreases range and efficiency of investigation. The control system of PIAUV is given in the figure below

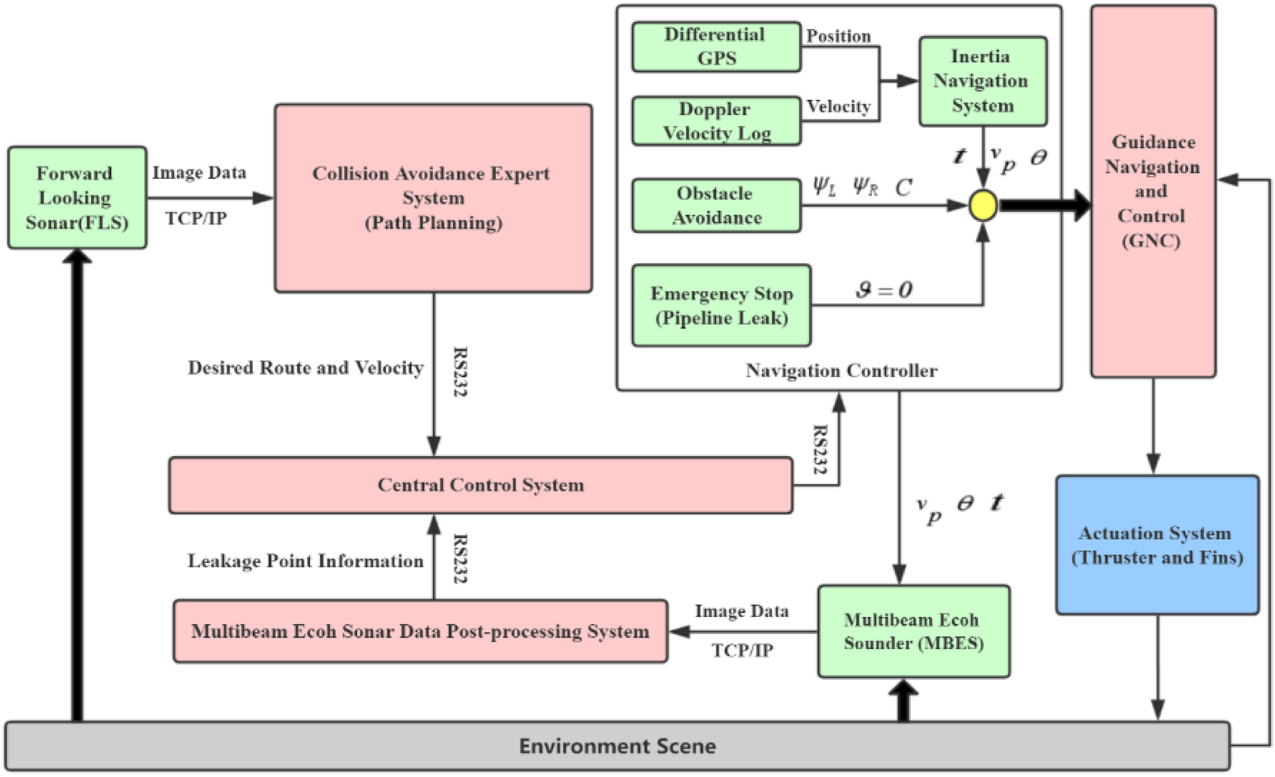


Figure 48: Control system of PIAUV (Zhang, H., 2021)

The experiments were conducted near Qingdo sea area in china.

(1) Pipeline leakage detection trial

First an steel pipe is sunken to an depth of 15m which is connected to an air compressor which inflates the pipe making the air bubbles through the holes in the pipe. Then passing the AUV over the pipe in a rectangular path, after the leak is detected, location of leak is transmitted to the command center. As illustrated in the figure below the AUV rises into a section as the leak is identified.

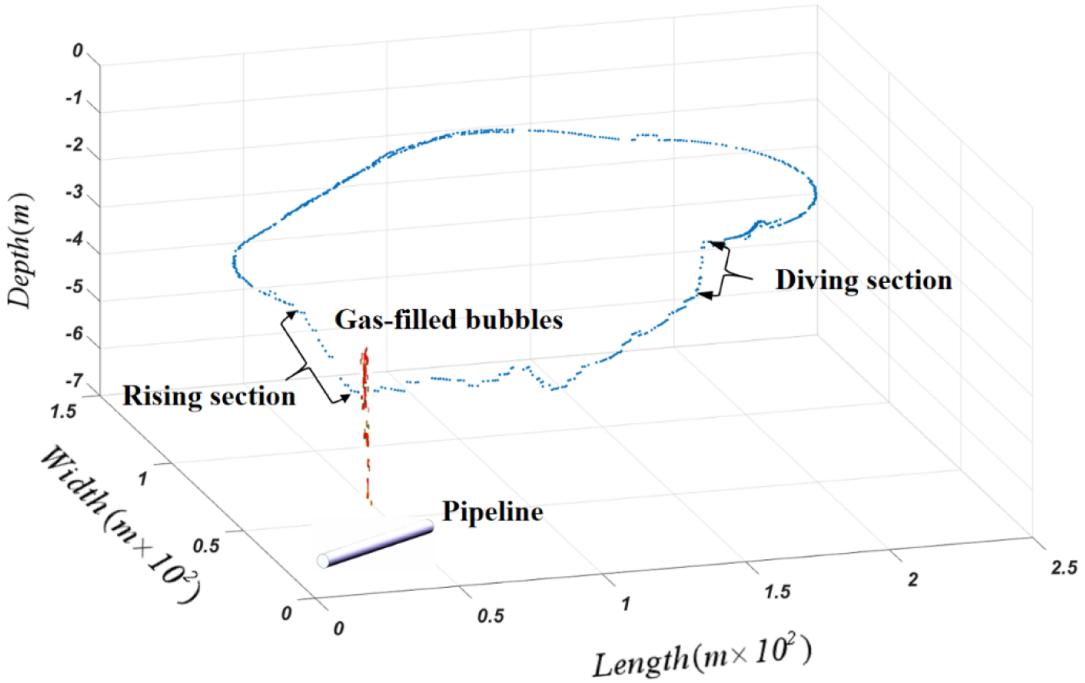


Figure 49: Pipeline leak detection trial (Zhang, H., 2021)

In case of minute leak points, the system faces difficulties to acquire several images of bubbles to estimate the leaks leading to false alarm, debugging is performed on the sensors parameter settings and echo sounder.

(2) Obstacle avoidance trail

Obstacles have been categorized into static and dynamic situations, most of the obstacles are seen as dynamic and can be seen in the figure below

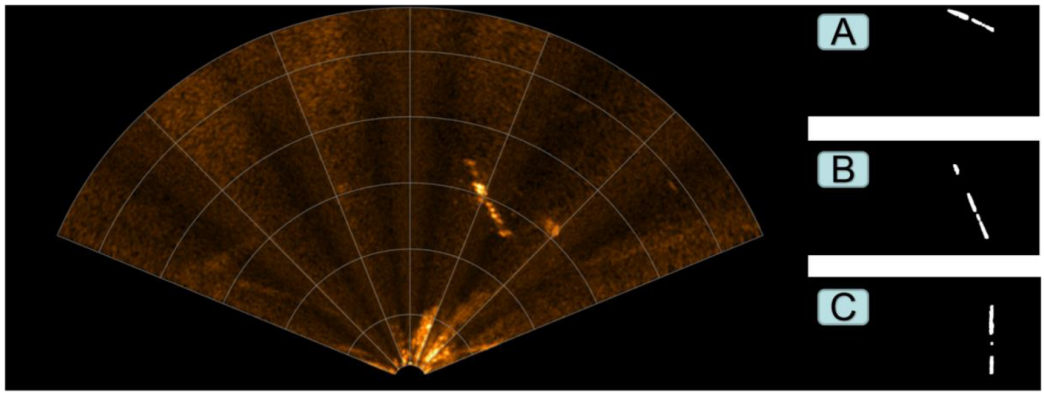


Figure 50: Sonar image. A,B and C being image processing diagrams
It can be seen in the picture that the obstacle is clearly visible. A, B and C are describing the improved Ostu algorithm after processing. The PIAUV upon approaching an obstacle the system slowly and gradually adjusts the distance and position in ordinance to the obstacle (Zhang, H., 2021).

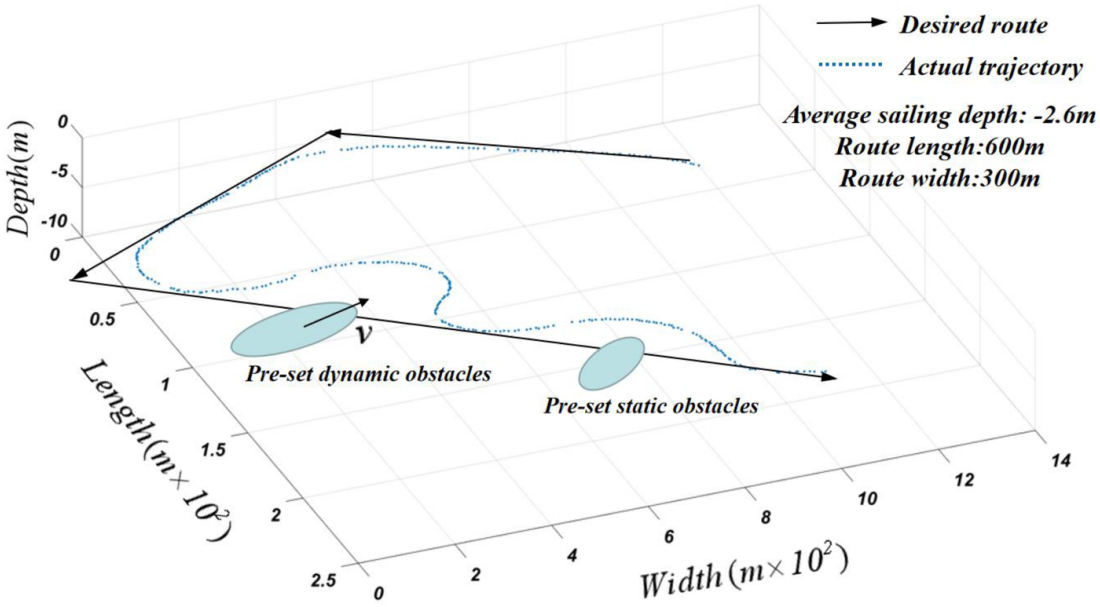


Figure 51: Avoidance static and dynamic obstacles (Zhang, H., 2021)

The figure above shows the avoidance process, when the system starts moving in the route the obstacles move perpendicular to route at an certain speed. The actual space between the system and obstacle is more than the safety distance and starts to pro-set-route.
In conclusion, use of AUV have significant advantages especially when the system has been equipped with collision avoidance.

4.5.6 A comparative study of underwater image enhancement techniques

(Deepa, D., 2014) explains how underwater images get darker with the increase in depth and reflection of light differs vastly based on the structure of the sea. The light enters horizontally and partly vertically making the objects less shinning and aids to capture deep colors which are not easy to capture.

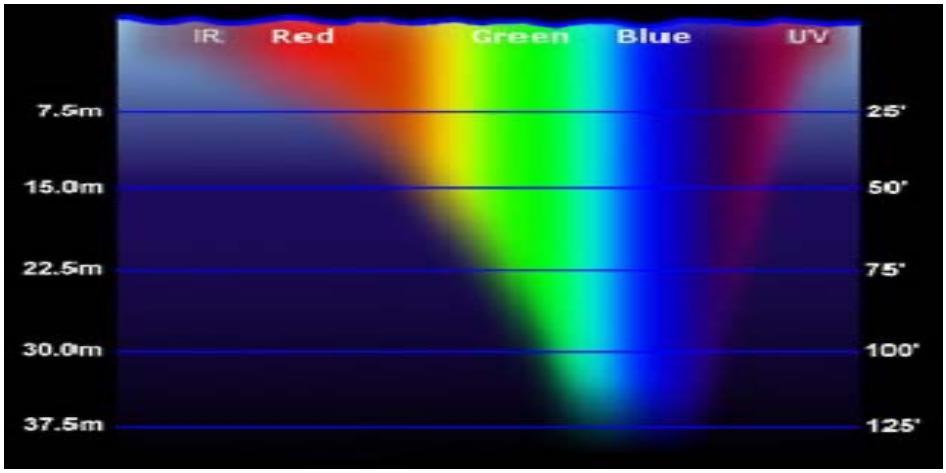


Figure 52: Color penetration pattern (Deepa, D., 2014)

The Figure above shows blue travels a long distance in water making the images dominated by color blue effecting the original color. To increase quality of image filtering operations are carried out on the pixels by moving the filter mask from point to point on the image. Inverse Fourier transform is used to modify the pixel values of a digital image.

Homomorphic filtering is a nonlinear mapping to different where linear filtering techniques are applied by mapping the original domain, this is used to enhance the image by increasing the brightness across the domain and removes multiple noises by decreasing the low-frequency components.

Spatial filtering reduces the noises and increases the contrast in the image using the principle of Fourier optics altering the structure of the focused beam, this filter is commonly used clean up the image.

Photographic Unsharp Masking creates a mask on the original image which changes the light source removing the blurriness, this is controlled by changing the contrast and density of the unmasked image. This results in a clear and less accurate representation of subject in the picture. It can be seen the figure below


Figure 53: Photographic Unsharp Masking (Deepa, D., 2014)

Nonlinear spatial filter removes noises that are not additive, this is conditionally based on the pixel values. The noise is smoothened in the object boundaries, nonlinear filtering process is considerably harder compared to linear process. This is seen in the Figure below.

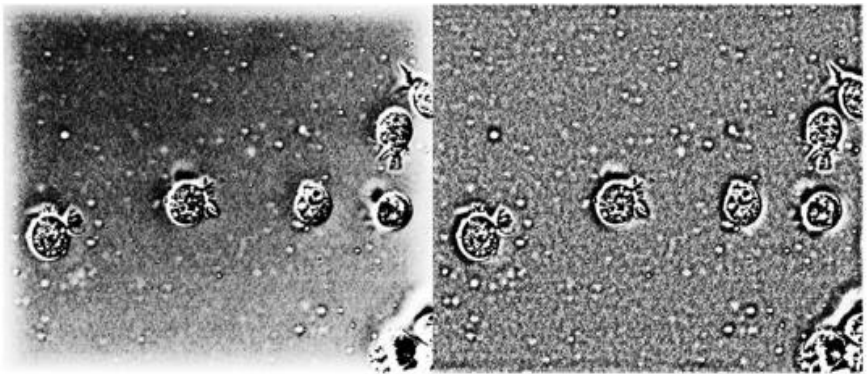


Figure 54: Nonlinear Spatial Filter (Deepa, D., 2014)

4.5.7 Next generation subsea inspection, maintenance and repair operation

(Schjølberg, I., 2016) This paper has been published by NTNU department of Marine Technology of Norway by (Ingrid Schjølberg, Tor B. Gjersvik, Aksel A. Transeth, Ingrid B.Utne) presenting the results of a conducted project on inspection, maintenance and repair(NextGenIMR). Most of the subsea IMR operation is carried out with the help of vessels, most of the vessels have an ROV operation room giving the operator continuous live feed giving complete freedom to perform an efficient operation.
The paper discusses the need for autonomy and best human-machine interaction for increased reliability.

The operation of ROV systems require a high level of flexibility due to the possible chances of system failure, to ensure autonomous functionalities a distributed control architecture is very much essential.

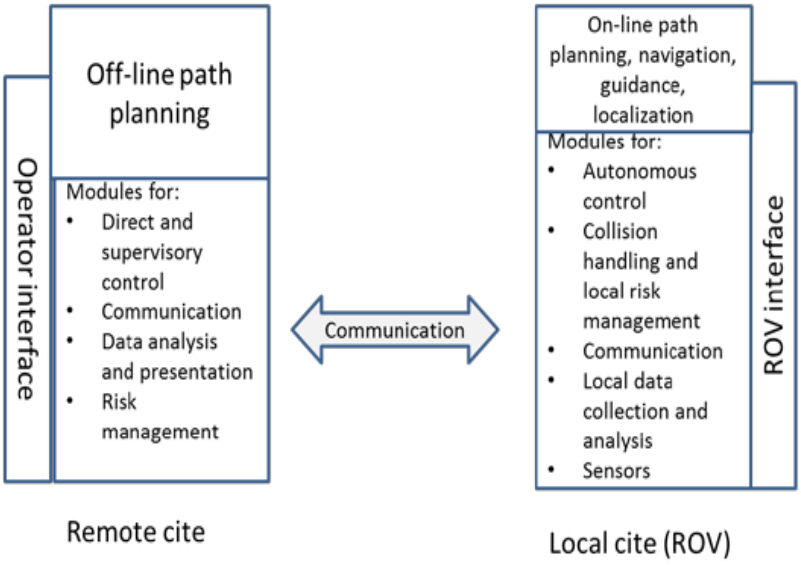


Figure 55: Allocation of the functionalities locally and remotely and figure shows the allocation of functionalities, to reduce the dependence on surface support; figure also shows the suggested step in the project (Schjølberg, I., 2016).

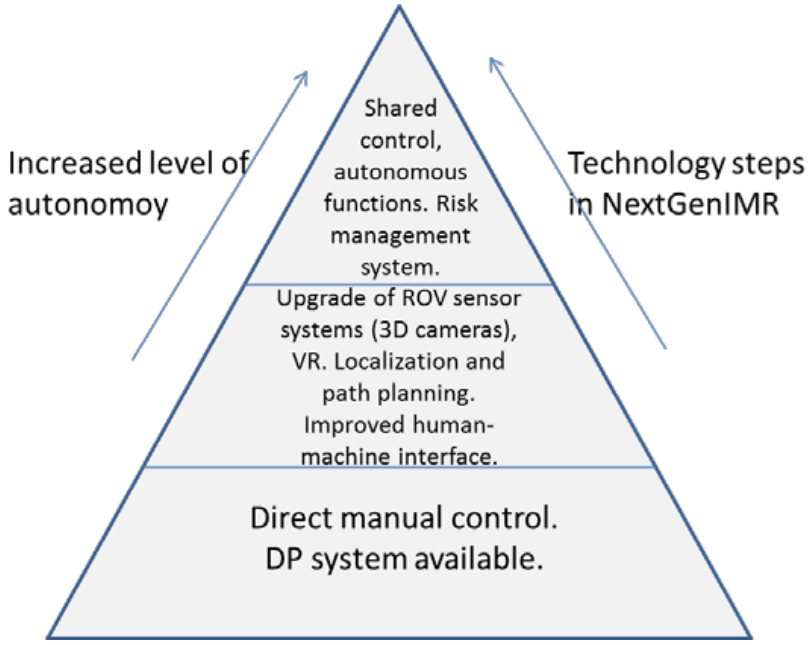


Figure 56: Technology steps for autonomy in ROV operation (Schjølberg, I., 2016)

Subsea control module (SCM) is replaced with autonomous job analysis (AJA) operation, AJA is a systematic approach to uncover overall operation modes, design, challenges, and requirements. A result of this operations gave a list of relevant necessary technologies to improve the level of autonomy

1. Perception: Object detection/localization and tactile sensing
2. Navigation: Localization of the system to the subsea template
3. Path-planning: Collision free path-planning for the system

Localization, path-planning, and perception are a necessary technology for increasing autonomy, the available new age must be combined to design a localization system that can give a high-precision. The current project includes development of a localization system which is scalable as new sensors or filters can be added and reconfigurable which can be adopted to a new system.

The implemented system has an error-state Kaman filter from the NTNU AUR-lab, and the output has been compared with a camera-based high-accuracy external localization system available at the university lab. This project presents an method of detecting and rejecting outlies in the navigation filters, the accuracy of this acoustic positioning measurements are combined with is absolute velocity measurements, ending with investigating the performance of structured-light based 3D sensing for object detection and localization and developed new algorithms so the system can be adopted to the subsea surroundings.

