Buildings construction in aquatic environment

Extended abstract of the MSc dissertation in Civil Engineering

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1 - Introduction

The construction of buildings in aquatic environment holds a vast set of particularities and difficulties that demotivate their execution. Corroborating these difficulties is the fact that there are still few examples of this kind of structures, although it is easily perceivable the impact that their existence could have in areas like tourism. However, a deeper study demonstrates that, at least to a large extent, these difficulties are surmountable with the existing materials and technologies.

The problems linked to the execution of buildings in aquatic environment are, innumerable times, of the same kind of those found in other types of structures, differing only in the requirement level. This means that in underwater buildings, some common problems are taken to the extreme level (durability, maintenance, monitoring, pressure, etc.). It also means that the acknowledgement of the adequate solutions to these problems helps to act efficiently in situations where the same problems are found, but to a smaller scale.

This thesis has the purpose of congregating some of the problems regarding construction in aquatic environment, to understand them adequately and to study satisfactory forms to mitigating them.

- The first theme is <u>reinforced concrete durability</u>. It starts with the definition of a set of aspects related to durability, especially regarding steel corrosion and impermeability. After studying the proper technical regulations (as EC2) and identifying the problems related to the aquatic environment, solutions are proposed, including several new materials and construction techniques. This chapter ends with information concerning monitoring and repairs.

- The second theme is <u>scour around the building</u>, due to water movement. Necessary concepts to the understanding of the scour phenomena and methods to estimate the involved depths are presented, in diverse environments: off-shore, river and estuary. A particular document is considered, the HEC 18. The effect of the building shape is studied.

- The third theme refers to the <u>structure of the building</u>, specifically its ability to support the requests that the aquatic environment generates. The analysis is made globally (considering the resultants of forces), but also locally (considering the surface pressure produced by water). The influence of the geometry is studied again. This chapter ends with the study of the visibility towards the outside of the building, explaining how big aquariums function (Lisbon's *Oceanário* is particularly referred), and with a possible construction method, developed considering bridge construction methods.

- The final chapter indicates a few <u>places in Portugal where buildings could be built in aquatic environment.</u>

During the text, whenever calculations or comparisons regarding the shape effectiveness are made, 4 different building sections will be used (circle, square, rectangle and ellipse). All of them fulfill the requirement of presenting the same area

($491m^2$), equivalent to the circular plant with a diameter of 25 meters. The sections' dimensions are:

- Circle: 25m diameter
- Square: 22.16m side
- Rectangle: 12.3m x 38.37m sides
- Ellipse: 17.68m x 35.36m sides

2 - Reinforced concrete durability

2.1 - Concepts

The degradation mechanisms studied in this chapter are those who were considered to be potentially harmful, under special conditions:

- Chloride penetration
- Carbonation
- Erosion
- Chemical attack
- Biological attack

The acknowledgement of the mechanisms that lead to concrete degradation, as well as knowing which are the environment´s characteristics that help them, is essential to the correct selection of the mitigation measures. This way, some concepts related to the durability of reinforced concrete must be understood, and are summarized in the next lines:

2.1.1 - Porosity

Porosity is the measure of emptinesses in concrete. Since it does not take into account the continuity and dimension of those spaces, it is not directly representative of the permeability to aggressive agents, but it is still strongly correlated with it. There are several kinds of porosity:

- macro-pores
- capillary pores
- gel pores
- Aggregates pores

They are described in the dissertation. In order to reduce the porosity of the concrete, a correct placement, compacting and vibration is necessary, together with a low water/cement (w/c) ratio. The use of superplasticizers allows drastic reductions, making it possible to obtain high-quality concretes with w/c ratios quite inferior to 0.40. High periods of curing are also recommended, so that the extent of hydration processes on the cover concrete is relevant.

