FOUNDATION OF THE FUTURE:

Pile Foundations of High-rise and Offshore Buildings

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ABSTRACT

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ABSTRACT

Urbanization, active lifestyle, and lack of space in capital regions drive people to build unusual structures or search for the valid space on the water. High-rise building and near-shore structures have become a good choice in such cases. The amount of such houses gradually grows every year. To ensure the stability of such structures engineers around the whole world attempt to solve some issues with the infrastructure – one of the most significant part of any structure. Pile foundation is an appropriate decision nowadays. However, the basic design should be modified dramatically and needs an unusual solution. Thus, piling engineering has progressed over time.

This thesis describes the basic design and some unique foundations of high-rise buildings and offshore or nearshore structures with the reasoning for their implementation. Meanwhile, the aim of the research work was to represent essential points of pile foundation for apartment buildings and offices within cities, evaluate the future possibilities and give room for the development of such foundations.

The result of investigation and comparison of built structures highlights the importance of further evolution in piling engineering, high-rise and off-shore structures, the directions for its research and innovations under research. However, the key ideas for infrastructure of the house should be reviewed and investigated more.

Keywords Pile foundation, high-rise buildings, offshore structures

Pages 62 pages including appendices 17 pages

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1 INTRODUCTION

Earth population is gradually growing day by day and, according to the United Nations' projects, the global population will reach 8 billion by 2024. At the same time more people move to big cities and capitals. UNDP research has represented the statistical analysis of urban growth and stated that by 2050 two-thirds of all humanity will be urban (UN news, 2018). Thus, the hectic lifestyle and fast rate of development attracts potential employees and young people to significant scientific and labour points. They need places to live and work, and it leads to city expansion. Sometimes cities increase in size so much that they merge with the neighbouring administrative units to form the metropolis.

However, the land is limited, and government cannot stop the process of urbanization. The solution is completely simple: more apartments and offices on smaller territories – high-rise buildings. Additionally, some engineers and scientists have started to think about the expansion towards the sea – marine structures. Nevertheless, there are huge disputes over the sustainability of such buildings.

From one point of view, such structures can require more human and material resources as well as have higher embodied and operating energy. Moreover, there is a possibility of interference with nature and its creatures (e.g. tides, fish, birds, etc.). Another opinion is represented by Dr. Anthony Wood and Peng Du (2017), Executive Director of the Council for Tall Buildings and Urban Habitat. In their complex study buildings were considered with other factors and infrastructure requirements. That research has shown that high-rise urban development requires 5-10 times less road and energy infrastructure.

Sustainability of marine structures is a more complicated question. Nevertheless, humanity will continue to use offshore space for oil and mineral extraction and erection of wind turbines. That is inevitable at the moment. It is also possible that with further development people start to construct more offshore residential buildings.

Listed facts reflect a tendency to trust such designs and, therefore, build and improve step by step high-rise and marine structures. Widely known, that one of the most important parts of any building is a foundation bearing the whole load of the superstructure above it. Basic and universal solution for such infrastructure is a pile foundation, which is gaining more and more popularity due to its characteristics and variety. Moreover, it is a suitable solution for different soil types and weather conditions.

Nowadays steel piles are used worldwide for tall buildings and, especially, for structures above the water or in humid climates. Although there is a huge range of products on the market, there is always a room for development.

2 BACKGROUND

2.1 High-rise buildings

From early ages people have had the tendency to live in a group; and the further development went, the bigger groups became. The density of population in the settlement and conditions of life demand a lot of apartments in a limited space. The prototypes of high-rise apartment buildings already appeared in ancient Rome, where tall buildings, known as insulae, could reach up to 10 or even more floors (Aldrete, 2004, pp.78-80).

However, the definition and parameters of high-rise buildings have varied over time. For example, medieval cities were protected by walls and tall towers that could also be considered as high-rise structures. Technological inventions (elevators, electricity, ventilation system, etc.) and development allow buildings to ‘grow’ higher. The heyday of high-rise engineering has come in the 20th century. (see Appendix 1)

According to the regulations, a structure can acquire the status of a high-rise building in case the total height reaches 75 meters and more or the amount of floors exceeds 17. In Finland 18 buildings meet these criteria (Appendix 2), only 3 of which belong to Tampere, while others – to capital region. The tallest tower at that moment is Majakka in Helsinki, 134 meters high.

2.2 Offshore structures

It is difficult to say, when population of Earth began to build stable constructions above the water. People could build bridges, piers and stilt structures already in antiquity. Moreover, some families have lived in floating houses such as in the Netherlands. “Amsterdam, founded about 1000 years ago, was built almost entirely on piled foundations of 15-20 meters length” (Fleming, Weltman, Randolph & Elson, 2009, p. 2).

Structures located above the water or only partly on the ground started to develop actively only in the middle of 20th century. Mostly they are connected to petroleum industry or wind turbines. However, recently engineers have begun to design projects with residential apartments above the water around the world.

2.3 Pile foundation

This type of infrastructure of building is considered as deep foundation, where ration of depth to width is bigger than 1 (Kameswara, 2011, p. 564). Such foundation is needed in case of huge loads, which soil at shallow depth is unable to support. Piles, the main element of deep foundation, were used for various purposes for many years. Mainly ancient population utilize wood piles in construction of bridges, stilt houses, and retaining walls or fences due to the preferable location next to lakes, rivers, and other water resources (e.g. in Switzerland, Scotland, Italy, etc.). Timber spiles were installed by hand and hammer. People dug pit, placed pile and after covered the left holes with sand and stones.

Later the process of pile mounting became easier: the early mention of pile driver was found in Francesco di Giorgio Martini's treatise “Trattato di Architectura”. According to that source (Reti, 1963, pp. 287–298), pile driver appeared already around 1475. Steam power had been introduced in Britain by John Rennie in the beginning of 19^{th} century. Due to changes in technologies and in terms of materials and power metal piles became available in the mid-1830s. They were casted in pipes from iron. Later, after invention of Portland cement by Joseph Aspdin and its popularization, engineers have started to use concrete piles for different structures. (Fleming et al., 2009, pp. 3-6).

With the development of engineering and mechanics various types of piles and equipment for them have begun to appear. Nowadays the most popular machines are piling rig, hydraulic hammer, and vibratory pile driver. Piles vary by materials and purpose of use, but can be broadly categorized as (EN 1997-1:2004, 7.1):

- End-bearing piles;
- Friction piles;
- Tension piles;
- Transversely loaded piles.