4.5.8 Overwater depth inspection on a submerged pile bent

(Wang, H., 2019) explain the importance of non-destructive testing in bridge foundation inspection, the study inspects an reinforced concrete bridge of eight 51m I-section girder and 45m wide tidal drainage canal which are supported through pile bents , located in Taiwan.

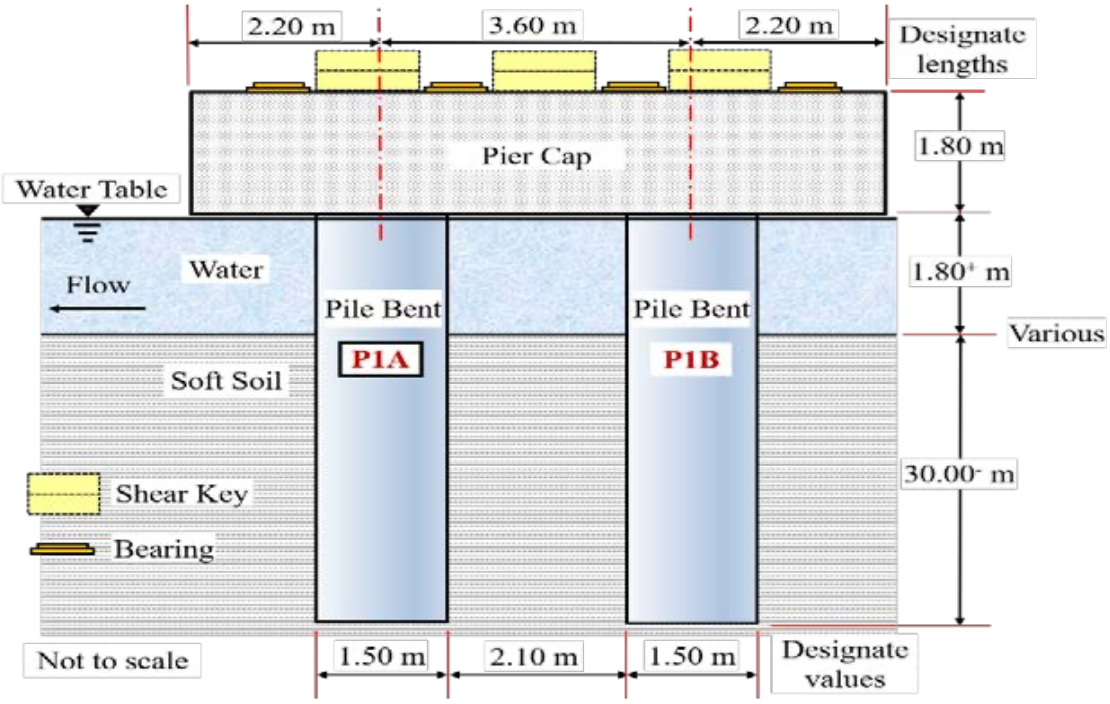


Figure 57: Substructure profile (Wang, H., 2019)

The bridge is tested by electrical resistivity tomography with SYSCAL Pro, Switch Pro, termination strip and electrode probes to show electronic potential field. This test is carried out parallel to the direction of water flowing and kept away at a distance of 0.5m away from the pile bents. All the electrodes are kept floating near the surface of water of the drainage canal, the total survey length is 150m and all electrodes are spaced with 3m. Another bridge 40m away from the upstream was marked in a resistivity image, With the help of pole-diploe inspection mode low resistivity were marked as dashed rectangles, showing high content of reinforcement in the bent. In theory, the bottom of the dashed rectangle is the foundation bottom. The structure is affected by flowing saline water.

The modified ultra-seismic method was implemented on the pier cap, which is supported through the submerged bents, over the pier cap a transducer packet was fixed at the upper position to measure transient seismic waves with the help of geometrics multi-channel start view seismography set. In the Figures below shows the execution of the experiment with the installation of the components. The investigator strikes the lateral side of the pier cap at an equidistance starting from the top to bottom, the waves travel downwards through the embedded components, reflection waves are created at the foundation bottom and underlaying stratum.

Figure 58: Installation of geophone (Wang, H., 2019)

Figure 59: Striking with an hand-held hammer (Wang, H., 2019)

Conventional waveform imaging is a vertical direction in which trigger peak needs to be found, followed by linking all points to create a direct wave line. The wave propagation velocity is computed then a draft reflection wave line is with a slope vale which is opposite to the direct wave line is drawn on the waveform image. The reflection wave lines are parallelly shifted to cross over the image until all impact reflection points, the intersection points show the reflection source.

Precision of this plot-based approach is affected by factors such as, overlapping echoes, identification, inconsistent responses, and installation condition, which can be justified only by an experienced professional.

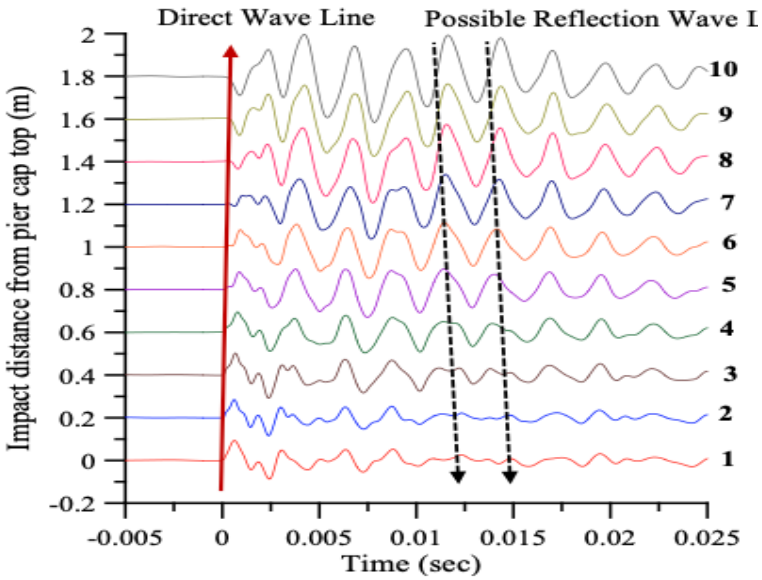


Figure 60: Ultra-seismic inspection waveform in longitudinal direction (Wang, H., 2019)

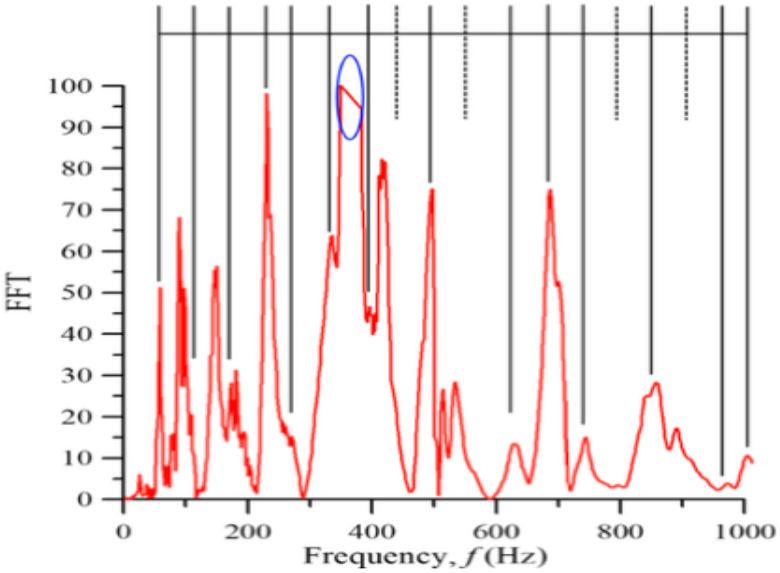


Figure 61: Vibration spectrum of impact (Wang, H., 2019)

This inspection methods precision is improved by transferring surface response time histories to spectra for analysing the frequency using the (FFT) First Fourier Transfer.
The project concludes by identifying the design length is greater than estimated length and with the modified inspection method the complete condition of the submerged pile bent is found. The frequency analysis provides an relatively reliable length to estimate through using the average frequency span between two frequencies.

4.5.9 Modelling and control of Industrial ROV's for semi-autonomous subsea maintenance service

(Mai, C., 2017) from the Department of Energy Technology, Aalborg University and SDU Mechatronics, University of Southern Denmark examined an industrial ROV designed for subsea inspection and maintenance tasks. The project focuses on developing a low-dimensional model prototype with a development of MIMO control strategies helping to improve the accuracy and speed of the system.

The ROV system used is VideoRay 4 Pro which weighs 6.1kgs with an waterproof electronic chassis and a frontward facing camera. The inbuild sensors calculate attitude, depth and heading of the system helping the system to automatic control solution.

Figure 62: VideoRay 4 Pro ROV (Mai, C., 2017)

The force model designed has been implemented in a non-linear Simulink using Simscapre Multibody which gives a multibody environment

- 6-DOF joint between the world and ROV body
- Buoyancy Force
- Gravity Force
- Thruster Force
- Drag Force

The implemented model is shown in the Figure below

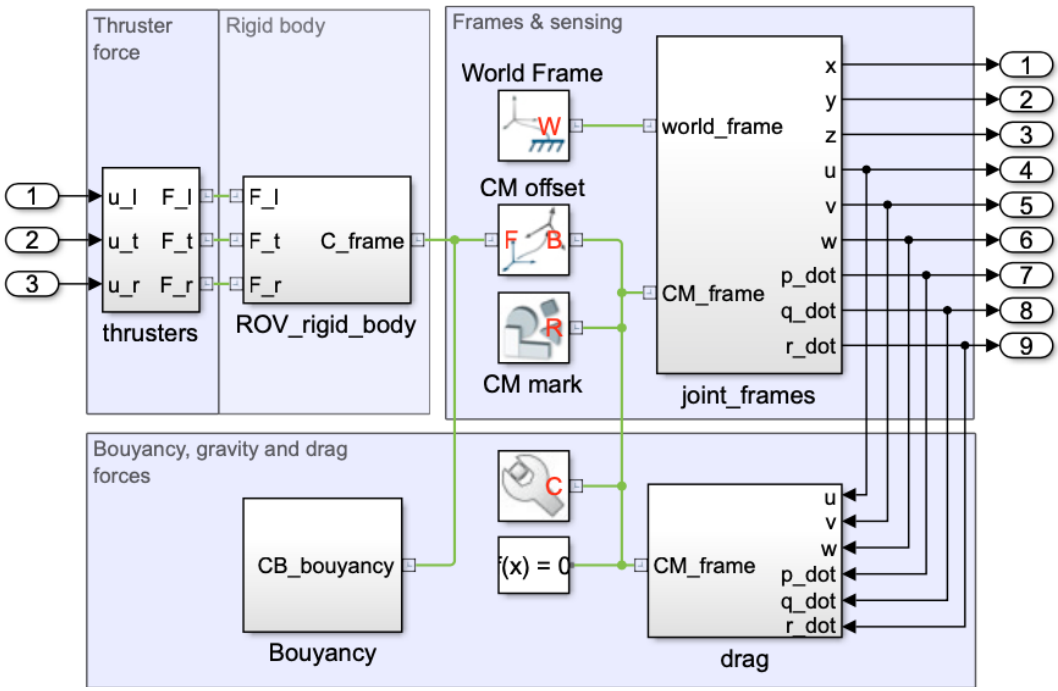


Figure 63: Simulink-Simscape dynamic model of the ROV (Mai, C., 2017)

A model linearization is carried out to develop the controller, linearization is done by comparing linear and non-linear models by Taylor expansion and Jacobian matrices for linear state-space models. The dominant deviation is linear velocity and non-linear drag force is quadratic but linear is not causing a huge deviation. In the beginning both models behave similarly at lower speeds, with the increase in speed the deviation increases.

The comparison is based on examination between built-in PID and LQR controller to study the position responses,

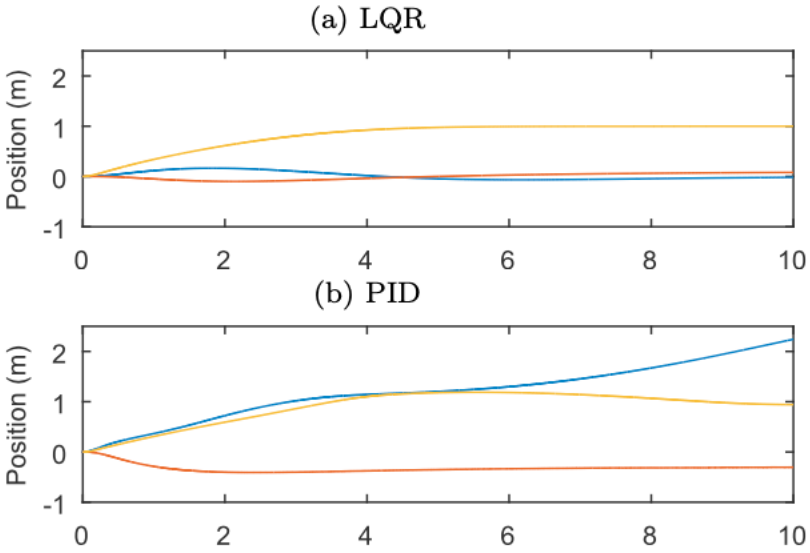


Figure 64: Controller comparison, linear responses X – blue, Y-red and Z- yellow axis (Mai, C., 2017)

The project concludes that the linear quadratic controller is faster, less sensitive to noise and less deviation, the model system is improved by using an MIMO controller that is installed in addition.

4.6 Concluding remarks

The overview of the inspection methods are represented in the flowchart as a general rule concrete is not to be inspected via destructive testing, this testing make the concrete more prone to deterioration which leads to failure. Non-destructive testing is widely preferred and used depending on the level of inspection that needs to be carried out.

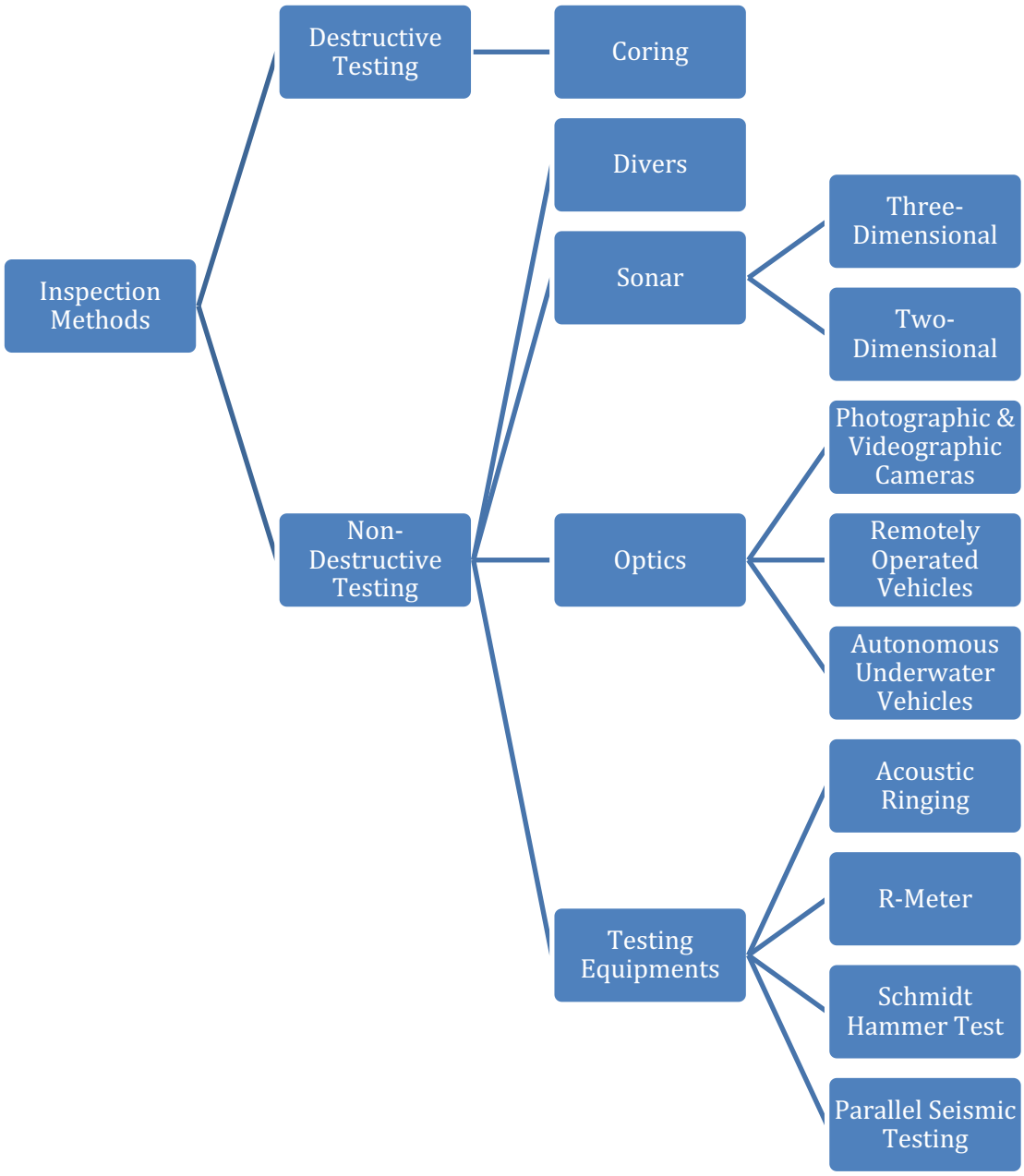


Figure 65: Overview of inspection methodologies

with the interview conducted with Dag Linghoff,Team Leader Marine Structures and Engineer Diving, ÅF Infrastructure AB and Ali Reza Mohammad Zadeh,Technical Manager at The Port of Gothenburg it was concluded that inspection through employing divers cannot be eliminated as they are versatile, In further discussions it was found that sonar-BATHYMETRY is employed every six years to study the bottom soil profile to estimate the load carrying capacity of the pile.

In order to suggest a suitable inspection method a simple evaluation has been carried out based on the criteria's created after the interviews conducted with Dag Linghoff, Team Leader Marine Structures and Engineer Diving, ÅF Infrastructure AB and Ali Reza Mohammad Zadeh, Technical Manager at The Port of Gothenburg and this evaluation is crucial to find which is an important criteria they are weighted on a scale from one to five, five being the highest value. After the criteria are finalized, the methods are evaluated to provide an optimal solution for inspection.

	COST EFFECTIVE	REDUCE THE LOOP	EFFECTIVENESS OF THE METHOD	EASY TO HANDLE AND MAINTAIN	AVAILABILITY	
EVALUATION CRITERIA	1	2	3	4	5	POINTS
COST EFFECTIVE	----------	3	5	4	3	15
REFUCE THE LOOP	5	----------	5	5	3	18
EFFECTIVENESS OF THE METHOD	4	5	----------	4	3	16
EASY TO HANDLE AND MAINTAIN	3	5	5	----------	3	16
AVAILABILITY	3	3	4	3	----------	13

Table 1: Evaluation criteria based on selected important criteria's

EVALUATION OF THE METHODS	COST EFFECTIVE	REDUCE THE LOOP	EFFECTIVENESS OF THE METHOD	EASY TO HANDLE AND MAINTAIN	AVAILABILITY	RANK POINTS
DIVERS	2	2	4	4	4	16
SONAR	2	3	4	2	2	13
==OPTICS==	========	=======	==========	========	==========	=======
PHOTOGRAPHIC CAMERAS AND VIDEO-GRAPHIC CAMERAS	4	2	3	4	4	17
ROV'S	4	4	4	4	4	20
AUV'S	4	4	4	4	2	18
TEST EQUIPMENTS	3	3	3	1	2	12

Table 2: Evaluation of the inspection methods

With the current advancements in optical robotic technology these will be the future of inspection.