2.1.2 - Mechanisms of Transport

The motion of aggressive substances inside the concrete can be given, essentially, by the following mechanisms:

- Permeation: entrance of liquids or gases by pressure. Only relevant at great depths;

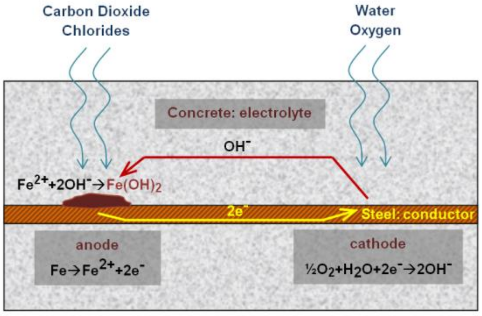
- Absorption: entrance of liquids by capillary suction;

- Diffusion: movement of water-vapor, gases or ions, due to the difference of concentration between the exterior and interior of concrete.

2.1.3 - Steel corrosion mechanism

Because of the existence of a great amount of hydroxides (especially calcium hydroxide) in the cement, concrete pH is alkaline, generally between 12.5 and 13.5. Inside this alkaline environment, the steel generates a protective oxide layer that makes the corrosion irrelevant. It is said that the steel presents a passive behavior.

The destruction of the protective layer and steel's consequent depassivation occurs when pH goes down below 9 to 10 (generally because of carbonation), or when a high chloride concentration (named critical) is reached. The depassivation enables the beginning of corrosion, according to a process equivalent to a battery:



Corrosion mechanism

- The depassivated regions become the anodes, where the iron dissolution occurs;

- Electrons move through the steel to regions with access to oxygen, which are the cathodes;

- Concrete is the electrolyte, and the moisture allows the migration of OH^- ions, generated in the cathodic region, towards the anodic region;

- The iron ions combine with the hydroxides, forming iron hydroxide.

All the previous points must be fulfilled for corrosion to exist. Therefore, depassivation isn't enough. If concrete has low moisture, its high resistivity disables ions' movement; if saturated, then oxygen doesn't reach cathodic areas. Therefore, higher corrosion levels usually show up in splash areas.
Besides iron hydroxide, several other products are formed, with much greater volume than iron (up to 6x). This justifies the habitual concrete cracking around corroded steel.

2.2 - Corrosion induced by chlorides

Chlorides can be found in concrete in 3 main forms:

- chemically bonded;
- physically adsorbed in the pores' surface;
- free, in the pores' solution.

Only free chlorides are harmful to steel bars. As the measurement of their concentration is complex, it is usually replaced by the measurement of total chloride concentration. In Portugal, EN206 indicates the value of 0.4% as the critical limit of total chloride concentration in reinforced concrete, and 0.2% in pre-stressed steel.

2.3 - Carbonation

The penetration of CO_2, by diffusion, leads to the reduction of concretes' pH, as it transforms hydroxides into carbonates, namely calcium hydroxide into calcium carbonate.

Carbonation is controlled by CO_2 entrance in concrete, so high levels of moisture brusquely reduce the diffusion of this gas and, consequently, carbonation. Consequently, carbonation is more obvious in sheltered places or in low permeability surfaces. However, given these places' low relative moisture, concrete resistivity is high, conditioning corrosion speed. This is why surfaces exposed to outside environment are more propitious to steel corrosion due to carbonation than protected ones.

2.4 - Erosion

Water and air containing solid particles in suspension (as sand) lead to the erosion of concrete surface, degrading its look, reducing covers, increasing the rugosity and consequently rising the easiness for seaweed and other living beings to prosper.
To prevent high rates of erosion, concrete must have good quality and an acceptable amount of aggregates. As curing is a basic process for the surface quality, EN13670 recommends that the period of curing is extended to twice the usual one, when concrete is subjected to erosion. Another method to increase surface resistance consists in the application of surface hardeners.

2.5 - Chemical attack

Sea-water contains about 35 grams of salts per liter of water, especially chloride and sodium. Chloride is the most aggressive ion, and its study has already been made in 2.2. The importance of sulfates in fresh water is reduced, except for situations of high concentrations, as potentially next to intensive agricultural explorations.
Another important chemical reaction is the so-called alkalis-silica reaction. The existing solution in the concrete pores contains sodium and potassium, which react with some existing forms of silica in aggregates, generating silica-alkaline gel. This gel swells in the presence of water, leading to cracking and premature degradation. The most efficient methodology to prevent this problem is to choose non-reactive aggregates, but it can also be avoided by the waterproofing of concrete surface.