3 BASIC DESIGN PROCESS FOR PILE FOUNDATION

3.1 OVERVIEW

Foundation design is divided into 3 phases: preliminary design, detailed design, and final design. Nevertheless, the process for pile foundations can be described in 10 main steps (Kameswara, 2011, pp. 572-574):

1. Calculation of the total load acting on infrastructure considering loads for bearing capacity analysis and settlement analysis.

2. Examination of soil and sketching of the soil profile to a depth beyond the expected maximum length of piles.

3. Piles' type and length determination with alternatives.

4. Estimation of the pile capacity.

5. Design of pile grouping.

6. Check of stresses transmitted to lower strata.

7. Structural design of piles and pile cap.

8. Settlement analysis of the pile group.

9. Check of the uplift pressure and lateral load capacity.

10. Verification of the design and test planning.

The design of foundation itself is dependent on the superstructure. It is assumed that all loads from superstructure shared by piles in the group in proportion to their cross-section area. Thus, obviously number of piles and their location are selected in accordance with axial and lateral loads that the pile or pile group should cater for. However, the primary design is based on initial guess and a set of heuristics inherent. (Kameswara, 2011, pp. 645-652)

The effects of actions due to transverse forces should be considered in combination with effects due to axial forces and applied moments. They can be evaluated separately or in combination, taking into account soil capacity and characteristics. The transmission of torsional moments can be neglected unless there is a special design which assumes the introduction of the torque into the soil. (EN 1993-5:2007, 5.3.2)

Basically, for the design safety all ultimate limit state load cases and load combinations should satisfy the following inequalities (EN 1997-1:2004, 7.6.2.1 & 7.6.3.1):

In compression $$F_{c;d} \leq R_{c;d} \quad (1)$$

In tension $$F_{t;d} \leq R_{t;d} \quad (2)$$

Where $F_{c;d}$ stands for design axial compression load on a pile or group of piles, $F_{t;d}$ – design axial tensile load on a tensile pile or a group of piles;

$R_{c;d}$ is design compressive resistance of the ground against a pile, $R_{t;d}$ – design value of a tensile resistance of a pile or a group of piles.

In general, design structural strength, as well as design geotechnical strength, should be more or equal to design action effect or factored load combination.
In case of serviceability, maximum computed settlement of foundation and local angular distortion should not exceed allowable values.

3.1.1 Single pile with axial load

The axial load on a pile is derived by the expression:

$$P_{zi} = \frac{P_z A_i}{\sum A_i} \pm \frac{M_x y_i A_i}{I_{xx}} \mp \frac{M_y x_i A_i}{I_{yy}} \quad (3)$$

Where $\frac{A_i}{\sum A_i} = \frac{1}{n}$ (4) , if A_i is the same for all (n) piles in the group, and thus

$$P_{zi} = \frac{P_z}{n} \pm \frac{M_x y_i A_i}{I_{xx}} \mp \frac{M_y x_i A_i}{I_{yy}} \quad (5)$$

Hereinafter: $\mathrm{P_{zi}}$ is the axial load on the i-th pile;
$\mathrm{P_z}$ is the resultant of all the vertical loads;
$\mathrm{M_x}$ and $\mathrm{M_y}$ are the resultant moment about x and y axes respectively;
$\mathrm{A_i}$ is the cross-section area of the i-th pile;
$\mathrm{I_{xx}}$ and $\mathrm{I_{yy}}$ are the moment of inertia of the pile group about x and y axes.

The distribution of stresses may be taken as constant over the length of the pile, except in the case of negative skin friction.

The determination of the characteristic pile resistance is based on empirical values, static and dynamic pile load tests, and soil mechanical methods. The settlement dependent pile resistance $R_c(s)$ includes pile shaft $R_s(s)$ and base $R_b(s)$ resistances (Equation 6).

$$R_{c;k}(s) = R_{s;k}(s) + R_{b;k}(s) \quad (6)$$

Based on the result of characteristic pile resistance in Equation 6 and partial safety factor γ_t , the design value $R_{c;d}$ can be determined and implemented into the Equation 1.

$$R_{c;d} = \frac{R_{c;k}}{\gamma_t} \quad (7)$$

The same idea can be applied for design value of a tensile resistance of a pile:

$$R_{t;d} = \frac{R_{t;k}}{\gamma_{s;t}} \quad (8)$$

Where $R_{t;k}$ refers to characteristic pile resistance in tension and $\gamma_{s;t}$ is a partial safety factor of the pile skin resistance.

For abandoned piles in soft soils under pressure, the safety against buckling should be verified if the undrained cohesion is $c_u \leq 15\, kN/m^2$.

3.1.2 Single pile with horizontal force

The lateral loads coming on a pile along horizontal axes can be calculated by following equations:

$$P_{xi} = \frac{P_x A_i}{\sum A_i} - \frac{M_z y_i A_i}{I_{zz}} \quad (9)$$

$$P_{yi} = \frac{P_y A_i}{\sum A_i} - \frac{M_z x_i A_i}{I_{zz}} \quad (10)$$

Therefore, the resultant horizontal load can be expressed as:

$$P_{hi} = \sqrt{P_{xi}^2 + P_{yi}^2} \quad (11)$$

Hereinafter: $\mathrm{P_{xi}}$ and $\mathrm{P_{yi}}$ are the lateral load on the i-th pile in x and y directions;
$\mathrm{P_x}$ and $\mathrm{P_x}$ are the resultant of all the horizontal loads in x and y directions;
$\mathrm{M_z}$ is the torsional moment about z axis;
$\mathrm{I_{zz}}$ is the torsional moment of inertia of the pile group.

According to regulations, piles with a diameter equal to or more than 0.3 m and with a length equal to or more than 0.3 m can be implemented in a foundation system to carry horizontal loads.

There are different approaches to estimate the lateral capacity of a pile. Main of them are:

1. Conventional statical approach
   The application of this method is Brom’s theory (1964)

2. Subgrade reaction approach
   The method is based on the assumption that soil reaction is proportional to pile deflection.

3. $p - y$ curves (represented by Tomlinson in 1977)

It represents the soil deformation at any depth for a range of horizontally applied pressure.

4. Characteristic load method (represented by Duncan, Evans & Ooi in 1994)
   This solution takes into account soil response to a lateral load.

5. BEF or Beam on elastic foundation approach
   It was described by Vlasov and Leontev in 1960 as a beam analysis method, but lately has been adopted for pile.

3.1.3 Efficiency of a pile group

The group of piles are usually arranged in raft pile foundations. Therefore, with assumption that the raft slab behaves as a rigid element, the axial load on a single pile $E_{i;k}$ in the group can be derived from Equation 12.

$$E_{i;k} = \pm\frac{\mathrm{V}}{\mathrm{n}} \pm \frac{M_y}{\sum x_i^2} * x_i \pm \frac{M_x}{\sum y_i^2} * y_i \qquad (12)$$

Where V is a vertical impact load on the foundation and n number of piles, meanwhile M_y and M_x are bending moments.