Though AUV's have ranked higher they cannot be employed AUV's are not much applicable to commercial use, they're availability is for the military and subsea exploration for archeological purposes, more over their hasn't been any experiments conducted where the employment of AUV's have made to inspect commercial structures, this system faces limitations when it comes to deployment against strong currents the post office in time of data is very time-consuming as many of these systems use side-scan sonar systems

The conclusion from the interviews after going over the evaluation, it was concluded that a combination of divers and optics are the best way to inspect the piles, with the divers facing limitations with strong currents, depths and visibility, the ROV's can easily maneuver these challenges and bring in the results, pilot on the shore who has clear vision of the structure can then pass the information could pass the information to diver while cleaning or inspection.

5 Industrial Restoration Methods

5.1 Background

As mentioned in chapter 3, the deterioration causes are to be noticed at the splash zone it is to be noted that not the complete volume of the structure is not under de- terioration. With, the interviews conducted with Dag Linghoff, Team Leader Marine Structures and Engineer Diving, ÅF Infrastructure AB and Ali Reza Mohammad Zadeh,Technical Manager at The Port of Gothenburg, it was mentioned that in- spection & maintenance work as not been carried out on a regular basis, creating an compulsion for repair and maintenance of the piles.

General inspection methods are described the previous chapter, routine inspection followed with detailed inspection shows the damage extend, giving the inspector ample knowledge to decide the required action. The results are completely analysed and possible repair solutions are presented to the project managers & administrator providing a fifteen year maintenance strategy, with a theoretical service life of fifty years.

There are plenty available repair methods that can be applied surface structures, very few methods can be effectively applied to substructures (Browne et al. 2010). To care out an effective repair planning is at-most predominant, the affected area is not accessible easily due to the marine vegetation and deck structure. To carry out the repair either work has to be carried out underwater or water should be cut out from the repair region.

A conventional method followed to access the affected area of the pile is by installing an temporary formwork consisting of sheet piles with braces. The trapped water present in the encasing is pumped out, providing an clear environment and higher quality of work. Nevertheless, this is a time-consuming work increasing the cost of repair (Browne, T. M., 2010).

The repair works are carried out through commercial construction divers, providing access and flexibility moving between areas of the substructure at ease (McLeish, A. 1994). They are extremely successful working with calibrated equipment, when the work is thoroughly planned.

5.2 Conventional Repair Methods

Conventional methods are opted in the industry due to its reliability and predictive nature; these methods vary from increasing the structural capacity and protecting the structure from further damages.

5.2.1 Pile Jacketing

Figure 66: Jacket casting (Röös, J., 2017)

This method of repair is to cast a jacket of concrete along the full length or at the deteriorated area of the pile (Browne, T. M., Collins, T. J., Garlich, M. J., O'Leary, J. E., & Heringhaus, K. C. (2010). The outer encasement is performed by construction divers giving a protective layer and an increased load carrying capacity by providing a layer of reinforcement.

Depending on the extent of damage a new pile is cast around the existing pile, which replaces the baring capacity of the old pile. As, a preventive step jacketing can be installed before any deterioration occurs, this is a method employed at Port of Gothenburg where the piles are protected by a thin layer of coated stainless steel which are applied in the splash zone to protect against ice and abrasion Installation is carried out in the following steps:

- Removal of marine vegetation is carried out through high pressure water gun.
- If the structural capacity is to be increased in the pile and reinforcement layer is provided around the pile
- A temporary formwork is made around the pile, this is made of two half cylinders which are clamped together to avoid seepage of water.
- Concreting is carried out; the concrete is pumped from a nozzle which is at the bottom to remove any entrapped water in the cylinder
- After the curing stage, the formwork is removed and inspected to ensure quality of work

This repair method increases the size, self-weight and effective area of the pile against strong currents and unpredictable waves, this also enhances the risk of buckling. The quality of work is a major concern with underwater concreting with the thickness of concrete that is pumped at high pressure.

5.2.2 Pile Replacement

Figure 67: Introduction of a supplement pile (Browne, T. M., Collins, T. J., Garlich, M. J., O'Leary, J. E., & Heringhaus, K. C. (2010)

when the concrete is subjected to severe damages the structural integrity is com- promised and repair will not give it any additional support, replacing the pile is the only option that is reliable. Pile replacement is a labor-intensive repair method (Browne, T. M., Collins, T. J., Garlich, M. J., O'Leary, J. E., & Heringhaus, K. C. (2010).

To avoid this highly intensive work, supplement piles are constructed in the region near by creating an access on the deck structure keeping in mind of the bracing systems to distribute the loads evenly, this is another method that is opted in the industry to avoid the removal of the damaged pile (Browne, T. M., Collins, T. J., Garlich, M. J., O'Leary, J. E., & Heringhaus, K. C. (2010).

5.3 Procedures Carried Out in Restoration

The restoration is carried out in steps as explained in the following sub-sections

5.3.1 Surface Preparation

Figure 68: (a)Before surface preparation (b) after surface preparation (Röös, J., 2017)

Marine vegetation can act as a protective layer to the pile (Mr.Ali Reza Mohammad Zadeh) against root-system plants. In order to inspect the pile for damages these vegetation needs to be cleaned, which is as labour intensive as construction of a pile. The cleaning is carried out by construction workers through using high pressure water gun, the water gun is help closer to the surface of the concrete in order to reduce the pressure decrease by the stream enlargement. The divers tie themselves to avoid the drag created by the stream and the gun.

5.3.2 Reinforcement

To replace the lost cross sectional by corrosion of steel another layer of reinforcement is provided to restore or improve the structural capacity. An hydraulic cutter is used to remove an ample amount of concrete to access the corroded steel to provide good anchorage area for the new reinforcement (Browne, T. M., Collins, T. J., Garlich, M. J., O'Leary, J. E., & Heringhaus, K. C. (2010). To reduce the removal of concrete area small diameter bars can be opted to reduce the anchorage area. The rust is cleaned with high pressure water jet to eliminate rust.

5.3.3 Concrete – Casting

In the year 1910, August Gundersen an Norwegian engineer patented the first method of underwater concreting (Thoresen, C. A. (2010)), August Gundersen showed the key success to this method is separating fresh concrete and water to prevent cement from being washed out (Thoresen, C. A. (2010)).

This is a complicated procedure which needs to be carried out by experienced divers to ensure good workmanship, divers with the help of a hydraulic pump to create the pressure to carry out the concreting (Thoresen, C. A. (2010)). Underwater grade concrete is used which has low permeability & frost resistance. The concrete is pumped from the bottom to eliminate any entrapped water in the formwork (Thoresen, C. A. (2010)).

5.4 Concluding Remarks

Once in every six year, the main inspection is carried out to decide the need of repair of piles, depending on the severity of damage the repair process is strategized and executed.

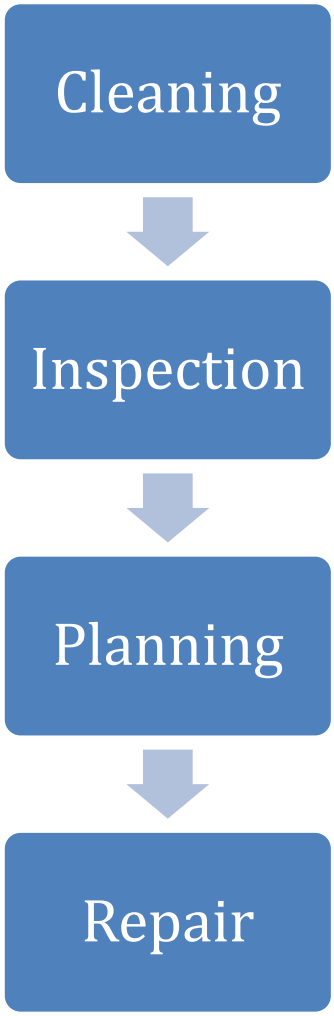


Figure 69: Overview of the repair procedure

The restoration is carried out to give a protective layer to the deteriorated region as a preventive measure to enhance the service life and also to restore the structural capacity. As, mentioned in the previous section the conventional pile jacketing system is a used commonly as it reliable method, to ensure a quality work well skilled people are to be employed to carry this method out in a timely schedule. flow chart to explain the advantages and disadvantages. With the lack of available skilled people has led to new repair methods, making the repair more effective and less intensive.

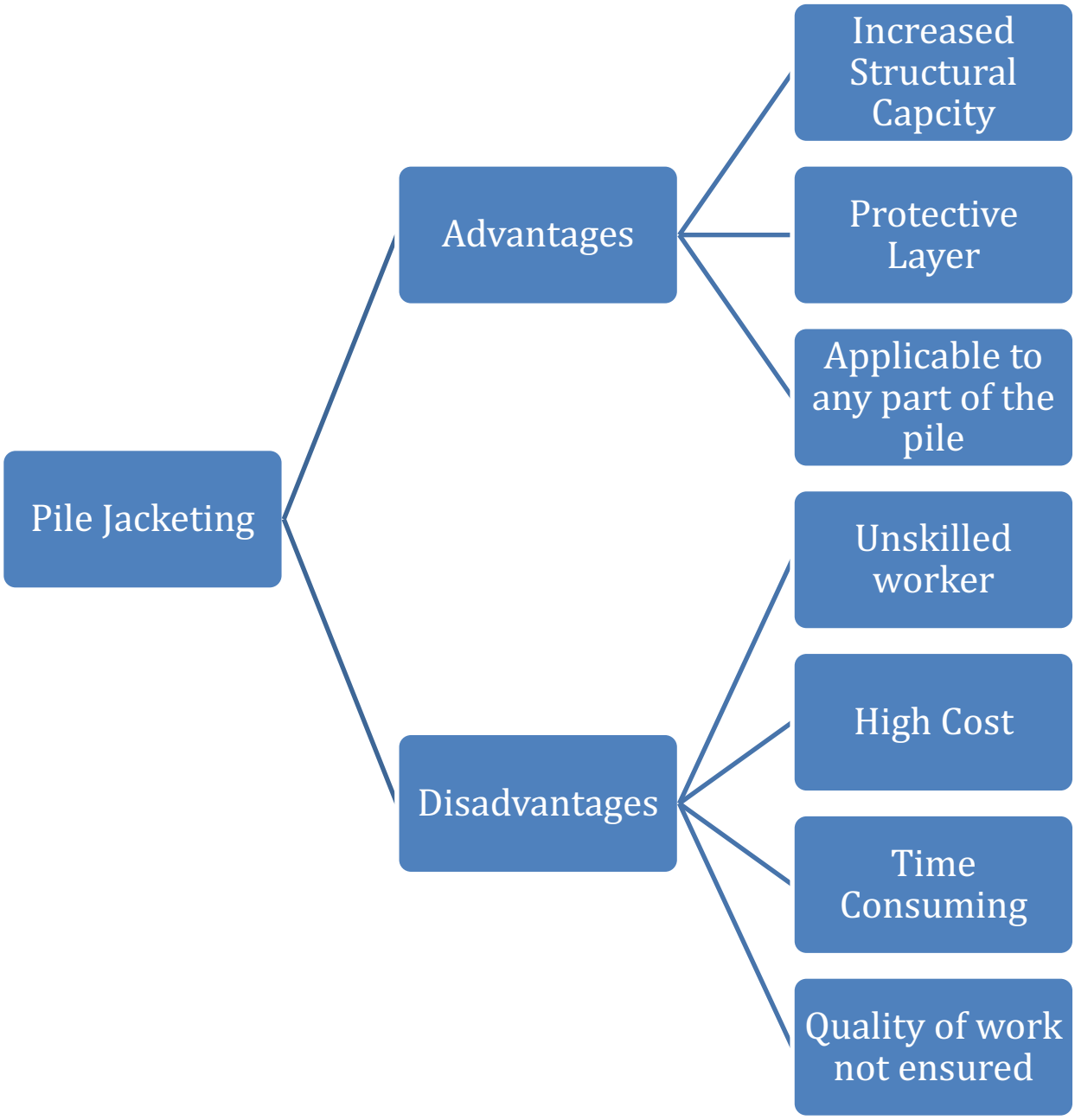


Figure 70: Advantages and disadvantages of pile jacketing system

6 Fibre Polymer Materials

6.1 Introduction

Fibres reinforced materials (FRP) are composed resin matrix made of least two materials with different thermomechanical properties, being superior to basic materials. The fibres bear the load while the resin hold the matrix together, generally anisotropic based on the fibre orientation. To optimise the use of FRP, arrangement of composite, specific material properties. The application area influences the choice of fibres, particularly the cost, environment condition, service life and required strength are other aspects that effects the usage of FRP (Au, C. 2001).

6.1.1 Fibres

The properties of the FRP material are dependent on both the fibres and the resin. The fibres can either be in different forms, such as discontinuous or continuous fibres weaved randomly or in specific directions to achieve the desired properties. In structural applications continuous fibres are mostly used (Au, C. 2001). The most common types of fibres used in the construction industry for FRP composites are glass, carbon and aramid fibres.

6.1.2 Glass Fibres

Manufactured through molten glass through platinum bushing, cooled by liquid. Glass fibres are classified based on application as:

1. Electrical glass fibre provides high electrical insulation, commonly used in construction as its cost effective (Berver, E., 2001)
2. Structural glass fibre has higher strength compared to electrical fibres
3. Corrosion glass

6.1.3 Carbon Fibres

Carbon fibres are manufactured through controlled pyrolysis and cyclisation of organic fibre precursors (Illston, J. M., 2010). These fibres are good electrical conductors having high strength, brittle than glass fibres (Berver, E., 2001). Predominately used in the aerospace industry due to their non-uniformity.
Characterised by long strings of molecules bound with carbon atoms, the exact composition varies based on the manufacturer (Illston, J. M., 2010).
Classified based on their mechanical properties:

1. High Strength
2. High Modulus
3. Ultra-high modulus fibres

6.1.4 Aramid Fibres

Produced through an extrusion and spinning process used to produce a thermoplastic acrylic fibre. Their high strength and stiffness property is attained by stretching and drawing process aligning the molecular chains, showing good toughness and well tolerance to damage (Illston, J. M., 2010).

6.1.5 Resins

The network is considered as the optional material in FRP and impacts the cross over strength, shear and pressure properties of the composite. Polymer grids are named thermoplastics or thermoset relying upon their design and conduct (Harichandran, R. S., 2000). Thermoplastics mollify or dissolve when warmed and solidifies when cooled. This is reversible and thermoplastics can be reshaped by warming. For thermosets, the polymers cross-connect and can along these lines not be reshaped in the wake of relieving and stay strong when warmed. As opposed to thermosets, thermoplastics have higher effect strength and show better protection from break and miniature breaking. Nonetheless, they are not regularly utilized in primary applications because of their capacity to be reshaped.

Epoxy and polyester polymers are the most widely recognized utilized thermosetting pitch lattices because of their great compound opposition and great grip capacities. The polyester pitch shows incredible mechanical properties and great natural sturdiness and is the most normally utilized network since it is more affordable than epoxy (Berver, E., 2001). In any case, the attachment for polyester to carbon and aramid is poor and the shrinkage during relieving is huge. Consequently, polyester isn't as broadly utilized in the development business (Au, C. 2001). Epoxy is better than polyester with respect to substance and dampness obstruction. Epoxy pitches show incredible mechanical properties and give better grip to a larger number of sorts of strands than polyester and furthermore great attachment to substrates. Consequently, epoxy is the most normally utilized pitch for fixing common designs, and the costliest one.

Progressions in tar advancement have brought tars that can fix submerged. These pitches are refined as in the amines, the hardener, are sweet-smelling and water repellent, so they respond with the base and not water molecules5 in contrast to regular gums, where the hardener depends on aliphatic amines that are water dissolvable.

6.2 Why to Promote FRP Usage

FRP composites have since the 80's been a promising material for fix and fortifying of substantial designs in structural designing because of its invaluable properties contrasted with other customary development materials (Sen, R., 2007). The advancement of gums that can be applied and relieved in water has made the maintenance and fortifying with FRP composites a substantial arrangement likewise for lowered designs.

Contrasted and cement jacketing, which is the most widely recognized fix technique for lowered substantial heaps, there are a few benefits of utilizing FRP composites all things considered. The composites high solidarity to weight proportion, which is a few times more prominent than for steel, and firmness to weight proportion, lead to that maintenance and reinforcing of designs can be made with no generous expansion of weight or sectional area (Berver, E., 2001).

Prior to relieving, FRP materials are truly adaptable, which considers fit to any state of the current construction. Since FRP materials are lightweight and simple to oversee, they can give a speedy and simple establishment without the need of large equipment or devices which are needed to introduce the weighty formwork for concrete jacketing.

FRP is a thick and strong material and has phenomenal protection from cruel conditions, for example, in marine conditions. By wrapping substantial heaps with FRP materials the movement of water, oxygen and particles into the substantial can be diminished and subsequently the consumption cycle and the arrangement of ettringite can be blocked (Wootton, I. A., 2003). FRP wraps likewise give imprisonment which will hold the substantial back from spalling because of the extensive powers brought about by erosion or ettringite. Imprisonment of the heaps additionally expands the pivotal strength and pliability because of expanded sidelong pressing factor.

FRP materials can fix quickly, which makes them gainful for crisis fixes where quick reclamation is of the pith. Despite the fact that the underlying expenses of FRP materials are high, the fast and simple establishment implies lower development costs and negligible time for the construction to be shut. In this manner, the all-out cost of fixing a design with FRP might be lower than for different strategies.

6.3 Limitations Of FRP

The long-term behavior is not well known but what is understood is that the properties of FRP composite materials are affected by temperature and moisture content variations and ultraviolet radiation.

The resistance of FRP composites to weathering is highly reliant on the resin matrix. The most notable cause of degradation of resins is ultraviolet radiation as it causes crosslinking degradation of the resin (Au, C. 2001). This results in chalking of the resin and making it more brittle.

High temperature variations increase the water absorption for FRP composites and moisture leads to bond failure between the fibres and the matrix (Harichandran, R. S., 2000). Glass fibres are liable to moisture attack as they swell when absorbing moisture causing expansive internal forces in the composite and moisture also causes strength reduction of the fibres.

6.4 Restoration Using FRP

The intention with an FRP repair method is to provide a quick and efficient repair with externally bonded FRP composites. It can be applied along the whole height of the pile or just over a particular area, such as the splash zone. The idea is that the low permeable FRP material with good resistance to harsh environments will provide the pile with a protective layer and thus increase the durability of the pile. Instead of replacing or installing new reinforcement the structural capacity can be restored or improved by the externally bonded FRP material. The usage of resins that can cure underwater allows the wrap to be applied by divers at the submerged area of the pile.

6.5 Limitation of FRP During Restoration

Following the wrapping method to repair, there are chances of trapping moisture and chlorides, not allowing the pile to dry completely which leads to accelerating the process of corrosion. Incomplete wrapping of the pile will aid moisture to seep through concrete and FRP deteriorating the bond, as the temperature drops during winter the moisture freezes increasing the volume also damaging the piles.

FRP are prone to physical damage caused by abrasion leading to cracks and breakage providing access to moisture, when wraps are exposed to the harmful direct sunlight rays it undergoes loss of ductility, lowering the resins resistance becoming prone to cracking. To achieve an effective bond between the pile and the wrap the surface preparation is very important, this could be a limiting factor based on piles condition.

FRP composites wrap applied to the pile covers the repaired section, not allowing any possibilities to carry out inspection behind the wrap.

6.6 Review on Experimental Studies

Various projects have been carried out to evaluate the durability of FRP wrapped on reinforced concrete, the following subsections are focused on the experimental studies carried out.