2.6 - Biological attack

Seaweed accumulation or other living creatures (namely clams) can degrade the structure, not only from the aesthetic point of view, but also because of the increase in cracking. The development of microorganisms can also lead to the formation of humic acid, which attacks the cement paste. Apart from special situations, this kind of attack has little relevance when using good concrete.

2.7 – Exposure classes

The choice of the proper classes of exposure is not a simple task, when concerning buildings inside aquatic environment. It is assumed that one is dealing with maritime environment, therefore much more aggressive than fresh water environment.

EN206 indicates that when one of the surfaces is immersed in sea water and the other one is exposed to air (as tunnels), they should be classified as XS3.

On subaquatic construction, the impermeability of concrete assumes a relevant position. So, reasons are given in the dissertation to show that maybe this is a harsh classification. Nevertheless, the difficulty and maintenance costs require that corrosion risks are minimized, so the hypothesis of adopting bigger covers than the ones prescribed should not be discarded. That is a healthy option, especially when the environment classification is not obvious.

The XC classification (concerning carbonation) is irrelevant when the building is in maritime environment. The prescriptive measures for each class of exposure are presented in the dissertation, according to the EN206 indications.

2.8 - Options Analysis

The manufacture of very low permeability concrete is possible, nowadays, given the evolution in materials.

Generally, a concrete is considered to have low permeability when it has a coefficient of permeability lower than 10^{-12} m/s. Much inferior values can be achieved and the problem of impermeability can be easily solved by the use of good quality concrete.

Some addictions like silica-fume or latex allow less permeability and greater resistance to the penetration of chlorides. For aquatic environment, the recommended cement is CEM IV (pozolanic). Although the quality of concrete is a major factor in low permeability and corrosion control, there are always defects and some places (like joints) that are more susceptible to degradation, so it's probable that maintenance procedures will have to occur. In order to delay these operations, as far as possible, complementary measures should be taken, applicable globally or locally to the building.

2.9 - Methods to improve the quality and durability of concrete

2.9.1 - Controlled permeability formwork

Although it is desirable that cover concrete has good characteristics, in order to promote the structure's durability, it is recurrent to notice that this concrete has poorer characteristics than the inside one, becoming a weak barrier to the penetration of aggressive agents.

The compacting and vibrating process leads to the migration of air and water in excess to the border areas of the concrete element, where they accumulate, since the traditional formworks are impermeable or have low permeability. After hardened, the cover presents bigger porosity and w/c ratio that the interior.

Controlled permeability formwork intends to mitigate this problem, allowing the controlled exit of air and water, at the same time it blocks the exit of cement particles (promoting its accumulation in the surface). Typically, it is made with a flexible polymeric membrane, attached to the interior surface of the traditional formworks.

There are several benefits to the surface concrete, including lower porosity (hence lower permeability), lower w/c ratio, better curing, less retraction cracking and improved surface hardness.

2.9.2 - Stainless steel

Stainless steel is an interesting alternative to regular steel as it presents a much bigger resistance to corrosion. The league formed between iron and other metals (especially chromium), guarantees the mechanism of passivation even if the concrete doesn't have enough alkalinity or contains high

chloride concentrations. There are innumerable types of stainless steel, with different compositions, costs and corrosion resistances. The most relevant to construction are the Austenitic and the Duplex. Their critical chloride concentration can be up to 8 times the one in common steel. Typically, their prices are around 5 to 7 times the price of current steel, but the much lower costs regarding maintenance may be able to widely compensate this initial investment.
The use of this steel might be important in critical places, like joints, as they usually present less quality, in places where cracking is expected to happen, or where concrete cover must be smaller.

2.9.3 - Superficial waterproofing

In large dimension structures, even if all measures are strictly followed, there will always be spots with waterproofing issues (as it happens in the majority of big aquariums). It's advisable to consider a waterproofing system, in order not to be necessary to totally trust the quality and homogeneity of concrete.
These products belong to two major categories: impregnation products and covering products.