The design of tension piles group depends on the case and can be defined by regulations according to the project needs. However, it is recommended to convey analysis of the safety against uplift and buoyancy of subsoil block. (Katzenbach, Leppla, Choudhury, 2017, pp. 80-88)

Due to the group interaction, the capacity of the group of piles should be smaller than n times the lateral load capacity of a single pile or lateral capacity of a similar single block. The same principle can be applied to axial capacity of a pile group. However, there are several formulas for reduction factor:

1. Converse-Labarre formulae (Poulos & Davis, 1980)

$$\eta = 1 - \frac{\varsigma\left[\frac{(n-1)m+(m-1)n}{mn}\right]}{90} \qquad (13)$$

Where n is a number of rows of piles in the group;
m is quantity of columns of piles;
$\varsigma = \tan^{-1}\left(d/s\right)$;
d is diameter of a pile;
s is spacing.

2. Feld's rule (Ramiah & Chickanagappa, 1984)
   The estimated capacity of each pile should be reduced by 1/16

3. Iyer's rule (was represented in 1995)
   Calculated total capacity is reduced by α.

$$\alpha = \frac{d}{8s} \tag{14}$$

All these methods are empirical with approximate calculations. (Kameswara, 2011)

3.2 HIGH-RISE BUILDINGS

The foundation of tall buildings depends significantly on some characteristics and facts. Due to huge loads from building weight, that increases non-linearly with height, ultimate bearing capacity and settlement should be considered carefully, soil profile and tests should be provided with great accuracy. Moreover, high-rise buildings are often surrounded by low-rise structures, which influence on differential settlements. A lot of attention should be paid to lateral forces imposed by wind loading or seismic actions (if applied). Such cyclic and dynamic loads can lead to degradation of capacity and increased settlements of foundation. Therefore, the effects of cycling loading from wind action on a tall building with the piled raft system should be considered and the design geotechnical shaft capacity must be reduced by ***η*** - a factor assessed from geotechnical laboratory testing. However, in most cases it can be taken as 0.5. (Poulos & Davids, 2005) Additionally, it is important to estimate ground movements in the projects, because they may have a twofold influence. This factor has to be considered in relation to serviceability requirements or in calculation of axial and shear forces with further influence on bending moment.

3.2.1 Aerodynamic Model Tests of Tall Buildings for live load calculations

As it was mentioned earlier, wind actions are crucial for high-rise buildings. Thus, complex load case calculations should be followed by an aerodynamic model test in an aerodynamic tunnel. (here and further Guzeev, Kornilov, Korotkin & Solovyev, 2015)

Determination of total and distributed aerodynamic loads.

Assessment of aerodynamic loads distribution is conducted by drain holes on the surface of the model. During the experiments, at each hole where the pressure is measured, the value of the pressure coefficient is determined:

$$Cp = \frac{2*(p-p_0)}{\rho*V_0^2} \tag{15}$$

Where p – the pressure at the determined point;
p_0 – static pressure in the flow;
ρ – the density of the air;

V_0 – the speed of the incoming airflow.

In that case the force acting on the structural element of S area will be:

$$F = w_m * S * Cp^* \quad (16)$$

Where w_m – the standard value of wind pressure at a height z from the ground level;
$Cp^* = |Cp_1| + 1$ and
Cp_1 – absolute value of the highest vacuum coefficient on the surface of the building.

Other tests and verifications, that should be considered:

- Investigation of possible occurrence of resonant oscillations;
- Identification of areas of snow accumulation;
- Searching for the solution to reduce or completely eliminate the negative impact of aerodynamic factors, etc.

3.2.2 Piled foundation

Although raft (Figure 1 a.) and compensated raft structures are acceptable solutions in various situations, with significant building loads it is common to integrate piles or pile groups (Figure1 b.) into the infrastructure. However, foundation of high-rise structure requires a large amount of piles and, thus, it is essential to consider the effects of the group interaction in the design. As mentioned earlier, the ultimate load carried by piles group may not be equal to the sum of the ultimate loads supported by each single pile in the group.

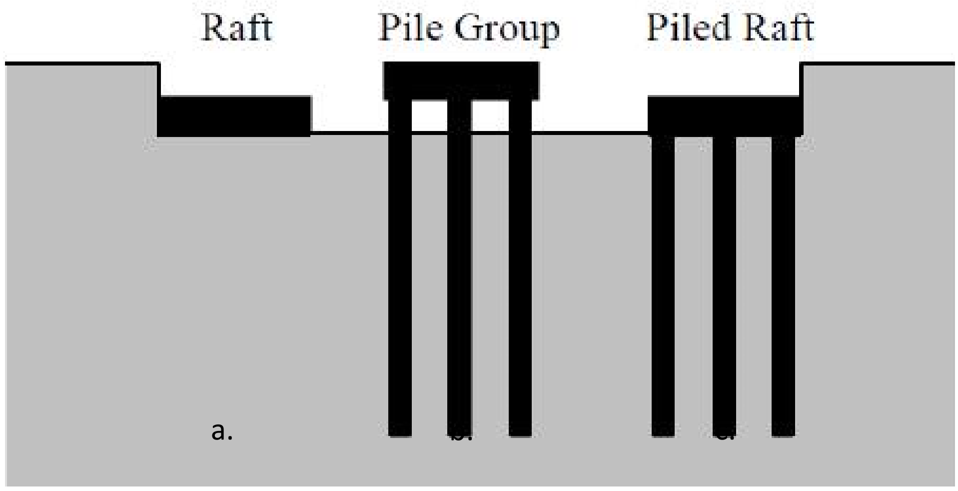


Figure 1 a.) Raft foundation; b.) Pile foundation; c.) Piled raft foundation (retrieved from Latin American Journal of Solids and Structures, 2019)

3.2.3 Piled raft foundation

To obtain an infrastructure satisfying both bearing capacity and settlement criteria, it is possible to implement the basement slab in conjunction with piles. That design idea is termed a piled raft foundation (Figure 1 c.). This is a common composite system for load sharing between structural elements: piles provide the foundation stiffness and raft – a reserve of load capacity. (Poulos, 2016). Therefore, such solution improves the efficiency of the foundation and leads to possible savings in materials and costs. However, there are favourable soil profiles for this structure such as soil consisting of relatively stiff clays or dense sands. The efficiency of piled raft foundation can be regulated by number of piles/pile groups and their configuration. According to Horikoshi and Randolph (1998), piles should be concentrated in heavily loaded areas, while the number of piles can be reduced or eliminated in places with less stress.