6.6.1 Corrosion potentials of lightweight concrete wrapped with fibre reinforced polymers

(Goucher, E. 2014) studied how wrapping reinforced concrete with FRP would affect the corrosion for both lightweight and normal concrete. Forty-two concrete cylinders with a diameter of 50 mm and a height of 100 mm with one single reinforcement bar in the center were subjected to an accelerated corrosion test by an impressed current. The samples were submerged in 5% saltwater and the test lasted for 50 days. As a sample failed, it was removed from the test and analyzed considering reinforcement bar mass loss and time to failure. Failure incorporated current spike due to concrete cracking, FRP separation from the concrete and rupture of the FRP. Goucher used three different FRP systems. One glass FRP Tyfo SEH-51A system, one carbon FRP Tyfo SCH-41 system and one carbon FRP SikaWrap Hex 103C system. To declare for the legend in the figures in this section, the labelling of specimens was according to: LW or NW (lightweight or normal weight concrete), G or C (glass or carbon FRP), F or S (Fyfe or Sika) and 1L or 2L (1 or 2 layers of wrap).

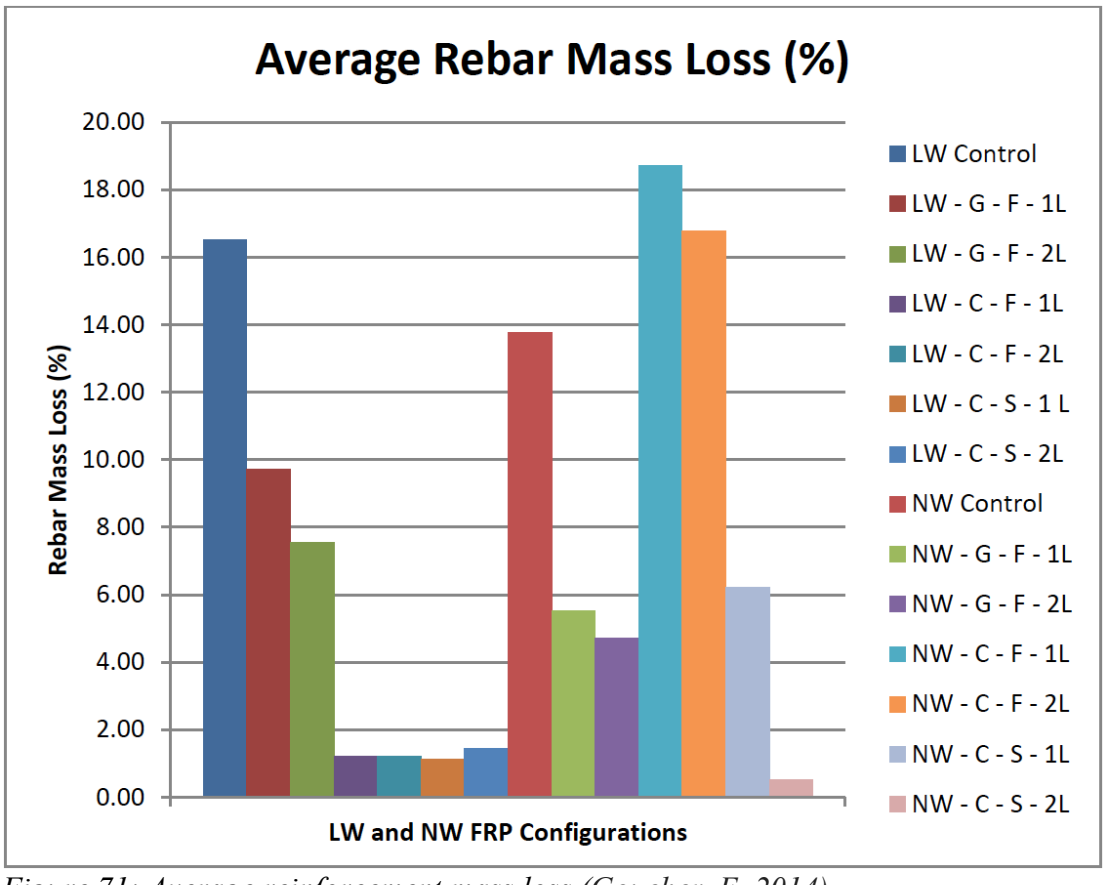


Figure 71: Average reinforcement mass loss (Goucher, E. 2014)

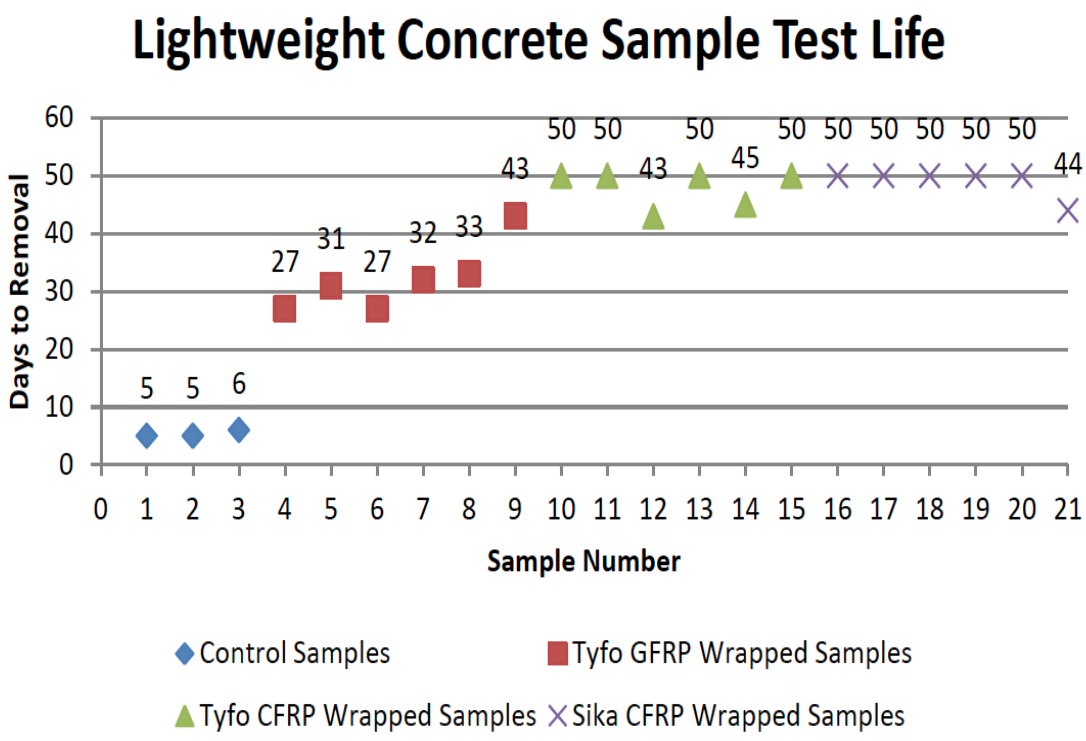


Figure 72: Light weight concrete sample test (Goucher, E. 2014)

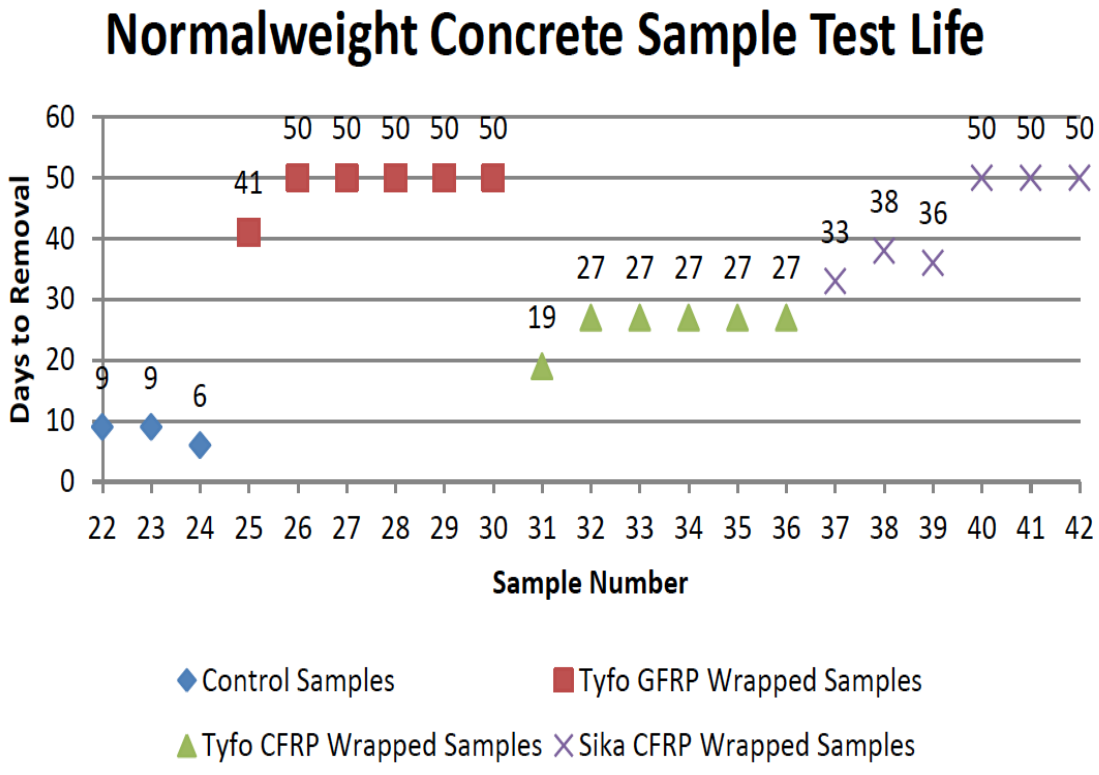


Figure 73: Normal weight concrete life (Goucher, E. 2014)

6.6.2 Repair of corrosion damaged columns using FRP wraps

(Harichandran, R. S., 2000) analysed the impacts of utilizing FRP wraps on concrete harmed by consumption. The toughness of the fixed substantial examples which is exposed to freeze and defrost, and erosion are inspected by sped up consumption test. The examples tried are of measurements 152mm distance across and 305mm tallness, given support. The examples were arrangement in a request than two bars are anodic and two cathodic. An all-out number 24 examples were lowered in saltwater of 3% and presented to sped up consumption for around 13 days prior to being treated with FRP wraps. After the maintenance cycle of wrapping the examples are exposed to sped up erosion then, at that point eliminated for various phases of 130 and 190 days and the outcomes were breaking down dependent on the deficiency of reinforming bar mass. The outcomes showed the maintenance successfully diminished the erosion rate by 59% when contrasted with the opened-up examples. The examples were inspected for fortified and un-reinforced wraps and examples with the un-fortified showed 20% higher consumption rate that fortified examples.

Every one of the examples are exposed to 300 patterns of freeze and defrost and sweeping interior power, crated by filled longitudinal driven opening with broad concrete and inner power actuated by eroded steel, afterwards the examples are exposed to pressure strength testing, the outcomes showed that the examples didn't show extensive harm to the wrapped examples yet there was no distinction in compressive strength.

6.6.3 Corrosion of steel reinforcement in carbon fibre-reinforcement polymer wrapped concrete cylinders

(Wootton, I. A., 2003) inspected carbon Fibre wraps on erosion built up steel in concrete. In this paper, different sorts of epoxies, distinctive direction of filaments are contemplated. 42 examples with a breadth of 51 mm and 102mm of heigh supported with steel bars at the focal point of the example are tried. The test examples are exposed to sped up erosion through anodic ebb and flow with the substantial example acting as cathodes, put in saltwater of 5%. The test was run till disappointment which included breaking of cement.

The outcomes were dissected to consider the support mass misfortune and chloride content, this investigation showed that the examples wrapped with FRP had expanded assistance life, mass misfortune and chloride content when contrasted with opened up examples. The investigation inferred that pace of consumption in steel is deferred with the wrapping with expanded life expectancy of 375% when contrasted with the opened-up examples. The examination inferred that the examples wrapped with two layers would be advised to execution than the ones with one layer wrap, however, concentrates likewise showed that there was no significant improvement when the layers were expanded to three.

6.6.4 Corrosion of steel reinforcement embedded in FRP wrapped concrete

(Gadve, S., 2009) contemplated the further advancement of erosion in built up concrete subsequent to wrapping the substantial with both carbon and glass FRP. The exploration comprised of substantial chambers exposed to sped up erosion by a dazzled current. The examples were chambers with a distance across of 100 mm and a stature of 230 mm with one support bar in the middle. The cathode comprised of a hardened steel network. The cathode and the substantial chambers were lowered in 3.5% saltwater and afterward presented to anodic momentum. Prior to wrapping the examples with FRP they were consumed in three distinct classes, pre-erosion of examples for 2, 4 and 8 days, separately. This was done to display elective erosion harm prior to wrapping. After the examples were wrapped, they were exposed to additional sped up consumption for 24 days. Toward the finish of the test, the examples were broken down by support bar mass misfortune and pull-out tests to contemplate the impacts of FRP wraps on the consumption of steel. The draw out power for examples with FRP wraps was altogether higher than for opened up examples, while the support bar mass misfortune was essentially lower for wrapped examples contrasted and opened up examples. Figure 29 shows the support bar mass misfortune versus pull-out strength. In the test, they additionally assessed the obstruction of the examples as higher opposition demonstrates better assurance of the support bar by exposing the examples to a consistent current of 100 mA and estimating the cell voltage. Figure 30, Figure 31 and Figure 32 shows the cell voltages for the examples wrapped following 2, 4 and 8 days separately. From the outcomes, they inferred that applying FRP wraps on concrete with installed steel obstructs the pace of erosion.

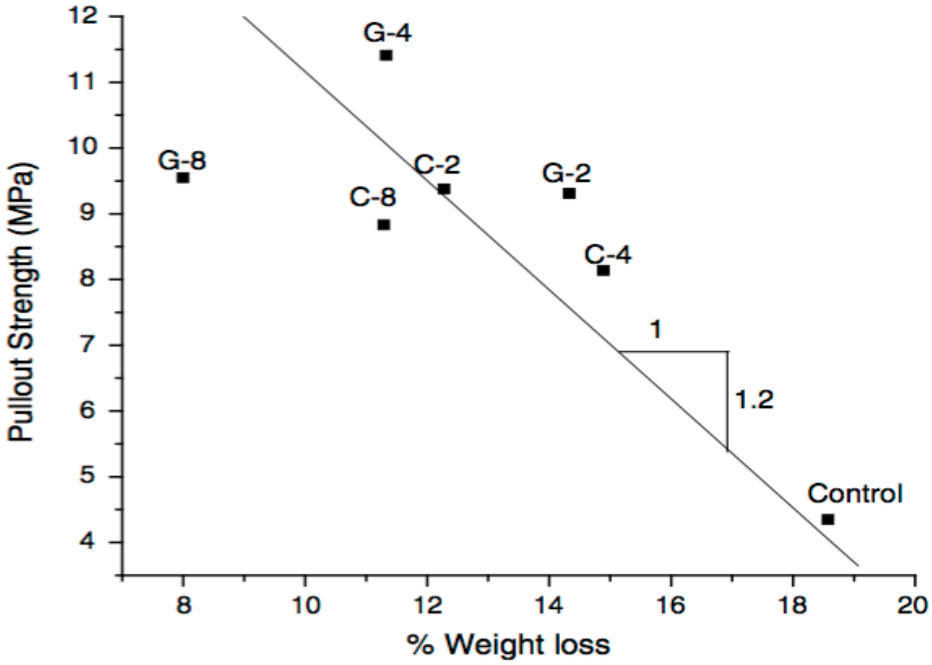


Figure 74: variation of pull out strength with mass loss (Gadve, S., 2009)

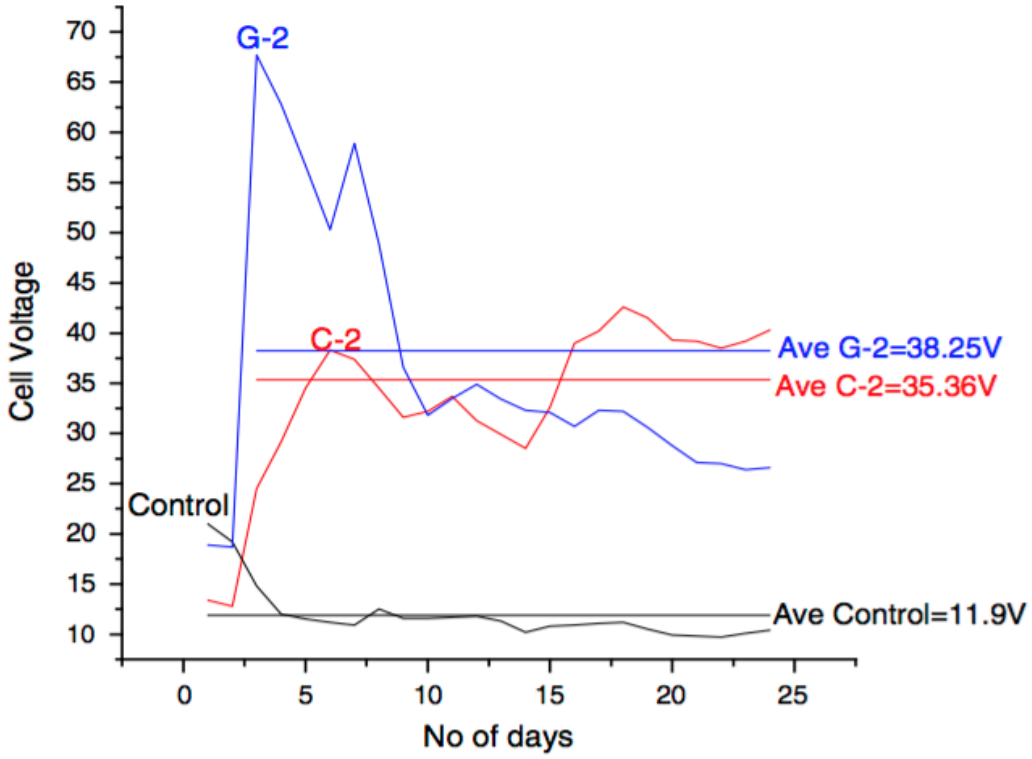


Figure 75: Cell voltage for the test specimen after 2 days (Gadve, S., 2009)

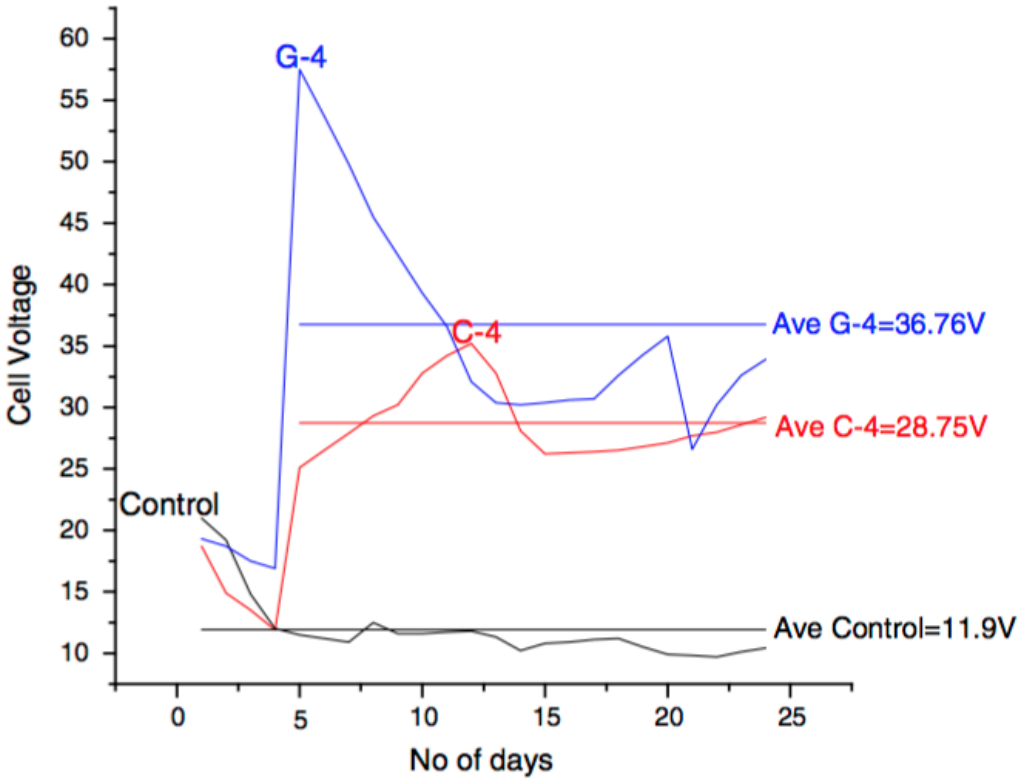


Figure 76: Cell voltage for the test specimen after 4 days (Gadve, S., 2009)