- impregnation products act by coating or blocking the pores, due to their high fluidity, creating a protective barrier to the penetration of aggressive agents. They can be split into simple impregnation products and hydrophobic impregnation products.

- superficial coverings act by creating a protective layer over the concrete surface, and can be divided in 3 different types: paintings, mineral and mist mortars, and membranes.

- There are also the sealants, which penetrate in the pores but also form a superficial layer.

Some of these products can be applied underwater, like the APE system, consisting on a thick resin layer of epoxy and aggregates, hold within a mold.

2.9.4 - Cathodic Protection

It consists on the inversion of steel potential, in order to increase its electro-negativity, so that bars become cathodes of the corrosion reactions. This effect is achieved by low intensity electricity between the bars and a new anode (usually titanium strips). This method also increases the alkalinity around steel and helps expelling the chlorines.

2.10 - Monitoring

There are several methods to evaluate in real-time the risk of steel corrosion. In this dissertation, steel potential and concrete resistivity measurements, and the usage of corrosion cells are referred.

2.11 - Repairing

Repairing works in underwater buildings have greater difficulty than in usual buildings. A classical solution is the creation of a dry environment, involving the element. The classic cofferdam is not possible on a building, but chambers that attach laterally could be created.
Without being necessary to use such complex systems, companies specialized in subaqueous works use materials developed in special to be applied underwater, with high performance characteristics. Concrete addictives can also allow regular concrete to harden with less wash-out.

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3 – Scour

3.1 – Introduction

Scour results from water flow around the building. It is a subject of great importance in bridges and other aquatic structures. Granular soil is quickly eroded by water, while cohesive soil will be able to resist the process longer; however, final maximum depth can be equivalent in both kinds of soil.
Determining the magnitude of scour is complicated. The existing methods and equations are based mainly on laboratory studies, with relatively little amount of information obtained *in situ.* The variety of conditions (speed, dimensions, etc.) can be easily simulated in laboratory, justifying the importance of these studies to better understand the phenomenon and to create more complete models.
In this dissertation, *Hydraulic Circular Engineering* (HEC) recommendations were used.

3.2 – Scour types

Total scour around an element is considered as the sum of several types of scour:

- Degradation (opposite to aggradation), consisting in the slow alteration of the stream bed level, either by natural causes or caused by Man's influence;

- General scour, corresponding to a reduction of the stream bed level, generally due to the section's contraction, where the obstacle (building) is inserted;

- Local scour, corresponding to the removal of material from the stream bed around the obstacle, due to the acceleration and formation of vortices.

3.3 – Basic concepts

Scour can be processed with or without generalized solid transport: clear-water scour occurs when there is no movement of bed material upstream of the building. Live-bed scour occurs when there is transport of bed material upstream of the building.

Though clear-water scour is processed more slowly, it presents a more continuous growth and a final depth about 10% superior to live-bed's one.

In order to know which kind of scour exists in each situation, there are equations to calculate the critical speed, equivalent to the beginning of the material's movement, which depends on the average diameter of particles and flow height. Most situations correspond to generalized material transportation (live-bed), due to the particles' sizes (small) and relatively high velocities.

The balance depth of a scour cavity is reached when its dimension reduces the dragging tension to a value that allows the same amount of material to enter and exit the cavity (live-bed scour), or to the critical value (clear-water scour).

It is demonstrated, during the dissertation, that general scour has little important for situations where the occupied fraction of the river is reduced, whether or not there is generalized transport.

3.4 - Data obtaining

Before calculating the scour depth, it is necessary to know the topography and flow characteristics. Public organisms supply most of the desired information.

3.5 - Local scour

Local scour depends on several factors:

- characteristics of the stream bed material: granular or non-granular, cohesive or non-cohesive, erodible or non-erodible, etc;

- stream bed configuration: dunes, ripples, etc.;

- stream characteristics: velocity and depth, angle of attack (angle between the stream and the building);

- geometry of the building/foundations: shape, dimensions, type of foundations (columns and its diameter, number and distance, or footing);

Existing equations are usually formulated for sand bed without cohesion. They usually indirectly consider water velocity, through the inclusion of the Froude number. This number is expected to be substantially inferior to 1, in places where the implanting of a building could be considered, even during floods.