3.2.4 Compensated piled raft foundation

The design is based on stress reduction in the underlying ground caused by excavation of the soil. Soil profile and other conditions can influence a lot the order of actions and constructions process itself. In projects with shallow excavations piles can be installed beforehand, while greater depth of work requires pile execution after the excavation. (Poulos, 2016)

3.3 OFFSHORE STRUCTURES

Offshore engineering has developed as a result of the growing demand for recovery of natural resources and for conversion of renewable energy sources. It is the most popular purpose of such structures. Jacket pile structures are common for that industry. They are usually assembled on land and then transported to their final location. The pile choice and method of construction depends on ground conditions. Thus, driven steel piles are used when ground consists of thick soil deposits; drilled, cast in situ piles – in a rock ground; a combination of drilled cast-in-situ concrete piles through driven steel casing is utilized when soil deposits overlay bedrock formations. (Chatzigiannelis, Elsayed & Loukakis, 2009)

In the civil and house construction a big variety of foundation can be suitable for offshore structures. Basically, all 'dry' foundations can be implemented in wet conditions, such as next to shore constructions, but with adjustments and additional protection. Moreover, additional research should be carried out: hydrographic survey and environmental data collection.

Although there is a huge variety in the foundations for offshore or next to shore buildings, I will represent only the most common structures. The following - interesting and popular solutions for water foundations.

3.3.1 Artificial island and land reclamation

Structures located relatively close to the shore can utilize man-made 'soil' – artificial island. The working process of island's creation and foundation's installation in the territory surrounded by water is always tough and difficult. Nevertheless, there are some similarities with on-ground construction. Any project starts with soil survey or – in case of artificial island – seabed studies. According to this investigation, the location of facility is selected. The next stage is the implementation of rock or pipe piling perimeter and wave breaking protection. After the breakwater is completed, perimeter walls and protective rock slopes around the island can be built. It is done to create multiple levels of defence from powerful ocean waves.

Figure 2. Construction site of the artificial island (retrieved from https://www2.deme-group.com/references/sarb-artificial-islands)

However, rock formation is not the only safety measure against currents. Huge concrete blocks in the form of X disperse the shock force of each wave and perform the last protective layer.

Before the final barrier layer can be built bulk of the island should be erected by a special method of "filling-in" and then stabilised by various mechanical approaches. It involves collecting the sand from certain areas of the seabed, transportation, its distribution, and compression to form safe islands' foundations. (IBC, n.d.)

These are the main steps in the process in brief, later, according to the project, the pile foundation construction and further actions can be carried out.

The coast land reclamation process is a similar procedure of creating new land from oceans, seas, riverbeds, or lake beds. The most common way to reclaim land is infilling, or filling the area with rocks, cement, clay, etc.

3.3.2 New use of old waterfront pile structures

Nowadays certain buildings can be located on old piers, bridges, or another waterfront structures. For example, Kraanspoor's foundation may be classified as such modification of an old pier with combination of concrete crane (Figure 3 and 4; Metz, 2011). In this case, it is appropriate to discuss the renovation, because old structures are assumed to be deteriorated or have structural deficiencies. There are several ways to enhance the pile foundation: remake completely or provide 'global change'; correct deficiencies (if applicable) or carry out local repair; strengthen the foundation by adding new elements. However, any renovation process is always unique and complex issue for each individual project.

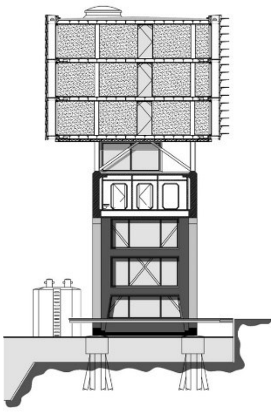


Figure 3. Cross-section of Kraanspoor, and Figure 4. Kraanspoor office building (retrieved from www.archdaily.com)

3.3.3 Pinned foundations

This type of offshore foundations includes piles and drilled shafts. They are implemented to achieve grate lateral stability, to provide sufficient uplift resistance and resistance to scouring, and finally, to minimize the potential of differential settlement. The variety of methods give the opportunity to install different piles. For example, **driven performed pile** and **self-penetrating or suction pile** are widespread solutions. The last one can also be called bucket, skirt, anchor pile, suction anchor, or suction caisson. It is usually placed on the bottom of water basins followed by pumping out the entrapped water. Thus, inside pressure is lower compared with the surrounding water pressure, and pile starts to penetrate into the seabed. (Lee & Peterson, 2011, pp. 52-57) Monopiles and pin piles (small in diameter, drilled and grouted piles) are common for industrial and civil construction or renovation industry.

4 UNIQUE BUILDINGS

4.1 The Turning Torso in Malmö, Sweden

Turning Torso is 190 m tower designed and built in 1999-2005. The famous architect Santiago Calatravia has created a concept of the structure based on his sculpture Twisted Torso. After its completion, the tower became "the first twisting skyscraper in the world, rotating a full 90 degrees along its height" (CTBUH, 2015).

4.1.1 Structural design

The building consists of 9 cubes attached to each other and supported by twisting spine. Each cube contains 5 stories and consists of 6 slabs. Upper 5 slabs adjusted to the core and supported by means of steel columns at the perimeter. This allows to transfer load to the bottom conical slab of each cube. Meanwhile, the upper deck level's slab is a connection point of diagonals and horizontals elements (CIGAR) of the spine.

Figure 5. Turning Torso in Malmö (retrieved from https://commons.wikimedia.org/wiki/Turning_Torso#/media/File:Turning_Torso_2.jpg)

The tower's circular reinforced concrete core with the inner diameter of 10.6 m is a main load-bearing structure. The thickness of the concrete gradually decreases from 2.5 m to 0.4 m towards the top of the building. The steel support outside the structure serves as the backbone and protects from wind loads (Figure 5). The total weight of the metal structure is approximately 820 tons. 20 horizontal and 18 diagonal rods connect the steel column, monolithic floors, and the central shaft into a single structural system. (Appendix 3)