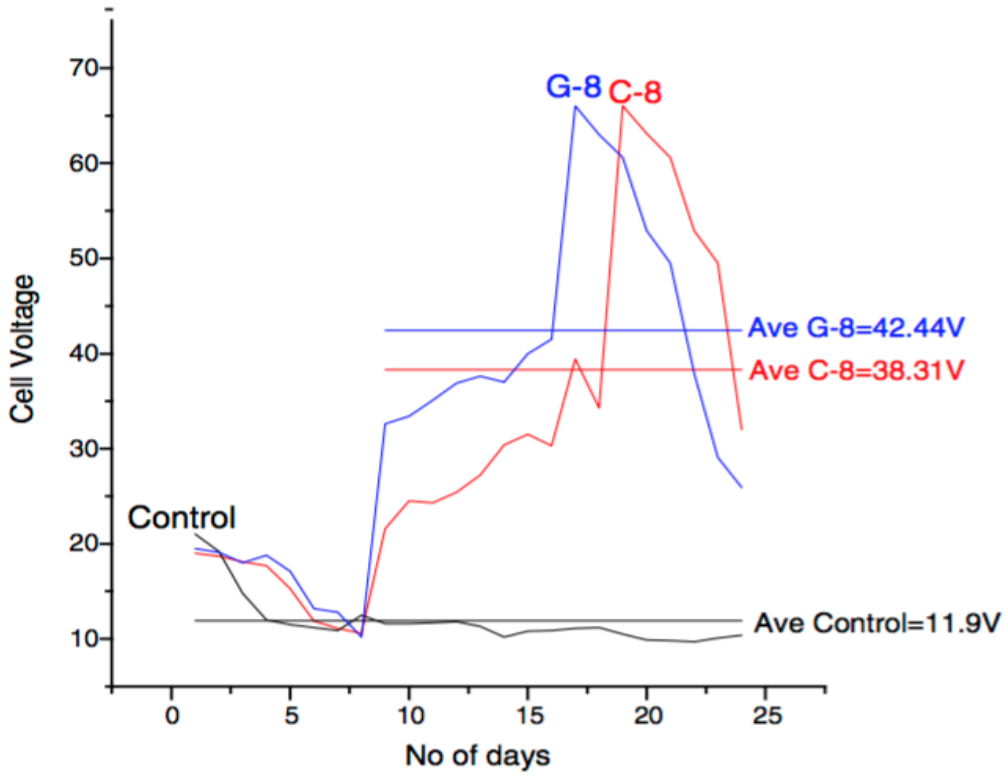


Figure 77: Cell voltage for the test specimen after 8 days (Gadve, S., 2009)

6.6.5 Effectiveness of fibre-reinforced polymer in reducing corrosion in marine environment

(Suh, K., 2007) investigated the effectiveness of FRP in reducing corrosion in a marine environment. This was made by accelerated long-term durability testing on twenty-two pre-stressed specimens with the cross-section of 150x150 mm and length of 1520 mm, see Figure 33. The splash zone was fabricated along 550 mm of the centre of the pile with a 3% chloride content by weight.

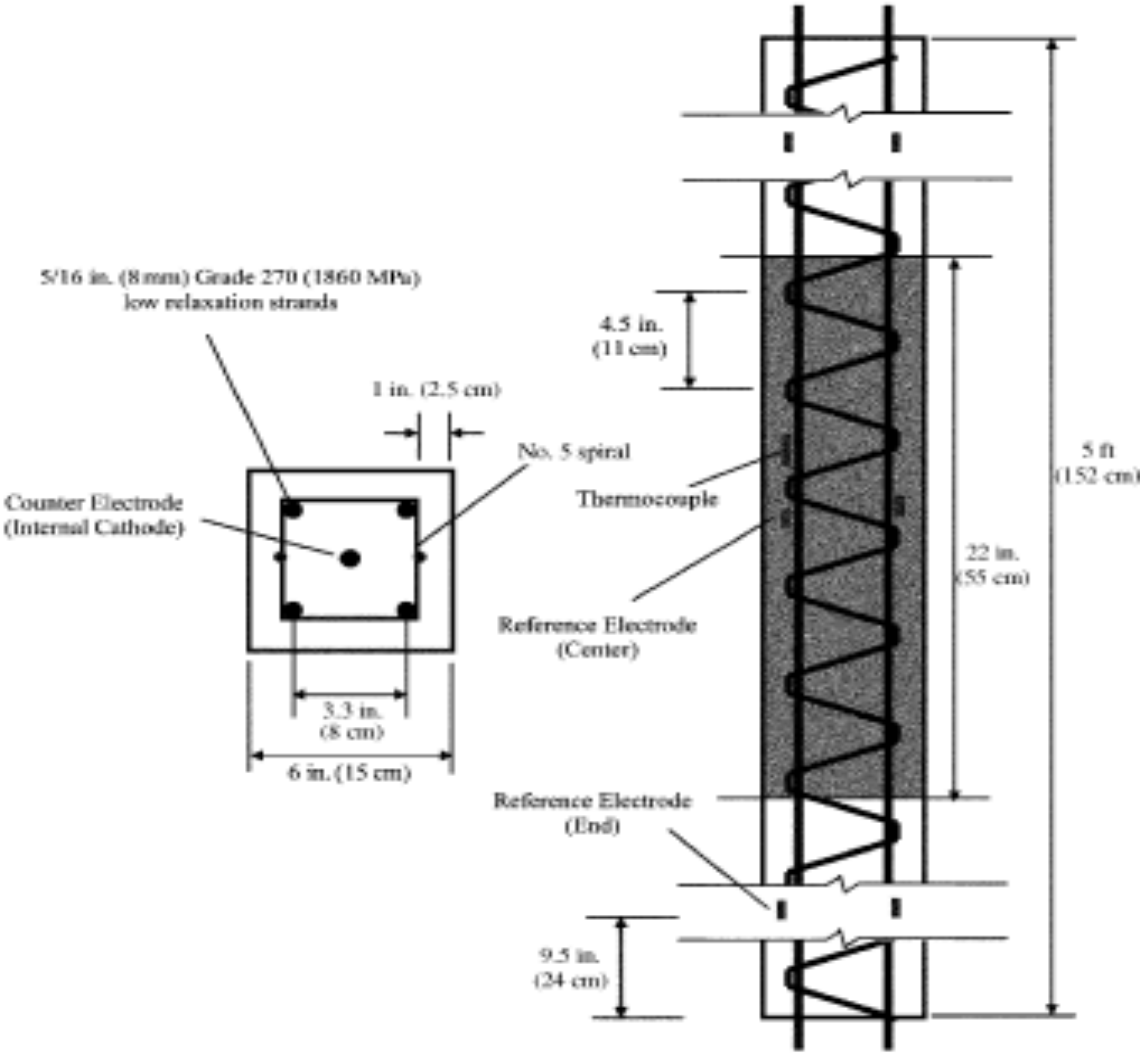


Figure 78: Geometry of the specimen (Suh, K., 2007)

The wrapping was made over a length of 910 mm at the centre of the specimen, extending 175 mm above and below the chloride contaminated area. Sixteen specimens were wrapped with 1-4 layers of FRP, eight with CFRP and eight with GFRP. The accelerated long-term durability testing was made during three years of tidal simulations in a 3.5% saltwater solution. Twenty specimens were placed in an outdoor tank and two of the control specimens were placed in an indoor tank to provide a controlled environment. The tide in the tanks were changed every 6 hours where the water level, from the bottom, changed between 800 mm at high tide to 350 mm at low tide. The corrosion rate was measured with linear polarization during the test. The result

showed that the average corrosion rate of the control specimens was 0.018 mm/year while the corrosion rate of the wrapped specimens was 0.0055 mm/year. Both the linear polarization and gravimetric testing showed that CFRP and GFRP were equally effective in reducing corrosion.

6.6.6 Bond enhancement for FRP pile repair in tidal water

(Winters, D., 2008) studied if pressure bagging and vacuum bagging could enhance the bond for FRP pile repair in tidal waters. The idea is to provide a pressure that ensures contact between the FRP and concrete during curing and thus enhance the bond.

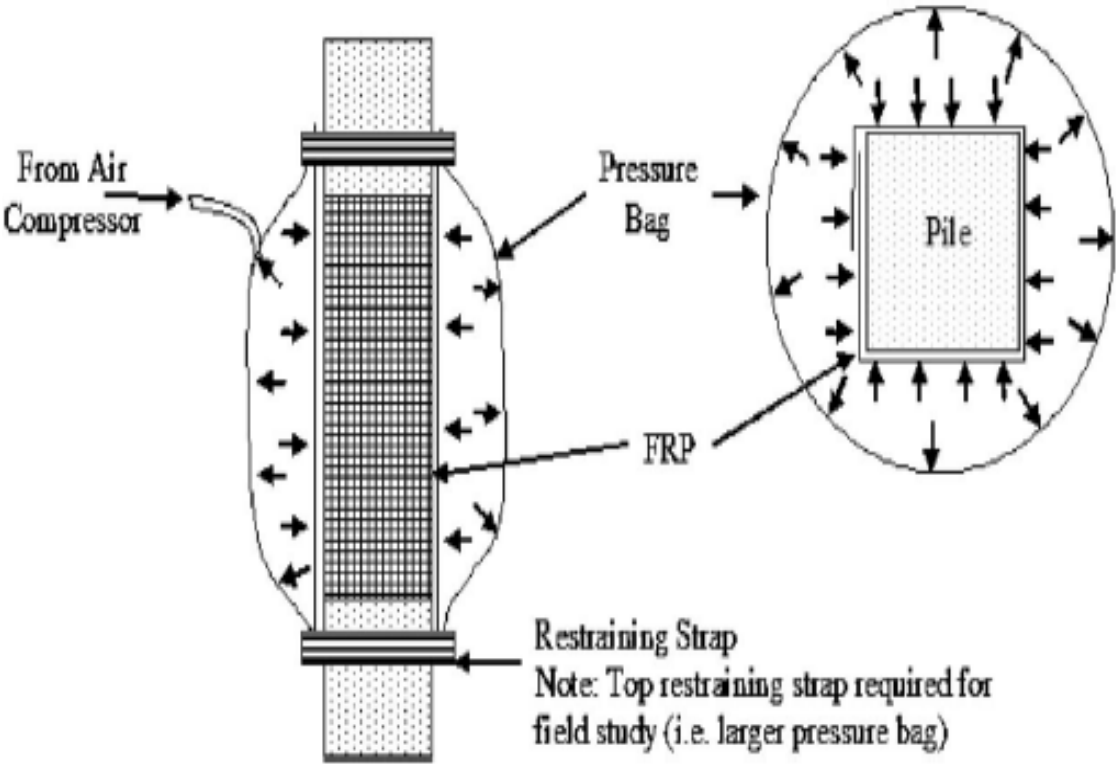


Figure 79: pressure bagging of the specimen (Winters, D., 2008)

Testing was made on eight pre-stressed concrete specimens with a cross-section of 305x205 mm and a height of 1520 mm. These samples were placed in a freshwater tank with the water level of 934 mm from the bottom. To encourage marine growth the piles was left in the tank for three months before wrapping. The wrapping was made from 457 mm above the water level to 457 mm below with two different systems. A pre-preg system developed by Air Logistic Corporation and a wet lay-up system designed by Fyfe. These systems were identical to the ones used in (Sen and Mullins 2007a)

For increasing the FRP-concrete bond, a base resin coating was applied before wrapping the pre-preg system. Two different resins were tested in this experiment, Aquawrap Base Primer 4 and Bio-dur 563. Both were applied at two surfaces each of the four piles The first pile (A4) to be tested with the vacuum system encountered problems to seal the vacuum bag due to cracks below and above the wrapping area. This was solved by filling the cracks with epoxy and vacuum was obtained 45 minutes after wrapping For pile A2 and A3, the base resin was applied beyond the wrapping area for sealing of the cracks. Pile A3 was wrapped before the applied base resin had cured and the uncured resin had difficulties in sealing the cracks and providing an airtight layer. The base resin on pile A2 was allowed to cure for 24 hours before wrapping. However, before installation, the bond between the base primer and the concrete was inspected and it was found that the bond was inadequate. Thus, no wrapping was made on pile A2. The difficulties to achieve an

airtight layer for the vacuum bagging in the experiment shows that this approach can be problematic for field repairs. However, the testing with the pressure bagging was made without any significant difficulties.

The bond was evaluated with the results from pull-out tests with and Elcometer 106 adhesion tester by ASTM D 4541. For the pre-preg system, the result showed that pressure bagging increased the bond strength, from 0.26 MPa to 1.17 MPa, in the wet region and, from 0.94 MPa to 1.57 MPa, in the dry region. The result from the wet layup was mixed with a marginal reduction, from 2.01 MPa to 1.95 MPa, in bond strength in the dry region and an increase, from 1.65 MPa to 1.77 MPa, in bond strength in the wet region.

6.6.7 Effective repair for corrosion control using FRP

(Suh, K., 2010) investigated the influence on corrosion by two different repairing strategies using FRP wraps. The first strategy, “full repair”, includes removing of chloride-contaminated concrete, cleaning of reinforcement and reshaping the cross- section while the second repair, “resin injection repair”, consisted of injecting cracks with epoxy and smoothening of the surface. Both strategies were then wrapped with bi-directional CFRP.

The testing was made on seventeen pre-stressed piles with the dimensions and splash zone set-up as in (Suh et al. 2007), see Figure 33. Before repair, the specimens were subjected to a constant current of current 110 mA during 125-days to achieve a 20% metal loss. For confining the corrosion to the splash zone, a soaker hose-sponge was used to keep this area moist.

After 125-days the specimens were repaired, three with the “full repair”, eleven with the “epoxy injection repair” and the three remaining was left for control. The wrapping was made in one to three layers of the splash zone or the whole pile.

6.7 Interview with a leading expert

To understand more about FRP repair methods in sub-zero temperature an interview was conducted with Professor Mo. Ehsani of University of Arizona and founder of QuakeWrap, Inc.The company QuakeWrap has been and still is employed by many U.S government agencies especially the U.S. Naval forces.

With many grants and patents under his company, most of the repair work carried out by QuakeWrap is based in tropical regions which have showed admirable performance, which lead to FRP performance in sub-zero temperatures an example for would be The U.S. Naval forces using QuakeWrap to repair a main pier of a naval base in Ukraine in the year 2020 in-order to better the relationship with the Ukrainian Navy.

The repair work carried out was to increase the life of the pier, which was based on routine inspection conducted by divers. The repair is very essential in-order to provide a stable foundation to the pier, there were 12 mats resting on piles over an unstable ground which require immediate repair.

In conclusion with this example, the weather in Ukraine is quite similar to Sweden. So, the performance of the FRP wrap seen in Ukraine would be identical in Sweden as well

Due to confidentiality, certain sensitive information hasn’t been disclosed in this section.

6.8 Concluding Remarks

As can be closed from the condition of training survey, fix of lowered built up substantial heaps with FRP composites is made fundamentally to accomplish tough assurance from deterioration. The FRP wraps are chiefly applied in the sprinkle zone where the decay is generally generous.

Since FRP composites are lightweight and adaptable, they give a fast and simple establishment and a more valuable workplace for the laborers. This may counterbalance the high introductory expense of the material and lead to a savvier fix technique contrasted with the ones utilized today. Since FRP composites don't erode and are a low penetrable material, it goes about as a defensive layer obstructing compound debasement and may likewise prompt a sturdier arrangement.

To accomplish a successful outcome with FRP fix the surface planning is critical to get a sufficient connection between the FRP and substrate. It is likewise imperative to give the FRP wrap a defensive covering to forestall corruption of the composite. As a result of FRP's high solidarity to weight proportion fix can be settled on thin and with the appropriate decision of defensive covering, it tends to be made vague from unrepaired heaps. Upon audit, epoxy is the positive tar to use in the composite since it is better than polyester in the considered application along with one or the other glass or carbon strands. Benefits and weaknesses of the FRP fix strategy are summed up

From the survey of the performed test tests in the writing, it tends to be reasoned that CFRP wraps are similarly compelling in lessening the consumption pace of supported cement. It is additionally tracked down those two layers of wrap are the best number of layers for lessening the erosion rate. Wraps with a superior connection between the FRP and cement end up being more productive in diminishing the consumption rate which further shows the significance of accomplishing a decent attach to get a powerful fix. The survey shows that the bond can be improved by pressure stowing the wrap while it fixes. It can likewise be presumed that the connection between the FRP and the substantial is crumbled by dampness as the disappointment, as per performed pull-out test, is in the epoxy for the lowered zone while in the substantial for the dry and flowing zones.

7 Cost Study

7.1 Introduction

To analysis if FRP repair methods are cost effective to conventional methods of repair, a simple and basic cost analysis is carried out. The analysis is based on a previous project conducted- Repair of submerged concrete piles with FRP composites.

7.2 Location of the Piles and Conditions

To know the economical differences between conventional and FRP repair methods of restoration, a previously conducted master thesis was studied to understand the costing.

The master thesis, studied the differences and performed a repair work on a pile with the materials provided the company of employment, the location of repair work conducted in Skarvijshammen berth, which is a part of Gothenburg's energy harbour, which harboured ships of length of 250 m with a depth of 12.5 m.
The repair has been performed on a pile along 10m to reduce the chances of sulphate and chloride attack. The following table explains the cost of conventional repair method (Röös, J., 2017).

7.3 Repair

7.3.1 Conventional Repair Method

As mentioned before, the primary data presented in the table below are obtained from a study conducted previously. The repair method followed is conventional pile jacketing over a circular pile of 670mm diameter, with a construction estimate cost of 200-250kkr. The complete repair procedure is carried out by construction divers from start to finish (Röös, J., 2017).

The procedure of installation carried out are as follows:

- Cleaning of the pile is carried out by hand and high-pressure water gun to remove any settlements present
- Installing a bottom plug
- Formwork installation
- Concrete pouring
- Curing
- Removal of the formwork

The table below shows the estimated time required to perform the operation with the approximate cost per hour.

SL.NO	ESTIMATED TIME	LABOUR COST
DIVING CREW FOR INSPECTON	8-10HR	2000[KR/HR]
DIVING CREW FOR CLEANING	8-10HR	16000KR
FORMWORK	16HR	16000KR
CONCRETING	4HR	12000KR
DEMOUNTING FORMWORK	8HR	16000KR

Table 3: Details showing the cost and time of conventional method (Röös, J., 2017)

7.3.2 FRP Repair Method

Since the maintenance in this relative contextual investigation just has been made with conventional concrete jacketing the FRP fix method is planned with the assistance of the discoveries in the writing audit above and by counselling specialists within the field. The complete repair procedure is carried out by construction divers from start to finish (Röös, J., 2017).