The equation recommended by HEC18 to calculate local scour is an adaptation of CSU equation (*Colorado State University*), valid both for clear-water and live-bed scour:

$$\frac{y_s}{y_1} = 2{,}0\ K_1\ K_2\ K_3\ K_4\ \left(\frac{a}{y_1}\right)^{0{,}65}\ Fr_1^{0{,}43}$$

Where:

- y_s Scour depth
- y_1 Flow depth upstream of the building
- K_1 Correction factor for building shape
- K_2 Correction factor for angle between the building and the flow (angle of attack);
- K_3 Correction factor for bed configuration
- K_4 Correction factor for bed granulometry
- a Building width
- Fr_1 Froude number upstream of the building

K values differ according to the author of the laboratorial tests, and some examples are presented in the dissertation.

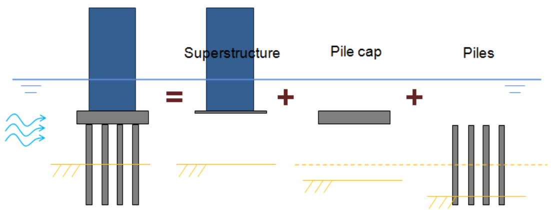
As scour depth equations over-evaluate scour around large elements, it is suggested another factor, K_w, obtained with indicated formulas. Even though, it is perceivable (through calculations and graphic observations) that local scour can easily reach substantial values, given the dimensions that a building might have.

Effective K_1 values are presented, when different shapes have the same area, so that a more realistic comparison can be done.

Generally, the most efficient method to reduce scour is to select an adequate building shape. It is also important to consider in calculations the real format of the building, taking into account that it is not a continuous element (the simple use of the CSU equation doesn't consider piles or pile caps).

3.6 - Complex foundations

HEC 18 methodology consists in calculating the generated scour per building item (superstructure, pile cap/footing and piles) and adding them. Each component calculation is affected by the previous ones, as the level reduces at each calculation step.



HEC18 methodology

The CSU equation is always used, given the correct adjustments, which makes this process simple.

3.6.1 - Superstructure scour depth component

A new factor, $K_{h\ building}$, takes into account the initial elevation of the building. It also considers the protective effect generated by a hypothetic salience (the pile cap can be wider than the building, so it reduces the vortices action), but this effect is almost negligible. The expression meant to calculate this factor is presented in the dissertation.

If the bottom of the superstructure is at the initial bed level, there's a valuable effect that reduces superstructure scour to only about 41% of the expected scour in a continuous element with the same shape.

3.6.2 - Pile cap scour depth component

There are two possible cases, which require different approaches.

- Case 1: The bottom of the pile cap is above the bed, either in the beginning or after superstructure scour is taken into account: The strategy consists in converting the pile cap width into an equivalent width of a continuous element.

- Case 2: The bottom of the pile cap or footing is always below the bed level: The strategy is to treat the pile cap (or footing) like a short pier in a shallow stream.

Either way, graphics and equations are provided to solve these problems.

3.6.3 – Pile group scour component

To determine this scour component, the angle between the flow and the pile group shape must be verified, so that the most influent piles are selected. A simple method is described in the dissertation. The following steps are:

- projection of the influent piles onto a plane normal to the flow;

- determination of the effective width of a superstructure that would produce the same scour, considering pile characteristics (diameter, number, distance between alignments);

- adjustment of flow characteristics, after considering scour produced by superstructure and pile cap;

- determination of $K_{pile\ group}$ factor, based in the height of the piles' exposure to the flow.

Each step requires expressions that are presented during the corresponding topic of the dissertation.

3.6.4 - Analysis of results

The consideration of the correct building shape can reduce scour to quite acceptable levels. Calculations made for hypothetical cases have given final scour depths of about 57% of continuous elements scour.