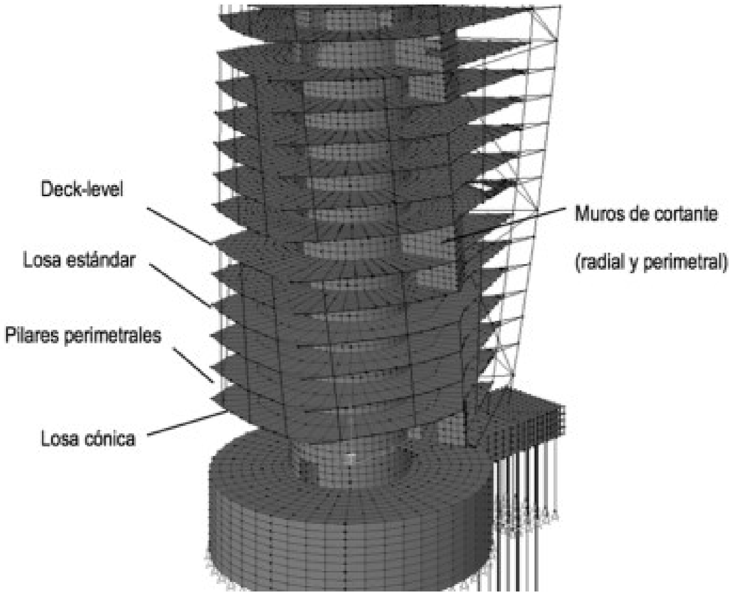


Figure 6. The bottom structure of the building (retrieved from https://artchist.blogspot.com/2015/10/turning-torso-in-sweden-by-santiago.html)

To withstand the total load accumulation from the superstructure, the cylindrical piled raft foundation with a diameter of 30 m and a depth of 18 m was created under the core element. The 7 m raft slab rests on limestone bedrock. Concrete columns at the corners of each floor slab are supported by piles driven into the bedrock up to 3 m. (Figure 7). (Hadakia, 2018; DesignBuild, 2006)

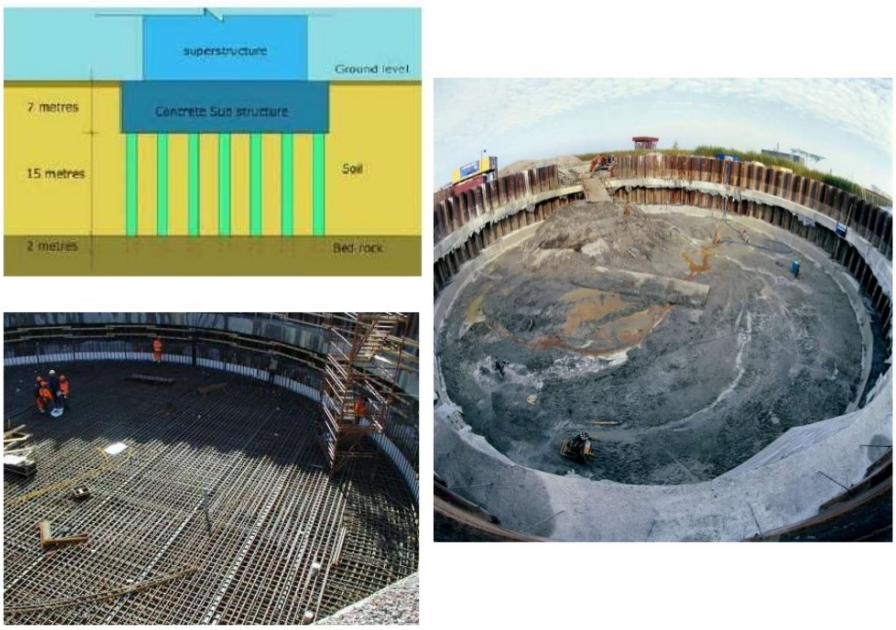


Figure 7. Foundation of the Turning Torso (retrieved from https://www.slideshare.net/MiralHadakia/turning-torso-102641605)

4.1.2 Wind load

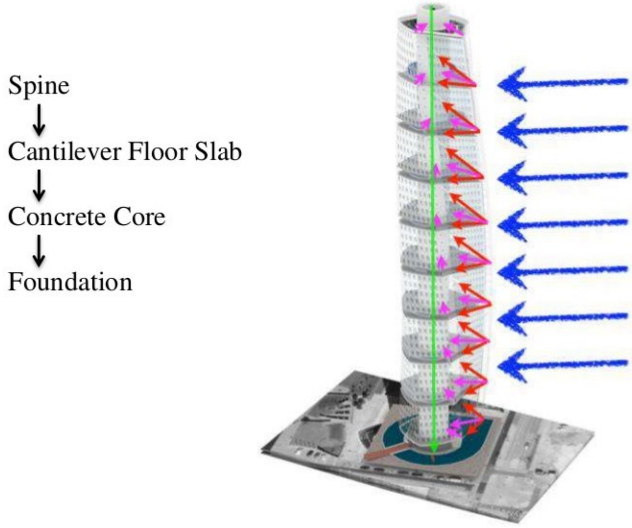


Figure 8. Lateral load transfer (retrieved from https://www.slideshare.net/MiralHadakia/turning-torso-102641605)

Due to the location of Malmö on the coastline of Öresund (The Sound), the territory is prone to storms. Thus, in tunnel tests at the University of Western Ontario in Canada the basic wind velocity was assumed to be 44m/s. According to the results of these tests, building would move at its summit only 30cm.

4.2 **Merenkulkijanrannan asuinkortteli, Helsinki, Finland**

Figure 9. Merenkulkijanranta site (retrieved from https://www.yit.fi/en/projects/merenkulkijanranta)

It is a residential block in the district of Lauttasaari. The part of the complex situated on the ground, while another part – over the Finnish Gul (Figure 9; Appendix 4). The construction began in 2007, and the last building was completed in 2015. The final design is a result of competition organized in 2002. Arkkitehdit NRT Oy won the invitational architectural design competition.

4.2.1 Architectural concept and structural design

The project consists of several parts: slab blocks, small point-access blocks shaped in dices, and two-storey terrace houses above the sea area. The concept represents the harbour theme and reflects the marine spirit. The buildings are located perpendicular to the coastline and gradually increase by the amount of floors towards the ground.

Building of the houses on the sea is a unique process in Finland and involved different challenges such as ice pressure, storm winds, stability, moisture conditions and protection, and others. (Saarinen, 2013)

Figure 10. Merenkulkijanranta building above the sea (retrieved from https://www.yit.fi/en/projects/merenkulkijanranta)

4.2.2 Structural design of the foundation

Houses built above the water stand on concrete columns and the pile foundation combined with massive weight caissons under the pier level (Figures 11 and 12) to allow use of slender columns and make foundation more stable.