The procedure of installation carried out are as followed:

- Cleaning of the piles is carried out by hand and high-pressure water gun to remove any settlements present
- Voids over the structure are cleared and filled with a cement filler to obtain a clear surface
- Application of a base primer followed by application of the wrap spirally with an overlap to secure any possible leaks on to the internal surface
- Application of a tight film of plastic stretched over the wrap area to keep the wrap in place and aid while curing
- Removal of the plastic film after curing period followed by application of primer over the wrap

SL.NO	ESTIMATED TIME	LABOUR COST
DIVING CREW FOR INSPECTON	8-10HR	2000-[KR/HR]
DIVING CREW FOR CLEANING	8-10HR	16000-KR
SURFACE PREPARATION	8HR	16000-KR
WRAPPING	8HR	16000-KR

Table 4: Details showing the cost and time FRP repair method (Röös, J., 2017)

7.4 Concluding Remarks

The FRP repair is a cutthroat option in contrast to fixes made with pile jacket in concrete.

The expenses of the performed pile jacket are from a maintenance of the pile, a maintenance of just one pile would prompt a greater expense for the pile jacket than utilized in the contemplated case. This further shows that the FRP fix strategy is a serious other option. A quicker fix strategy, as FRP fix contrasted with substantial heap coat, isn't just financially helpful as to less worker hours yet in addition in the feeling of orderly expenses in the perspective on stoppage of the compartment.

While repairing a large project consisting high number of piles, it is time consuming and space-restrictive to install formwork. This benefits the FRP repair method as they are lightweight and easy to handle.

8 Artificial Intelligence (A.I)

8.1 Background

Artificial intelligence is a structures capability to explain external source data accurately, learning from data to reach specific goals and tasks by adapting flexibly. A.I evolution can be classified into four seasons – spring, summer, fall and winter and the seasons outcomes are summarised in the following paragraph (Haenlein, M., & Kaplan, A. (2019)).

Artificial intelligence can be tracked back to 1940s and the word was conceived later in 1956, when a computer scientist from Stanford hosted an eight-week long Dartmouth summer research project on Artificial intelligence followed by two decades of significant success an example would be the processing tool ELIZA created in 1964-1966 capable of simulating conversation with humans, another successful implementation would be the GENERAL PROBLEM SOLVER developed by Herbert Simon a Nobel Prize winner and group of RAND scientists (Haenlein, M., & Kaplan, A. (2019)).

Initially the progress lacked due to the fact reality fell back to expectation early to ELIZA even with expert systems capable of performing impressively. An example would be IMB's deep blue chess playing program processing 200 million moves per/second but their performance in other areas did not lend sufficient formalization (Haenlein, M., & Kaplan, A. (2019)).

Achieving true A.I was discussed and explained in the early 1940s through theory of learning as Hebbian Learning that could replicate process of neurons in a human brain which led to research in Artificial Neural Networks (ANNs), but systems did not have sufficient power to process to handle the computational requirements (Haenlein, M., & Kaplan, A. (2019)).

ANNs has made a great impact in through the form of Deep Learning forming the basis of many applications under the label of A.I, it is very clear that this system has become a part of everyone's day-to-day life in the forms of internet and social media impacting not only a being personal live but also transforming firms on how decision making, and interactions are carried out with their stakeholders and consumers. (Haenlein, M., & Kaplan, A. (2019)).

The construction industry deals with design and execution of structures such as buildings and bridges involving many professional with specific knowledge and expertise and the industry is classified as a knowledge intensive requiring knowledge-based technology (Andersen, T., & Gaarslev, A. (1996)).

Relatively many companies have been investing in various forms of A.I technologies to transform high amount of data into useful knowledge and adaptation process lags behind compared to other industries (Pan, Y., & Zhang, L. (2021)).

8.2 CASE STUDY

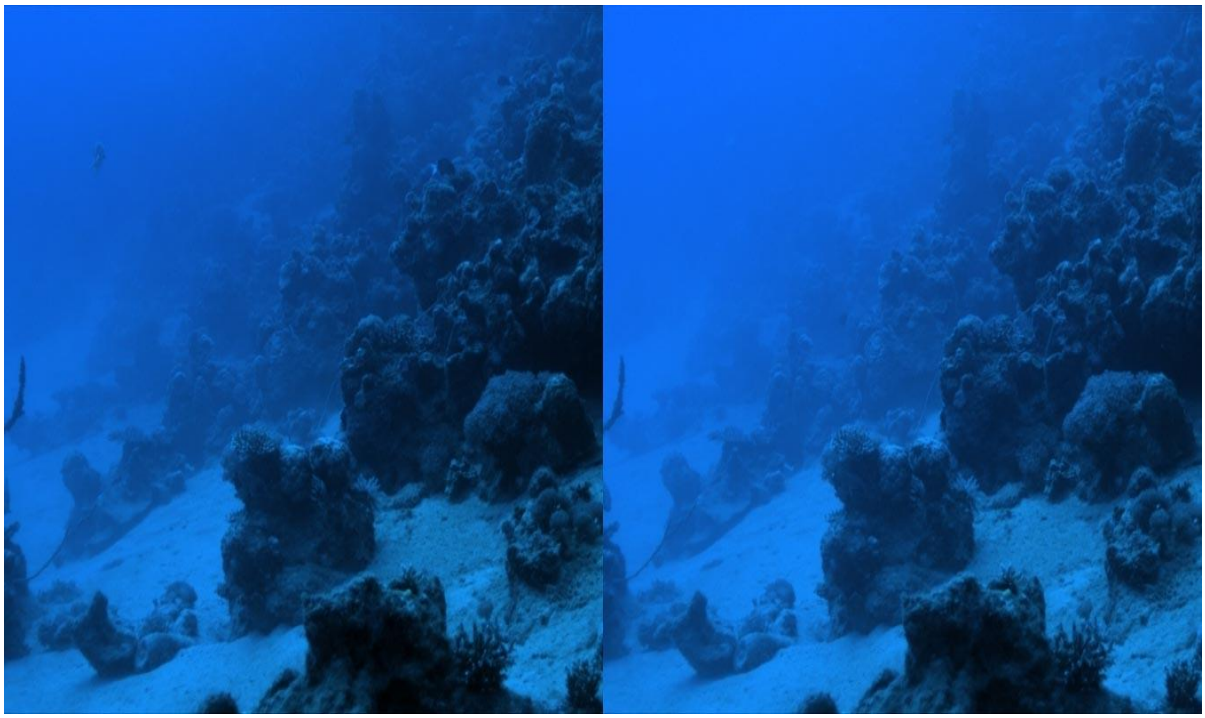
To find and suggest autonomy in the inspection methodology literature review has been carried out to review all the experiments/ research and pilot projects, who have tried to implement Artificial Intelligence.

8.2.1 Underwater optical image processing: a comprehensive review

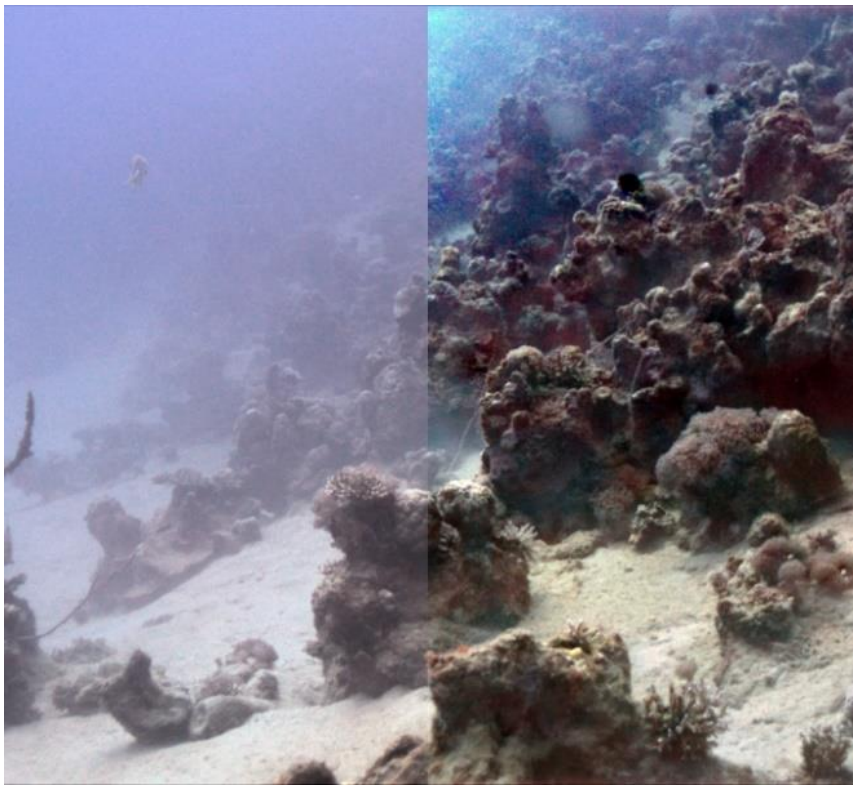
(Lu, H., 2017) reviewed two underwater imaging methods: Hardware based, and Software based approach and summarized the commonly used colour restoration methods followed by covering underwater image quality assessment methods which are reference-based indexes and non-reference indexes.

Underwater image processing methods are categorized into hardware-based and software-based methods.

(A) Hardware-based methods which are sub-categorized into polarization, range-gated imaging, fluorescence imaging and stereo imaging. The primary study conducted showed that natural light is without polarization and the backscatter seen in the optics can be reduced using polarization by two methods either by attaching a filter on the camera to obtain better results or use polarized light to source to obtain different illuminated images of the same surrounding.



(a)



(b)

Figure 80: Underwater Polarization Imaging – (a) Raw image (b) Recovered image (Lu, H., 2017)

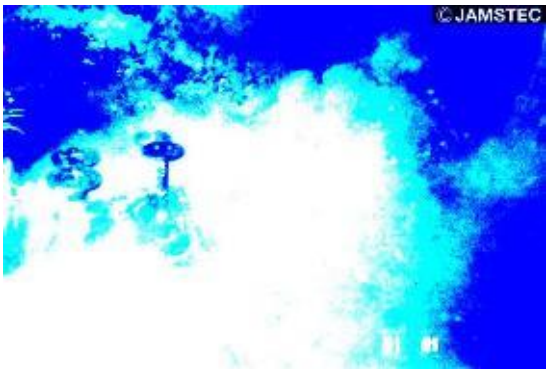
The authors also gave a brief review of fluorescence method used to recover shapes in an distorted underwater image. This method is commonly used to detect organisms in coral reefs.

(a) (b)

Figure 81: Fluorescence Imaging – (a) Raw image (b) Recovered image (Lu, H., 2017)

(B) Software-based methods is used depending on the outcome of the results and the approaches are sub-categorized into wavelength compensation (sediment scattering) and color reconstruction (light absorption). The authors have reviewed various research work conducted on solving scattering problems by physical model-based and non-physical-based methods, where the physical model uses designed color-line methods to determine turbidity in haze. The results of a physical model-based are shown the figure below. Similarly, non-physical based model employs local histogram to shed light on non-uniform lightings and haze surroundings, it has been observed that local histograms performance is not sufficient enough considering underwater surroundings but limited application of local histogram between neighboring regions are noticed to be effective.

(a)



(b)

(d)

(c)

(e)

Figure 82: Physical model-based methods : (a) Input image (b)Fattal's Method (c)He's method (d)Chiang's method and (e)Lu's method (Lu, H., 2017).

8.2.2 Cracks detection using artificial intelligence to enhance inspection efficiency and analyze the critical defects

(Habbal, F., 2020) conducted an extensive literature survey on methods that could implemented to enhance the crack detection using Artificial intelligence.

Artificial Neural network (ANN's) as approximate similarities to a human brain which can be considered as Artificial Intelligence (AI), these systems can be employed when there is a complicated input and output or if computational process of another method is higher. This system is powerful that can be employed to solve many real-life problems, it adapts from their experience to improve themselves.

Damage identification is classified into the following:

1. Identification of the presence of damage
2. Determination of location
3. Determination of severity of the damage
4. Prediction of the residual life

Many literatures reviews discuss methods of crack detection but none yet to show a comparison between them which can be used to obtain an accurate result.

The authors have worked on a machine learning algorithm (ML) to detect failure with pattern recognition (PR) which was implemented on a damage and fatigue phase model. The model was simulated using finite element methods and semi-implicit time-integration scheme to obtain time-series data of the damage phased model.
The PR scheme being a part of ML was introduced on the test specimen after node positioning at different location, by the time a considerable amount of data from the FEM nodal response which are considered with a corresponding label. The labels are named in order as no failure, onset of failure and failure of the specimen which is based on tensile test and damage threshold concept. When the patterns are identified based on different states, the ML approach is employed to detect the presence and location of failure using the patterns. The ML framework is verified by considering different failure modes and the robustness of the system is checked by introduction a series of noise to the data to run a analysis on the noise polluted data. The authors have worked towards using this data to pave the way for data-driven failure prediction frameworks.

With many methods of crack detection present in the current day, the ANN method is effective as the location of damage is found precisely and providing accurate level of damage relating to vibration changes that can be simulated numerically. The prediction efficiency of the ANN model is completely dependent on measurement of uncertainties and modeling training parameters, if uncertainties aren't calculated it could lead to false predictions. Thus, the authors have emphasized the importance of training to increase the reliability of ANN.

8.2.3 Automated infrastructure inspection based on digital twins and machine learning

(Furtner, P., 2021) explains the implementation of a pilot project for inspection of structures using drones and digital image processing technologies especially artificial intelligence methods. The papers aimed to check objectified and comprehensible damage detection through cost effective methods.

This pilot project was joint research with ÖBB for evaluating the extent of inspection supported using UAV's. Selection of the drone is doned based on the sensors(cameras) with additional pilot monitoring to ensure safe trajectory in restricted areas.

To ensure an accurate 3D model is created it is crucial to obtain pictures with much information as possible which completely relies on flight planning plays. The planning is carried out either by studying a previously carried out 3D plan or with on-site flight plan. When a plan unavailable, a manual flight plan is carried to create a 3D. Software used for creating the 3D model employs robust photogrammetric evaluation-based bundle adjustment algorithms to orient the images taken. This process is backed with using pre-geodetically measured control points.

Damage detection is carried out through the onboard sensors and software for image evaluation and pattern recognition is employed. Where the pixel in an individual picture is divided into different classes based on their absorption and reflection properties. After marking spectral properties, machine-learning algorithms is employed to automate the process. The damages noticed are discoloration, spalling, exposed reinforced steel. The exact location of the damage is detected, and cracks are classified based on lengths and width.

The Falkensteinbrücke pilot project is inspection of the longest ÖBB Tauern railway bridge spanning over the valley. The ariel survey is conducted to inspect support plate, pillars and bow. The flight control was carried out manually from the ground assisted by an observer.

Figure 83: Pillars in the recording area (Furtner, P., 2021)

Evaluation is carried out by creating an 3D model of the aerial photographs using photogrammetric method (Dense image matching). The algorithm used searches for equal points over several images and calculates their coordinates results in a point cloud which serves as a basis for BIM or an 3D mesh model. In this project damage detection is carried out using neural networks with software tools as FALCO and IRIS, training the neural network (using FALCO) and analyzing the large number of pictures (IRIS) based on the classifier created by the training. Every picture is analyzed for every-type of damage and the detected flaw is marked on the image and saved for further evaluation.

Visualization is done by web-GIS software developed for view the results. This method provides the inspector to view the 3D model with damage list with its description. For assessment an detailed view is created with individual defect. The results presented by the web-GIS is interpreted and evaluated during the next step by an experienced engineer.

8.2.4 Review and analysis of crack detection and classification techniques based on crack types

(Scholar, P. G. 2018) discussed the existing work where the use of Otsu's thresholding-based method is used as it employs the automatic thresholding principle to detect cracks based on the class-invariance principle. The input image at stage one is moved to stage two where the image is contrast stretched by normalizing the intensity value, at stage three the stretched image is converted to grey scale followed by stage four the crack regions are segmented from the non-crack region and the final stage the crack region is shown in a colour.

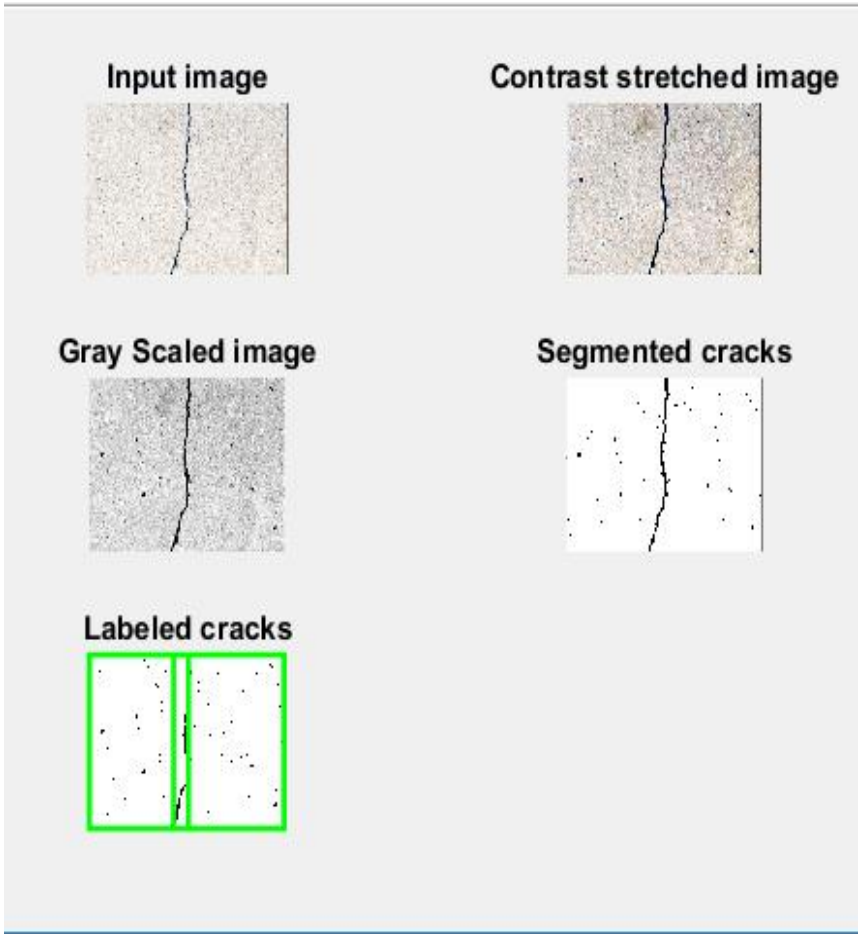


Figure 84: a) Preprocessing module b) Resize the image c) Normalizing the intensity value d) Segmentation by thresholding e) extracting crack region (Scholar, P. G. 2018)

The authors proposed a system, where the pre-processing step would use wiener filter to remove any blurriness in the image. To overcome issues faced, wavelet transform, and singular value decomposition is proposed, but the grey scale processing also shows the unaffected regions are identified as cracks.
To overcome the issues faced by grey scale, morphological operation and KD-tree are introduced to the design where the morphological operation enhances the image and KD-tree is employed to connect the discontinuities the crack area.

8.2.5 Comparison analysis on present image-based crack detection methods in concrete structures

(Wang, P., & Huang, H. (2010, October)) of Tongji University express the importance of crack detection to adopt appropriate repair methods, there has been an increase in image-based inspection but there also has been many difficulties in this method due to random shapes and irregular sizes and noises in the image.