3.7 - Scour analysis in tidal areas

Next to the coast are found most of the best places for aquatic environment construction, as estuaries or bays. These are places whose hydraulic characteristics are usually controlled by tides, not floods. The analysis of this kind of problems starts by getting information, as the tidal magnitude, and the verification (when a river is also present) if whether scour will be conditioned by the tide/storm, river flood (usually far away from the coast) or both (when the river can provide significant flow, that competes with tidal flow). A special particularity regarding tidal scour is the fact that water movement will occur in both directions, depending if it's high or low tide. One could think that scour would be eliminated each time water changes its direction, but actually it can progressively increase. All of this offers a new set of difficulties, but approximate expressions to determine corresponding flow are available in the dissertation, and may then be inserted in the CSU equation.

These expressions vary whether or not the inlet (connection to the ocean) is narrow (existence or not of constriction). Generally, bays can be classified as constricted and estuaries as unconstricted.

3.8 - Coastal areas

The big difference to protected areas is the effect of local streams and undulation. The calculation of scour in sea requires the definition of a new variable, the Keulegan-Carpenter number. Studies indicate that scour in maritime environment is almost negligible in elements of great dimensions (with reduced numbers of Keulegan-Carpenter), generating scour depths inferior to 18% of the building width.

3.9 Laboratory models

Although the existing equations supply a good estimative of scour depths, in more complex situations it is always recommendable the execution of physical models, in order to optimize the structural solutions. The model scale must have the same Froude number, in order to keep its characteristics.

4 - Structure

4.1 - Effect of the stream speed

Total water pressure is equal to the hydrostatic pressure γh, plus the dynamic term. This term can be interpreted as an equivalent water column, added to the static water column. In order to estimate its importance, several considerations must be taken into account:

- velocity is not constant; actually it follows approximately a logarithmic curve, decreasing in depth. So, the maximum hydrostatic pressure corresponds to the minimum dynamic term of total pressure;

- if the building presents a hydrodynamic shape, water isn't blocked against its walls, so the generated dynamic pressure can be smaller (it depends on water's speed variation);

- maximum velocities available in places adjusted for the construction of underwater buildings, even during floods, are relatively reduced.

Considering this information, and after presenting a simple calculation, it is perceived that the importance of the dynamic term is reduced when compared with the hydrostatic term.

4.2 Global effect of water pressure

There are three orthogonal resultants:

- Impulse: ascending vertical force, equal to the weight of an amount of water with the same volume as the submerged part of the building.

- Resistance: dragging force, parallel to the stream direction, generated by the resultant of contact forces that moving water produces in the building.

- Sustentation: Horizontal force (but perpendicular to the stream), generated by this direction's dynamic pressures. If the section of the building is symmetrical to a plan parallel to the stream, it doesn't exist. This force is more relevant in aerodynamics, and is named after the sustentation effect of airplane wings.

Impulse is easily calculable, but the same is not valid in the others two resultants, as they would depend on the knowledge of pressure in each point (including the effect of turbulence). This way, its calculation is generally done experimentally, or using listed resistance (C_R) and sustentation (C_s) coefficients, also obtained experimentally. These coefficients depend on the Reynolds number.
Resistance coefficient multiplies the dynamic pressure term and the projected area of the building.

After simple calculations, it is observed that impulse isn't equilibrated by the building self-weight, if it is totally underneath water, except if a massive amount of concrete is poured into its piles cap. The construction of several floors above water level can avoid this method, but another solution consists in dimensioning the piles to resist traction forces. As lateral friction is relevant in piles, this is a relatively used solution. The dragging force effects (shear cut in foundations and global moment on the building) are easily resisted, calculations demonstrate.

4.3 - Influence of shape in generated stresses

As already observed before, the building shape is one of the key factors when projecting a building inside water. More hydrodynamic shapes can reduce scour, dynamic tensions and resistance force, but will be more difficult to execute and could be less efficient in the distribution of hydrostatic tensions (arch effect in the circular section is better than in the ellipsoidal section, for example). Using *CSI SAP2000*, a study has been developed to understand the difference between the 4 studied sections.

It is usual, when dimensioning water tanks, to define the cracking moment as the maximum allowable moment, when considering characteristic values of pressure and material properties. It helps improve waterproofing and durability. This condition usually allows ultimate limit states to be verified easily.