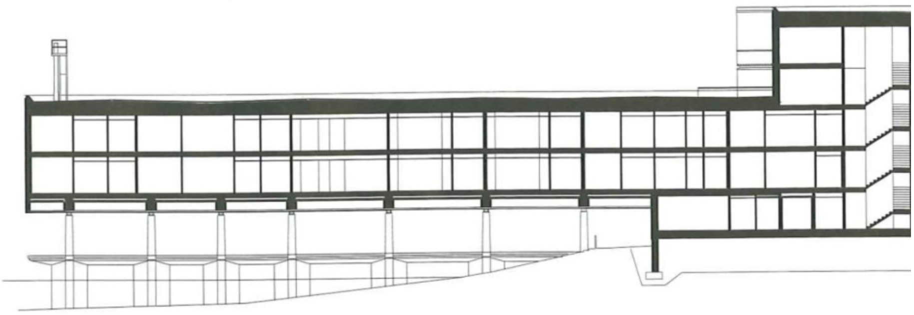


Figure 10. Cross-section of the offshore part of the structure

The caissons are installed on auger piles embedded in bedrock. Piles are provided by SSAB. Steel drilled pipe piles RD 610 are filled by reinforced concrete with 12 steel rods of 32 mm in diameter (12TW32) and 10 mm diameter stirrups with varying spacing from 300 to 150 mm (TW10 k300/k150). (Figure 13) Piles were drilled 2,5 m in rock within the dry cofferdam structure. (Saarinen, 2013)

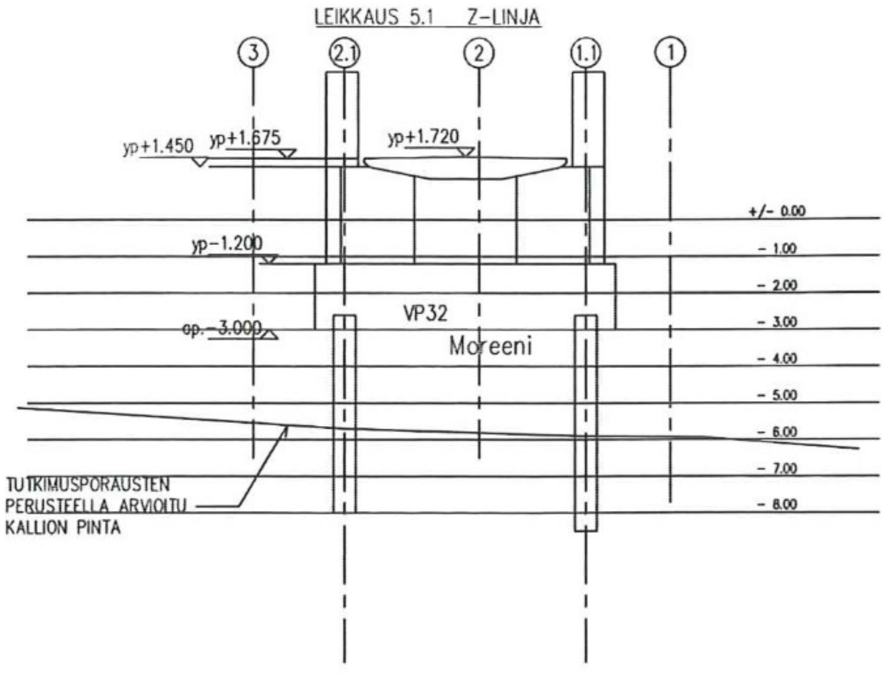


Figure 12. Foundation of the offshore part

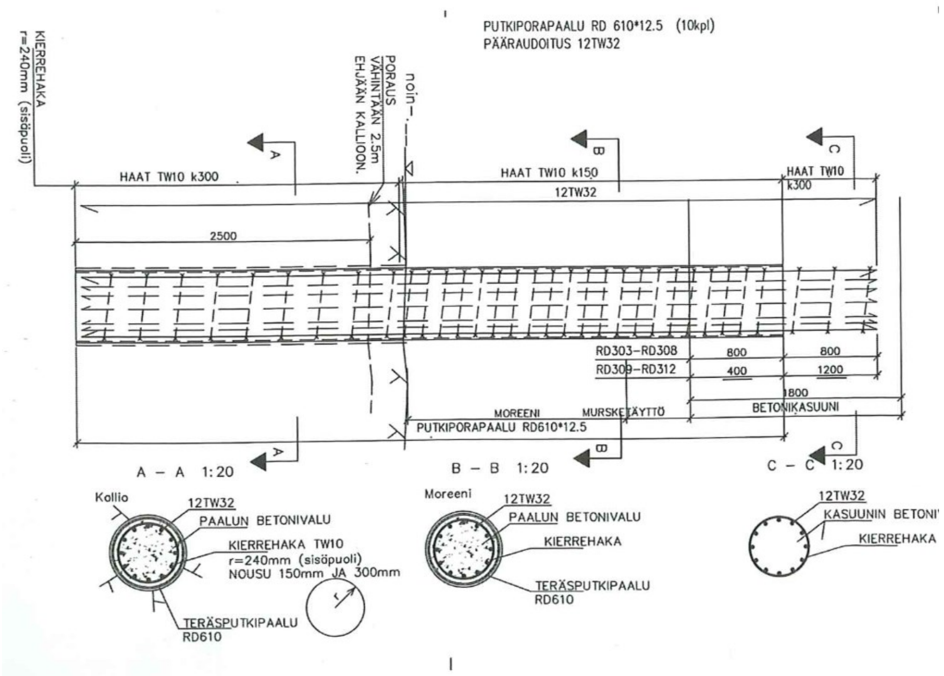


Figure 13. Pile design

4.3 **Lakhta center in Saint-Petersburg, Russia**

Figure 14. Lakhta Center (retrieved from CTBUH)

Lakhta center is a skyscraper located in the northern part of Saint-Petersburg, Russia. It was built in 2018 and, being 462 m in height, became the tallest building in Russia and Europe and at the same time the 17th-tallest in the world (Appendix 5). Additionally to this achievement, Lakhta high-rise building gained the 5th place in the list of most eco-friendly skyscrapers (RIA news, 2019, Appendix 6).

4.3.1 Architectural concept and main design

The final architectural concept prepared by RMJM company was selected in the international contest in 2006. The idea is closely intertwined with the maritime theme. “An organic form of the building symbolizes the power of water, the flow of space, openness and lightness” (Lakhta center, n.d.).

The structural design of the project was conducted mainly by Gorproject and Inforceproject. The superstructure is a five-pointed star in plan. The each wing rotates from floor to floor by 0.82 degrees relative to their centres, or about 90 degrees along the entire height. The main idea behind the infrastructure was to create a box-type foundation. Mentioned structure is accomplished to protect the adjacent foundations of the structure from the vibration of the rotating or vibrating machines. It consists of hollow concrete block and has advantages over the block-type structure: lighter in weight and increased in the natural frequency.