The process opted in this project are provided in the figure below

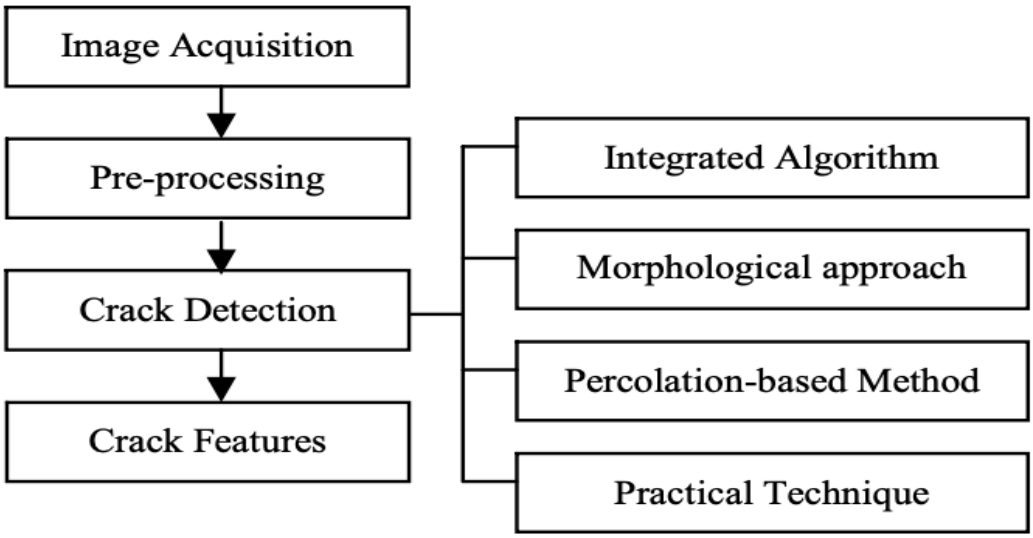


Figure 85: Flowchart of crack detection (Wang, P., & Huang, H. (2010, October))

The crack detection methods are briefly explained.

A) Integrated Algorithm: This approach has two steps, the first step involves pre-processing to remove noises in the input image simultaneously highlight crack features, second step involves separating cracks from background. One technique has been highlighted in this project was the Fujita's technique, where crack is detected in the first process, the pre-processing removes irregular illuminated conditions, after which Otsu's thresholding is applied to separate cracks from the background.

B) Morphological Approach: This is an approach has been based on mathematical morphology and curvature evaluation to detect crack patterns even in an noisy image, this is a set-theoretic concepts based on nonlinear super positioning of signals. The shape properties and effectively been employed to detect cracks even in a complex background. This approach is subdivided in to three steps, first the dark pixels are enhanced also increasing the contract of the image followed by performing crack enhancements, last step involves applying filters with linear structural elements that removes noise patterns.

C) Percolation-based method: This approach is based on an physical model on natural phenomenon of liquid permeations, this approach uses assumptions that cracks are based on two characteristics being their brightness lower than the background and shape being slimmer than other textural patterns. While

other integrated algorithms depend on brightness of image leading to unclear crack identification. This method evaluates central pixel in local window according to cluster formation. This approach uses local image processing while considering neighborhood pixels connections.

D) Practical technique: Desiring an automated crack detection method in principle giving appropriate image quality which is viable to find crack edges and detecting them automatically, this is achievable due-to the irregularity of cracks and noises in concrete image. As crack is detected an automatic algorithm can be employed to measure width of crack which starts with polyline representation of crack.

Numerous experiments have been conducted by using the methods above and the results have been compared to arrive at a reliable method of crack detection, integrated algorithm is effective when removing shading, pre-processing is dependents on size of median filter including parameters of line emphasis, but Otsu's threshold technique is effective in flawless image where histogram as an sharp valley between peaks and backgrounds. While considering practical applications size of median filter and line emphasis which cannot be easily selected lowering the effectiveness of the technique.

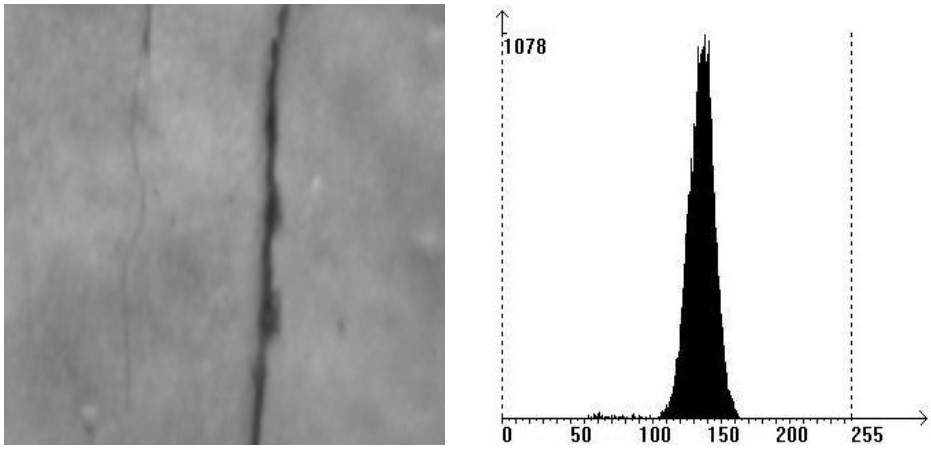


Figure 86: Concrete image and histogram (Wang, P., & Huang, H. (2010, October))

Morphological approach depends on size of structural elements and their degree of rotation, the result of this method varies with different structural elements as seen in the figure below, crack pixels cannot be detected exactly.

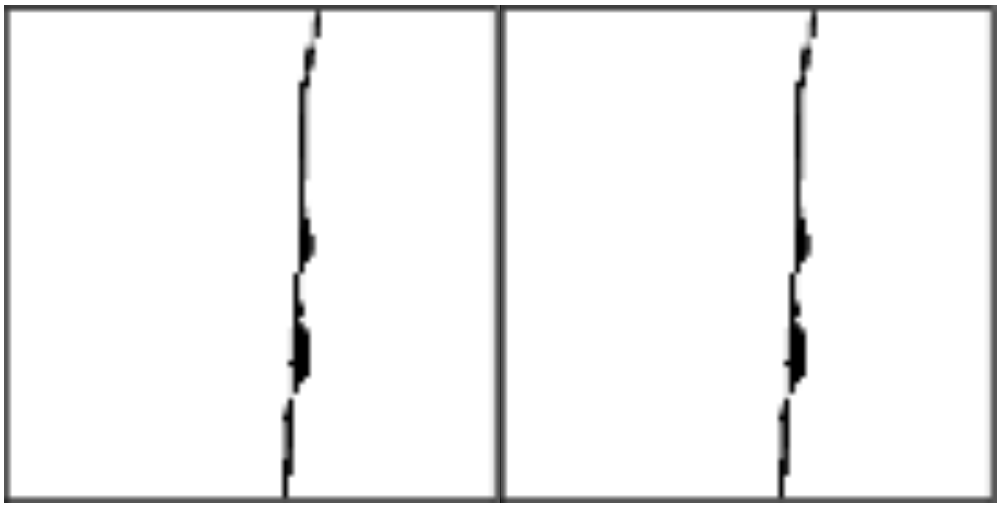


Figure 87: Results of morphological approach (Wang, P., & Huang, H. (2010, October))

Percolation based method distinguishes the focal pixel that belong to cracks by determining shape of the crack, this method is very effective in unclear crack detection. This method is a local image processing which requires high time for processing where micro cracks are eliminated.

Practical techniques use route finder algorithm which depends on selections performed by the user, this process is initializing the start point and end point on the image, this is a semi-automated crack detection system which also detects micro cracks.

This paper has been concluded by referring practical techniques the semi-automated crack detection method can achieve excellent performance in various images

8.2.6 Advances in computer vision-based civil infrastructure inspection and monitoring

(Spencer Jr, B. F., 2019) outlines the recent research conducted in vision-based condition assessment of civil infrastructure, this method is used to automate tasks of the human visual cortex. Optical character recognition (OCR) was the initial stage of automation used by the United States postal service and license plate recognition, later facial recognition used detecting pattern representing the human faces. Current advances have been largely using end-to-end artificial neural networks (ANNs) based on input-output relation of data is analyzed by parametrized nonlinear functions which are defined by units known as nodes and convolutional neural network (CNNs) uses each node convolution followed by nonlinear activation functions, CNNs is particularly used for image and video data as the use of arbitrary complex parametrization of input-output relation.

One set of algorithms are significantly advanced over a period in computer vision and artificial intelligence (AI) are optical flow, this estimates the motion field through pixel correspondences in an image frame. The optical flow is opted due to its ranging applications in processing video data to segmentation and vision-based navigation.

The envisioning of automation in inspection process is carried out by completing two steps,

(1) Utilizing UAVs for data acquisition
(2) Data processing and inspection using computer vision techniques

The rapid advancements of drone have replaced the use of UVAs but many of the federal agencies are still relying on the UVAs due to the conservatism. The main purpose of these systems is to pictures and videos of evaluation. The challenge faced in this process is automatically converting data into actionable information

Damage detection in any inspection system is crucial, images are characterized by ratio of pixels showing damage to undamaged part on the structure surface, this is a challenging task. Further complications are faced by features such as dark edges, grooves misunderstood as cracks. Different approaches and techniques are developed to tackle the challenges

1. Heuristic feature extraction method

   The principle of method is using machine learning classifier to the obtained output through hand-crafted filter for damage interest, concrete cracks are identified by heuristics filters such as edge detection filters to identify cracks of different thickness. A typical result of this method is represented in the Figure……. The first column represents original picture and other columns shows the results of the bottom-hat method, another method used is quantifying the centerline of every crack by computing the distance from the edges.

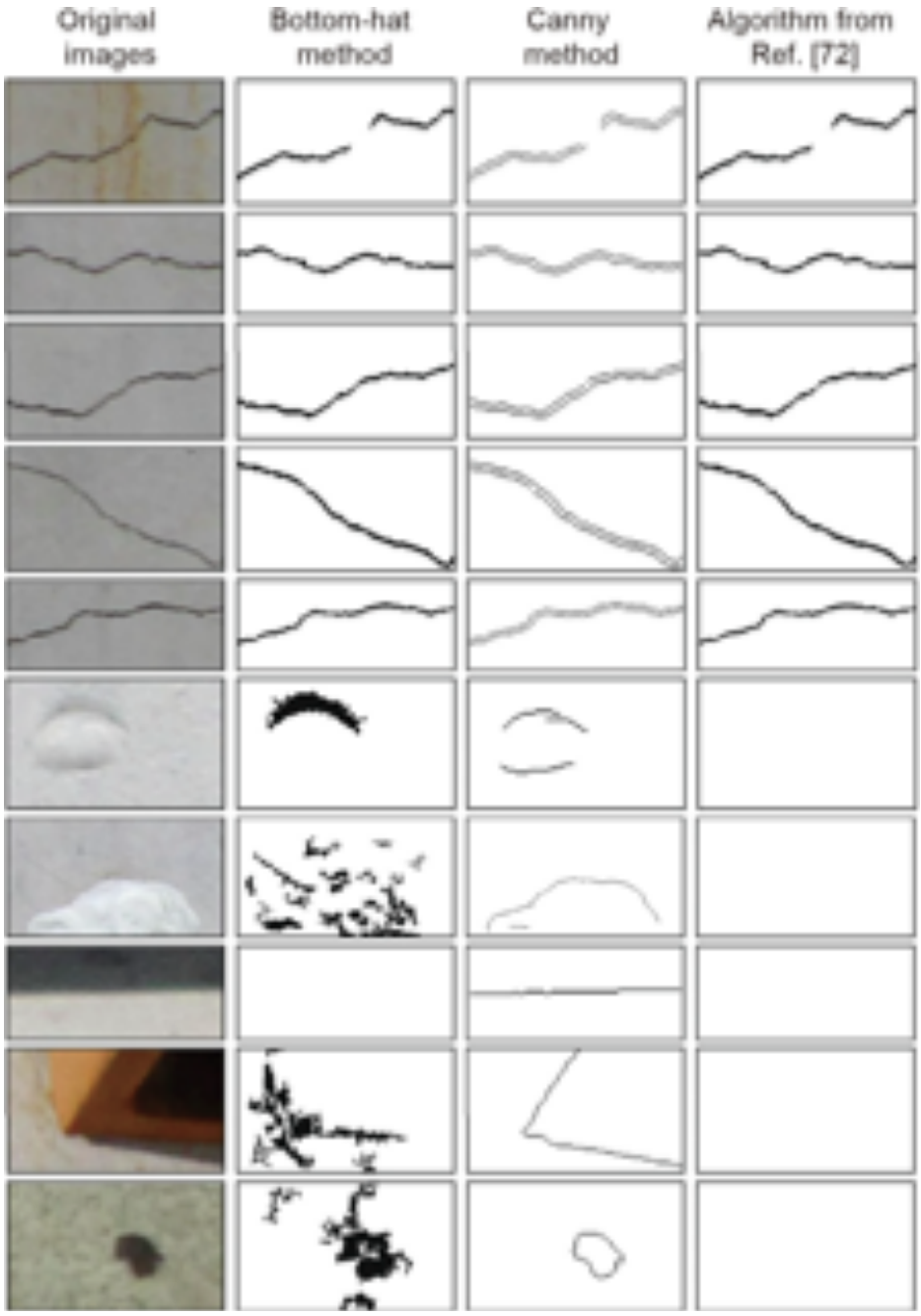


Figure 88: Comparison of different crack detection (Spencer Jr, B. F., 2019)

Concrete spalling is identified through detecting defects in concrete through novel orthogonal transformation which is combined with the condition index to quantify degradation and subsequently map to conditions. Fatigue cracks in steel are a major concern as they reduce the lifespan of the structure significantly, but have been inspection have been fairly limited, this analysis is carried out by conducting experiments by manually creating cracks then combining region localization by object detection and filters to detect the created fatigue cracks.

2. Deep learning-based damage detection

Automation is limited has these techniques does not employ contextual information which is available in region around where defect is there, the filtering techniques are needed to be manually tuned based on appearance of structure being monitored. In deep learning image classification, autonomous

transportation system which is successful in cases. Image classification is carried out by employing CNNs for crack detection in crack detection in steel decks, concrete surfaces with good precision. Object detection is applied for damage detection where this method creates bounding box around a damaged region, regions with CNNs features are employed to detect spalling in post scenarios. This technique is used for a single damage type, deep learning can learn general representations of characteristics in images over huge number of cases, there has been limited research that has been carried out in detection of multiply damage type including cracks and levels of corrosion. Object based methods cannot describe shapes in damage which are isolated, the aim is to fit a rectangular box in the region of interest, another method is to isolate the regions of interest in a picture which is termed as semantic segmentation which is more accurate, the obtained results are an segmented image where each segment is assigned an certain class, after which the detection technique is applied and accurately locate and shape of the damage.

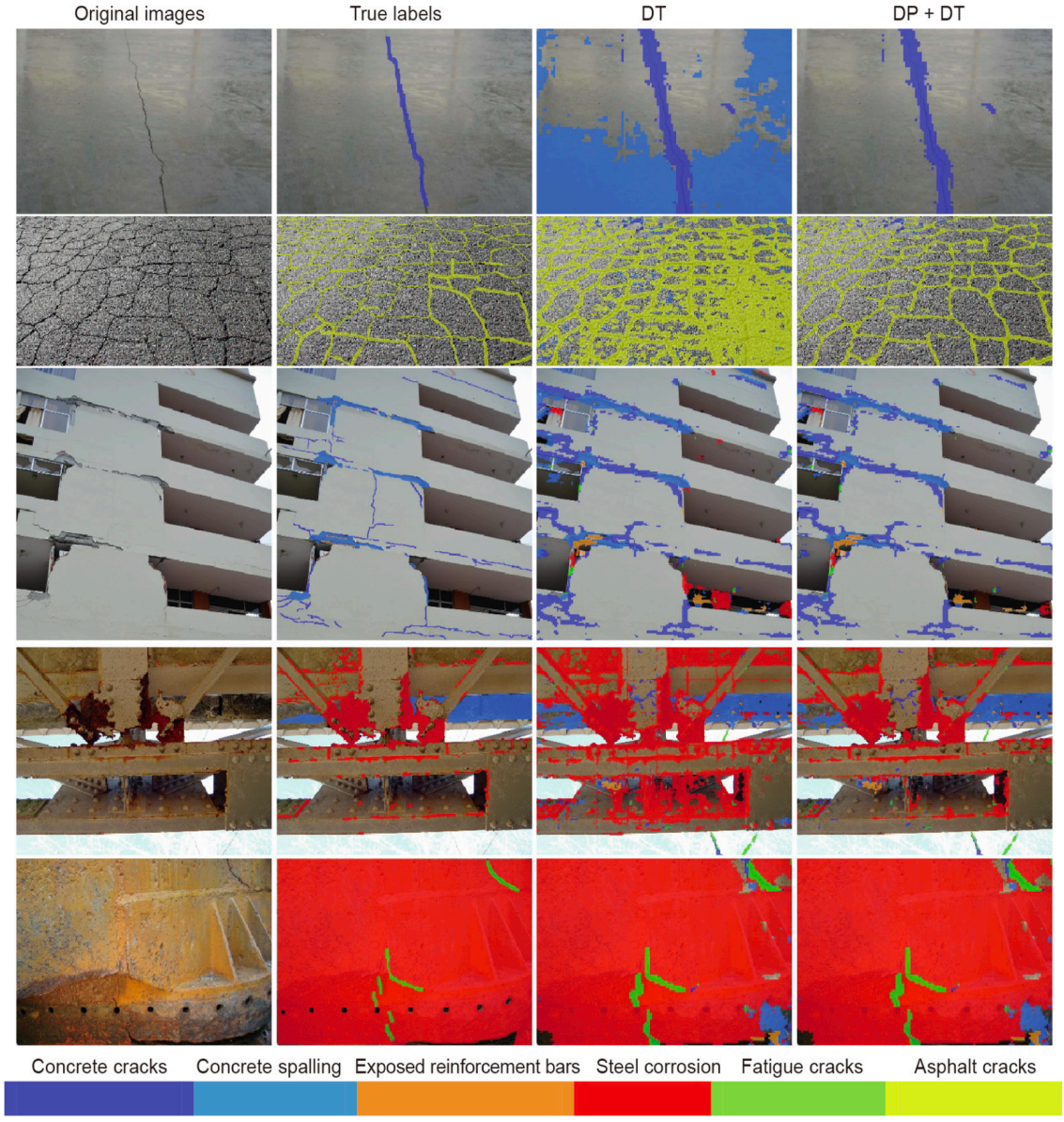


Figure 89: Deep learning based semantic of multiple DT's (Spencer Jr, B. F., 2019)

3. Change detection

When structures need to be constantly inspected a base line representation is given which can later be used comparison after data subsequent inspections. Detecting changes help in reducing workload during work processing after inspection, as damage must manifest as change in surface, identifying a change will reduce false positives. Structures from motion and multi-view stereo are the techniques that generate point-based clouds as structure, change detection is carried out after a baseline is created, subsequent scans done during the inspection are then registered with the baseline cloud information where alignment is carried out through iterative close point algorithm (ICP), this method are very accurately. The ICP program is implemented with an open-source program.

Change detection on images is a problem commonly faced in computer vision, due to its widespread applications, before the change detection is performed, image is pre-processed for removal of environmental variational effects after which registration is carried out before processing.

One key step that is highlighted in this paper moving towards automated inspection methodology is that the recognition of structural components, which can be accomplished by added information about the structural components giving semantics to the 3D point cloud helping humans acquiring knowledge about the current situation of the structure and for safety evaluation. Recognition is achieved through use of CNNs as they are very reliable and accurate and object detection algorithms.

A combination of structural components and damage state information is vital, picture or video acts a framework, and each column has assigned to an damage index. The damage index is classified by column failure mode into shear or flexure based on cracks, this information is described through BIM approach has it helps analyses by heuristics to incorporate strength and visual damage assessment.