If in a tank it is easy to perceive which one is the biggest possible water height, in a waterway this parameter depends on statistical values. It is supposed, however, that the condition of non-cracking should be guaranteed at least to flows with a rare period of return.

The calculations and produced models were meant to study the viability of low thicknesses in the exterior walls. Values of 30cm and 40cm were considered, but the results indicate the necessity to guarantee a thicker wall bottom, usually around 55cm, to resist without cracking the high moments generated by water pressure.

The effect of intermediate slabs (which act as supports) was considered. Different effectiveness was found on the studied shapes, with or without the middle slabs. Generally, the circular section is the most efficient, as expected, due to its way of equilibrating the pressure (low flexion but significant arch effect). As the walls are compressed by water, there isn't the regular traction force found in water tanks, so no vertical cracking is expected. It doesn't even need the support available by slabs. The ellipsoidal section comes next, requiring a bit more thickness (but it still has a relevant arch effect). Last place goes to square and rectangular sections, because they generally function only by flexion, so high moments are generated and are incompatible to walls that don't have the support of slabs or beams.

Nevertheless, if properly supported by slabs, square and rectangular buildings are also possible. Their thicker walls mean bigger weight, so these sections can even become a positive choice when trying to control impulsion by means of mass. Their construction can also be simpler.

The effects of openings are easily absorbed within the structure, and their influence area is reduced (a few meters away from the opening, structural elements don't show any differences). This means the pressure generated by the transparent panels can be absorbed by an independent frame, built mostly to stand these stresses. This frame, constituted by beams and columns around the openings, must have high stiffness, to guarantee small deformations in the joints between concrete and transparen panels.

4.4 Visibility to the outside

One of the great advantages in subaqueous construction is the possibility to contemplate the involving aquatic environment. In order to achieve it, transparent panels are necessary, and they must be able to deal with high pressures without having small dimensions. Many examples of these panels' application are found in Civil Engineering, especially in big aquariums. Their viability is guaranteed by the materials they are made of, usually acrylic. This material would allow about 70 MPa of tensile strength and is not fragile. Nevertheless, calculations are based on deformation issues, so much lower tensions are considered.

As important as the panel are joints. Generally, these places present great difficulty in waterproofing and durability for long periods of time. However, in aquariums, it is unconceivable to empty them to proceed to repairing. This way, high-quality materials are required. High performance silicones have been used, with excellent results.

The solution used on Lisbon's *Oceanário* is studied.

Acrylic has other advantages; for instance, it has high luminosity transmission, almost the same density as water (about 1.2), and less refraction than glass.

Theoretically, a building could be totally covered in acrylic, only with a structure providing its support, given the high resistance of this material.

Scratches can be avoided by the use of protective layers.

4.5 Construction methods

The construction methods for this sort of buildings can be adapted from the ones used in bridges.

Considering bridge foundations' construction, several techniques are used worldwide, but this dissertation focus on the ones that allow prefabrication. This way, concrete can be applied in better conditions and its surface is more easily protected by coatings. The explained method allows the assembly and connection of each level outside water, so that only minimal underwater works are performed.

5 - Possible places in Portugal

There are, worldwide, countless places where buildings could be inserted into water. Portugal isn't so prone to these perfect aquatic conditions but, given their characteristics, several places would probably allow aquatic buildings, and a few of them are referred and explained:

- Viana do Castelo;
- Alqueva;
- Setúbal, Tróia and Arrábida's coastline;
- Caniço, Madeira;
- S. Martinho do Porto.

The lack of luminosity can substantially diminish visibility, but an adequate study of artificial illumination can provide solutions to overcome this problem. Exterior lights might even have different tones, in order to create unique environments (a bright red sea, for instance).

When not totally clean, water can have its tonality corrected by the use of color filters, applied to the inside of the acrylic panels' surface.

6 – Conclusion

Several questions related to building in aquatic environment have been identified, and appropriate answers to these questions were found. Despite all the other unstudied important factors, the possibility of viability for these structures is real. As long as extreme environments aren't selected, unbearable costs aren't expected, because the studied problems have executable and usual solutions.