4.3.2 Geological survey

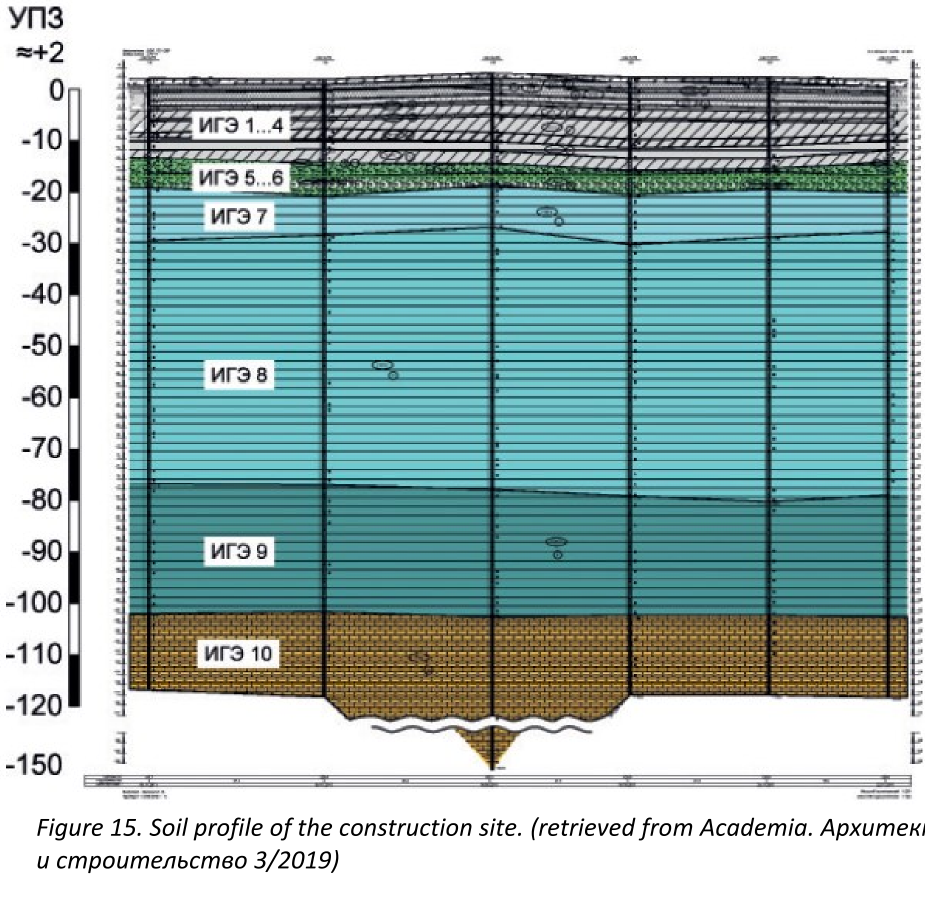


Figure 15. Soil profile of the construction site. (retrieved from Academia. Архитектура и строительство 3/2019)

After the deep examination of construction site in Lakhta (the location of Lakhta center) several layers of soil were indicated from top to bottom (Figure 15):

- Interbedded weak layers of band clays, sandy loam and sand (grey color);
- Moraine (green color);
- Vendian clays (blue shades);
- Sandstone with combination of siltstone and mudstone beds (brown color).

Further investigation of Vendian clays has showed:

- Deformation modulus changes with depth by 5-6 times;
- Clays are over consolidated OCR = 2…3, that decrease the possibility of settlement;
- Clays have anisotropy and creep, increasing the additional settlement by 30%.

According to that survey, top layers (15-20 m from the top) of the soil are not sufficient to withstand enormous loads from the superstructure. Due to overall characteristics of the soil profile, it was decided to implement pile foundation, that will transfer the main load throughout dense Vendian clays to the rocklike sandstone layer. Moreover, drilling in such soils is reasonably comfortable if moisture contact is prevented. (Ilyuhina, Lahman, Miller & Travush, 2019)

4.3.3 BIM design and load calculations

The vertical loads on the building were taken in accordance with the current design standards and technical specifications. It is notable that dead load including self-weight comprises about 84% of the total tower weight of 493,000 tons. However, along with gravitational loads, wind loads were decisive in the structural design. The verification of Lakhta tower model behavior under wind loads were carried out in a wind tunnel by RWDI.

The pulsation component of the wind load on the tower was determined based on a dynamic calculation in the Lira CAD software taking into account the value of the logarithmic damping decrement $\delta = 0.2$. The sum of all horizontal forces from the design wind load was 4836 tons: from the average component of the wind load - 3079 tons (64%), while from the pulsating component of the wind load - 1758 tons (36%). The total moment from the design wind action on the top of the lower slab of the box-shaped foundation accounts 937,900 tm (628,200 tm from the average component of the wind load and 309,700 tm from the pulsation).

Basic calculations of load-bearing structures were performed in Lira CAD software package, while verification calculations were conducted in Sofistik software. The total number of finite elements in the tower model was 524,000.

Reinforced concrete floor slabs of the underground part of the building and reinforced concrete walls defined by shell finite elements; load-bearing columns and beams in the structure of the floor are defined by core elements. The stiffness of the pile foundation under the box foundation tower was assigned by defining bar finite elements with address stiffnesses corresponding to the stiffness of specific piles. During the calculation, the rigidity of all piles was refined using the iteration method. For stiffness assignment of reinforced concrete and steel-reinforced concrete elements the structures used the reduced modulus of deformations.

4.3.4 Structural design solution of foundation

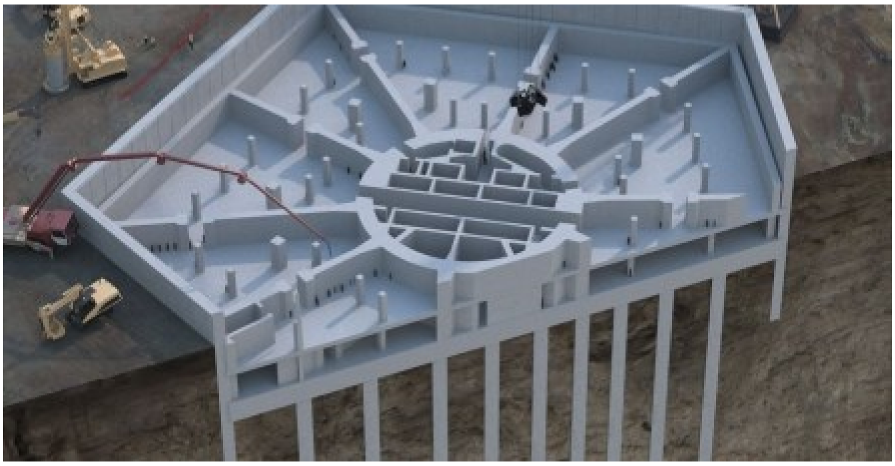


Figure 16. Foundation model (retrieved from https://lakhta.center/ru)