Another approach discussed in the paper is use of FCNs for segmentation of damage and building components to get semantic information, the sub structure of networks is (SB) scene & building information to identify DP and DT, the accuracy of this sub-network is 88.8% and combining DP & DT makes this system 91.1%. The results of this method have been presented below in the Figure

8.2.7 Deep Learning- Based Crack Damage Detection Using Convolutional Neural Networks

(Cha, Y. J., Choi, W., & Büyüköztürk, O. (2017)) employed the convolutional neural networks (CNN's) for building a classifier to detect concrete cracks in images. The authors have worked towards their aim to construct a robust classifier which is not influenced by noise induced by lighting, shadow, casting, blur to secure an wide array of adaptability and to construct an base-line that could be used for other types of damages. This method is advantageous as it does not need any feature extraction nor caparison of calculation methods.

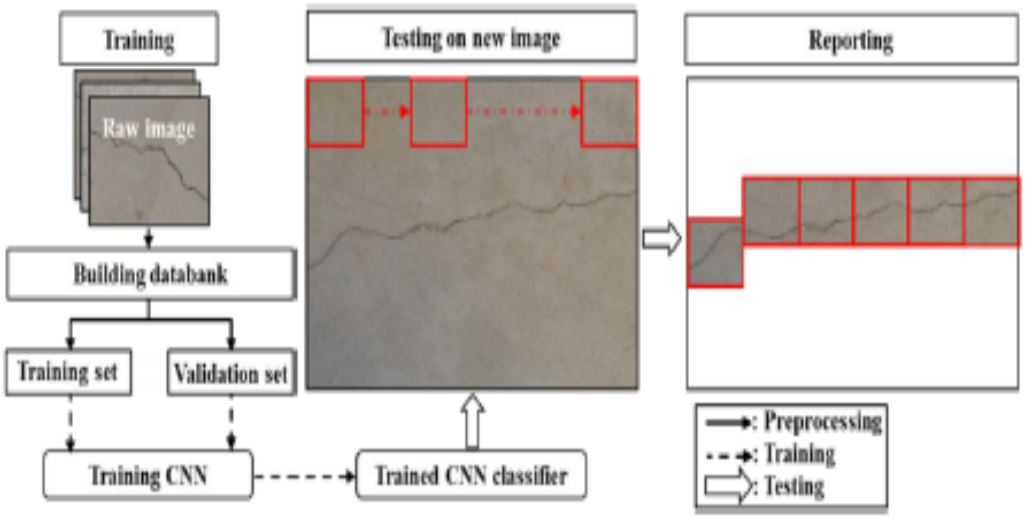
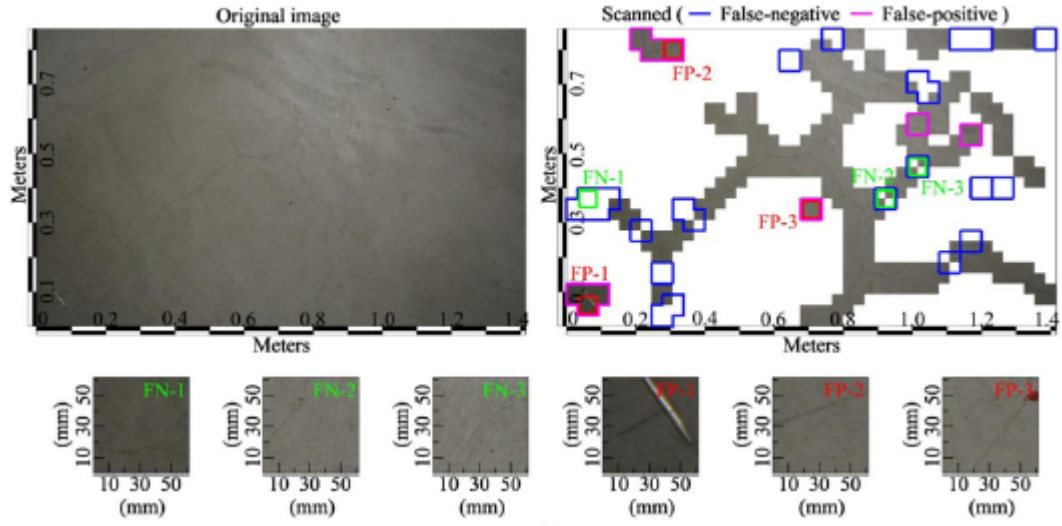
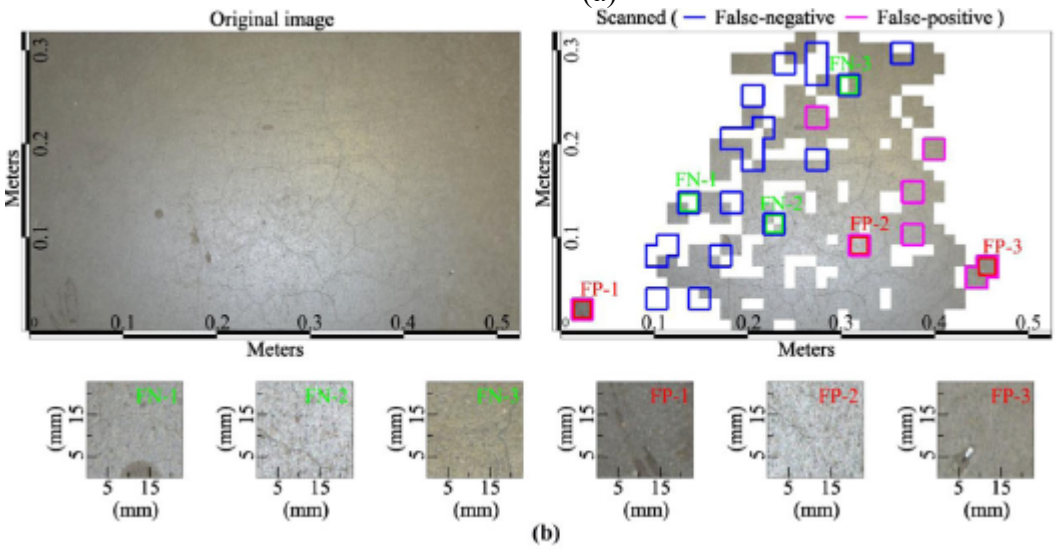


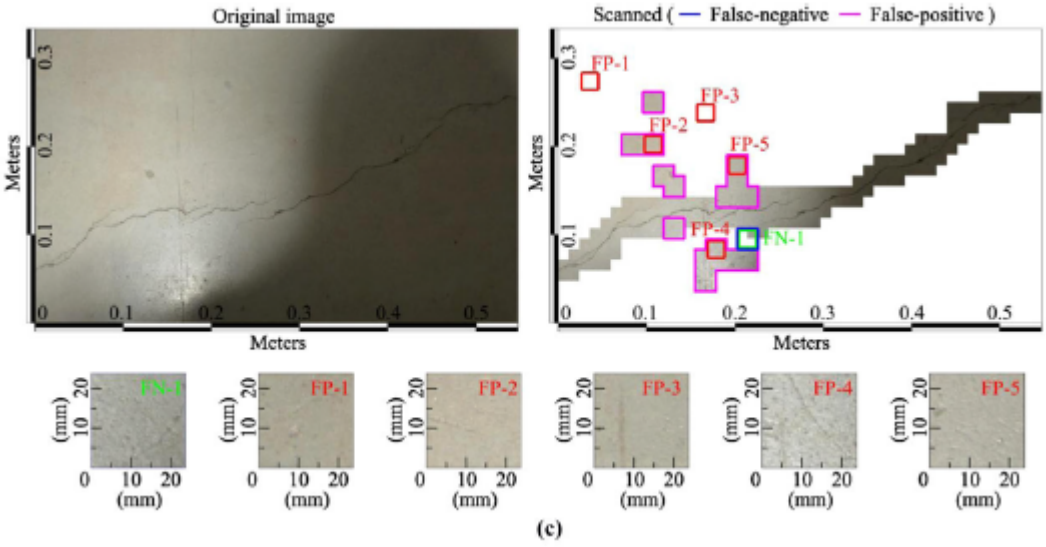
Figure 90: Flowchart for detecting concrete cracks Cha, Y. J., Choi, W., & Büyüköztürk, O. (2017)

The complete process of the framework has been shown in the flowchart above. The training of CNN's is carried out by using a raw image to create a database. Images are cropped into smaller pieces that are given as an example of crack that are imputed into the database which are employed to generate training and validation sets. These sets are inputted into classifier for building a crack separation from the images.

The CNN's performance is examined and validated by using images that are not used in training, these images have been extracted from various locations and the obtained results are very much accurate. The network showed good performance throughout with different image input. The figures given below are show the function framework output.


Original image
Scanned (False-negative False-positive)
Meters
FP-1
FP-2
FP-3
FN-1
FN-2
FN-3
(mm)
(a)


Original image
Scanned (False-negative False-positive)
Meters
FP-1
FP-2
FP-3
FN-1
FN-2
FN-3
(mm)
(b)


Original image
Scanned (False-negative False-positive)
Meters
FP-1
FP-2
FP-3
FP-4
FP-5
FN-1
(mm)
(c)

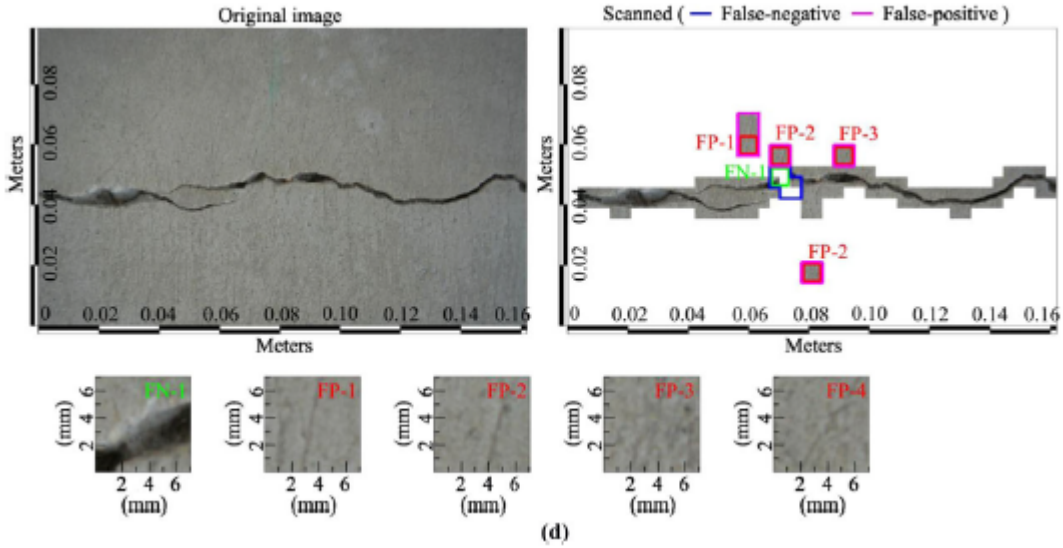


Figure 91: (a) thin cracks (b) thin cracks and lighting spot (c) shadowed image and (d)close up image Cha, Y. J., Choi, W., & Büyüköztürk, O. (2017).

The authors conducted a comparative study based on the performance of the new crack detection with the already present methods, the commonly employed methods Canny and Sobel edge detection are chosen for this part, the CNN's provided much better information of the crack while other methods didn't provide relevant information which the authors expected. In conclusion, employment of CNN's method is advantageous as it learns from a vast set of database providing a clear solution with inputs.

8.3 Concluding remarks

The construction industry has experienced rapid development in digital technology and with the expansion of big data in the recent decades, attempts in adoption of A.I to behave like human intelligences and thinking has received attention, numerous strategies being discovered to transform the industry.

A.I implemented in the construction industry are based on machine learning, most of the research conducted in the recent years are leaning towards image processing used to identify the location, extent of damage and including extract specific information about the damage to provide accurate repair solution.

The methods discussed in the above case studies are all relatively applicable to post inspection and monitory purposes, no relevant experiments or projects have been conducted to automate the inspection process to reduce time consumed for inspection.

The accuracy of A.I algorithms relies on the network training with parameters to automate the process of detection, the processing time is considerable reduced in comparison to conventional methods of analysis.

9 Discussion

At the end of each section, the obtained results are discussed. Though, a few topics are further disused:

With the literature review and interviews conducted with the industrial experts it was conclude that concrete permeability plays a key role in the deterioration processes in the concrete structures and are unavoidable, either the physical mechanism or chemical mechanism or both can lead to the failure of the structure.

9.1 Deterioration

Freeze & thaw is a gradual process which is very crucial as this leads to loss of concrete cover providing way to moisture and chlorides, damage induced by a single cycle is minimal and untraceable, very dangerous when the structure undergoes repeated cycles during the winter season, the concrete exposed to cold ambient air, which is cold enough to freeze the pores. Doubling the cycles to uncommon numbers causing tremendous damage.

Chloride ingress is a major concern, when it comes to structural integrity as presence of chloride ions activates the de-pacification of the steel's passive protective layer localising the corrosion. With the sub-structure undergoing constant wetting and drying cycles, chloride threshold exceeds leading to accelerating the process of corrosion leading to localised cracking along the bars spreading outwards affecting the surface.

In order to control and avoid the deterioration process in marine structure it is very import to achieve a highly impermeable reducing the inward transfer of chloride ions by reducing fine cracks.

9.2 Inspection

The prolonged exposure to marine environment gives way to growth of vegetation, sometimes this vegetation is looked like a protective layer to piles preventing the chloride ingress, before the inspection is carried out on the piles, the surface preparation is carried out to access the piles surface, the limitations faced during the surface preparation is that the employed commercial diver is not well educated about the depth of cleaning which increases the preparation time for inspections.

Sonar provides the image irrespective of the water low visibility but faces a versatile number of limitations such as high-water currents making it hard to deploy the head, marine growth which redistricting the waves from hitting the surface of the pile, depth is a more crucial aspect as very deep deployment will affect the quality of the image and shallow water will present deployment issues.
Sonar is very reliable to detect scour, which is difficult for divers to inspect and detect as the diving depth restrictions.

Divers use tactile methods to touch and feel the surface of the pile, to assess the level of abrasion and freeze thaw and measure the widths of exciting cracks, certain optical equipment's such as cameras and video-cameras are employed via the divers and face the similar limitations as the divers.

Implementation of visual technology such as ROV's very feasible, as they have unlimited power and can acquire data through the inbuild sensors and camera these machines are controlled from the shore deployed into the water with a power cable from the surface transmitting real time through tether.

Regarding the other testing equipment's rely on the diver's capabilities to understand the instruments operations and uses.

As disused in the chapter 3, a combination of divers and optics systems are used as the best optimal inspection method. Divers inspect the pile in a circular motion starting at the top moving down, if the visibility of water decreases the diver as to inspect the same pile repeatedly to get accurate results it is the same procedure is followed while using ROV's.

9.2.1 Port of Gothenburg (GÖTEBORGS HAMN)

The interviews conducted with Ali Reza Mohammad Zadeh, Technical Manager at The Port of Gothenburg, it was brought to notice that despite the technological advanced equipment's that are available, yet experienced divers have been employed, who have assumably acquired the knowledge that is required to assess and complete the inspection.

The divers rely on the tidal conditions, visibility and tactile methods to view the structures, which limits their employability. Any other equipment's that are used like cameras or video cameras also depended on the diver's condition.

In order to study the mud profile, sonar barometry is employed every five to six years to estimate the load carrying capacity of the piles, this inspection is not carried out regularly due to economic reasons, when compared even employing divers are expensive.

9.3 Current Repair Methods

Pile jacketing system is a conventional retrofitting repair method which currently employed in many repair processes, this process is very time consuming, and the finished product may provide satisfaction in terms of visual appearance but will not ensure future deterioration nor provide any evidence about the ended process corrosion of reinforcement before the repair.
There's are several future complications which needs to be addressed in this method of repair.

During the repair process the jackets are bound together by a clamping system or are bolted together to hold the provided reinforcement, but still providing minute space for moisture, vapor and salt to enter resulting in complications in the future and giving way to more repair making it unsustainable and unreliable method of repair for submerged structures.

9.3.1 Port of Gothenburg (GÖTEBORGS HAMN)

At the Port of Gothenburg, the conventional repair methods such as jacketing and pile replacement are currently employed, even though these methods are unreliable when thinking about the futures repercussions they are still followed as these methods will still provide ample chances for routine inspections of the surface, yet there is still no evidence provided and found about the repaired members not showing ongoing corrosion and deterioration

9.4 Use of FRP

The FRP is an emerging solution opted to repair many structural members, these composites can be engineered to provide the required strength to withstand the axial and bending forces acting on the structure. FRP is very reliable when time is an essence and during emergency.

Due to the environmental restriction in certain countries glass fibres, aramid fibres and epoxy resins cannot be employed as a suitable repair material.
Carbon fibre polymer is a very suitable method that could be employed, but with an uninterrupted connection to steel reinforcement will lead to corrosion injury to the surface leading to failure of the structure, it has been described in many literatures that these materials possess good long-term durability, but these materials are new comparatively to concrete and masonry, but there is solid evidence to verify the claim.

Handling of these materials needs to be carried out carefully in an exposed environment has it could lead to serious injuries to the user, these bonding agents rely on temperature and moisture not sure how would the process of application be carried out in the open marine environment.

Cost is very curial aspect of fibre repair products; the materials are very expansion compared to conventional building materials and as opposition to change from conventional methods is very hard to overcome in the construction world. While looking at the comparative time consumption with using the conventional pile jacketing systems, using FRP wrapping is more of a simpler solution in considering time, long-term durability and serviceability including estimation of future repair cost.

9.5 Reduction of Loop Process and Case Study

The literature review conducted on A.I implementation provides us the basis on how we could be implementing such machine learning to optimise the process of inspection with the help of ROV's, the visual data obtained can be used to implement machine learning with image-processing algorithms to assess the piles conditions. Machine learning has been a booming field which has been used or altered to the users' choices as the case studies have showed, their use in the underwater inspection has been less due to the lack of proper training data needed to teach/ train the network to obtaining proper data required, this is achieved by human operations as adequate information needs to be manually added that are available in the real world. This high-cost process of tedious work process tend puts seekers out of interest.

The low visibility conditions of the water reduce the ability of the camera, which needs to be a curial point that the inspector needs to understand before to enhance the performance of the algorithm. Even thou image enhancement can be employed but are not reliable enough to identify the damage undergone by the structure. The inspector may come across a thought about how reliable this method is, the only answer that can be provided is that this visual data must be an aiding tool in the inspection process and repair planning process.

10 Final Remarks

Though the conclusion is provided at every section under concluding remarks, now the conclusion for the thesis is followed by suggested future studies and recommendations.

10.1 Summary

Globalisation has led to more shipping in the world, the increase in use of the harbours has increased the demand to maintenance of the structure to provide more usability. As many of these harbour structures are built during the 60's and 70's, they have been exposed to prolonged hash environment and damage, constant maintenance and repair is must and with time being very curial in this money run world and with the clients growing impatient with the consumption of time during the repair period. An optimised method of inspection and repair is a very much necessary to ensure and maintain good structural integrity, durability, and earnest reduction of long-term risk & cost.

10.2 Future Studies and Recommendations

In the recent times there has been a lot of developments and advancements in the inspection and repair in the onshore construction, yet the progress is slower in the underwater inspections, more research needs to be carried out to overcome the limitations faced by divers.

The use of A.I in inspection and monitoring structures have been drastically implemented in the recent years during post processing but research must be carried on How the use of current high-tech technologies and AI can be used to reduce the inspection time.
A few thoughts on research

- AI to process images on real time
- Program the visual module of the drone to detect changes / damage
- Reduce the processing time of the system by training and using a larger dataset

Future recommendations looking into FRP usage would be to conduct experiments on

- Check the durability of the FRP wrap in marine exposure
- How to check the rate of corrosion and surface deterioration after wrapping
- Resistance of the wrap against wear and tear caused by the moving waves

The industry must overcome these opposition to change and adopt new methods of inspection. a lot of the above shore methods, archaeological inspection technology to the underwater inspection methods.

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