The corresponding initial calculations, carried out to determine the required thickness of the foundation slab, indicated that the traditional foundation slab even 7–8 m thick was not sufficient to ensure uniformity of the foundation settlement. The circular central structural core receives most of the vertical load - about 70%. As a result, a major proportion of the building weight is carried by a small section of the foundation within the limits of the central core. Thus, the settlement under the core was about 180 mm, while at the periphery the value was about 60 mm (Figure 17). In this regard, it was decided to create a box-shaped foundation as a more efficient solution. (Ilyuhina et al., 2019)

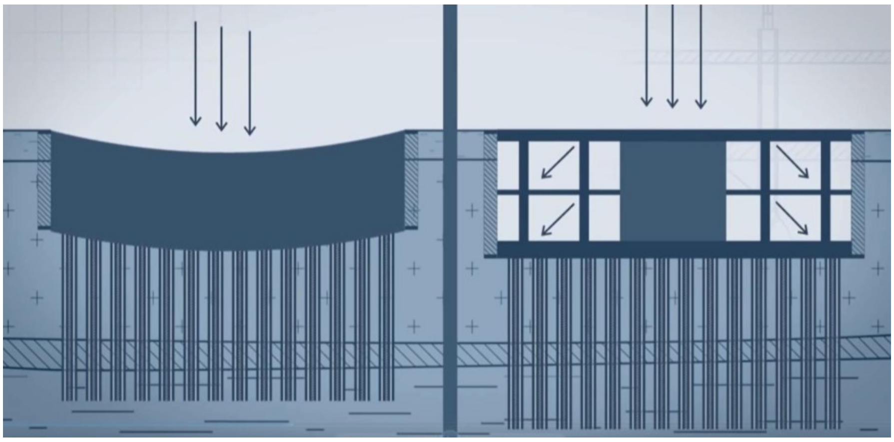


Figure 17. Slab and box-type foundations comparison (retrieved from https://lakhta.center/ru)

The structure of the underground floors forms the box-shaped foundation (Figure 18), comprising the 3.6 m thick bottom slab, the 2.0 m thick top plate, the central structural core 28.5 m in diameter and 10 vertical stiffening diaphragms with the total height of 16.6 m. (Travush & Shahvorostov, 2015, pp. 92-101)

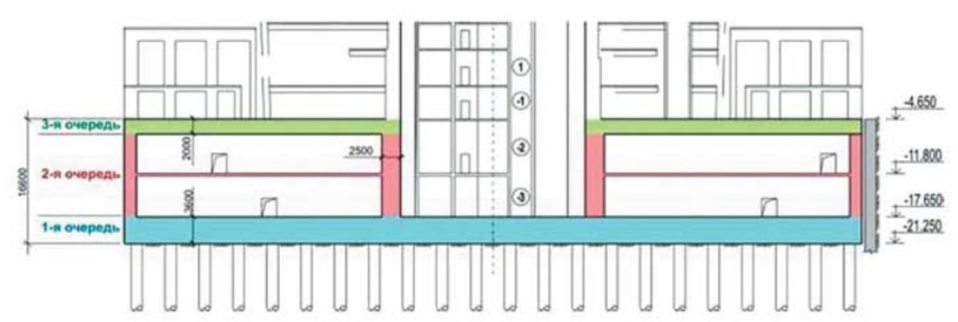


Figure 18. Box-shaped foundation (retrieved from Tall Buildings 1/2015)

The box-shaped foundation leans through a concrete bed upon the pile foundation of 264 CIDH (cast-in-drilled-hole) piles 2000 mm in diameter and 55 and 65 m long, that performs the function of even load distribution. It is an interesting fact that piles were installed before the excavation (Figure 19) due to technical limits. Thus, the depth of their immersion ranges from 72.5 m to 82.5 m, which is comparable to a 25-storey building. The space between piles was taken as 2- or 3-times diameter of a pile – in other words, from 4 to 6 meters. (Appendix 7 and 8) The core element is founded on the piles 65 m long due to the big load going from superstructure. The design bearing capacity of these piles was 4300 tons by standards and 7700 tons according to the results of the O-cell test. The design bearing capacity of peripheral piles (55 m in length) was 3600 tons as standard and 6400 tons according to the results of the O-cell test. (Shahvorostov, Timofeevich & Desyatkin, 2018; Appendix 9)

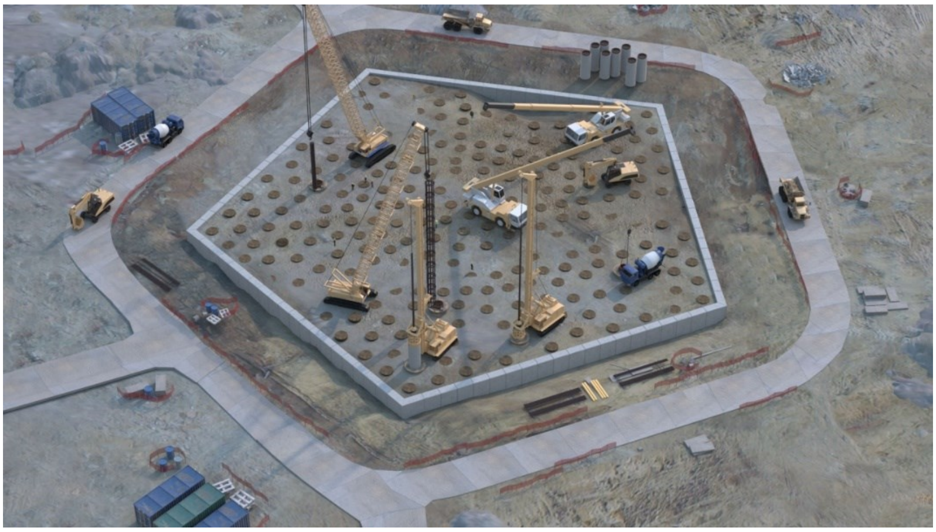


Figure 19. Piles installation (https://lakhta.center/ru)

Building of the box was divided into 3 main phases:

- 1st phase – the bottom cast-in-situ reinforced concrete raft (blue solid hatch in Figure 18);

- 2nd phase - the central part of the foundation, comprising the cast-in-situ reinforced concrete walls made from compressive strength class B80 concrete and reinforced concrete floor slab with the thickness of 0.40 m made from compressive strength class B60 concrete (pink solid hatch in Figure 18);

- 3rd phase – the top cast-in-situ reinforced concrete slab (pale green solid hatch in Figure 18);

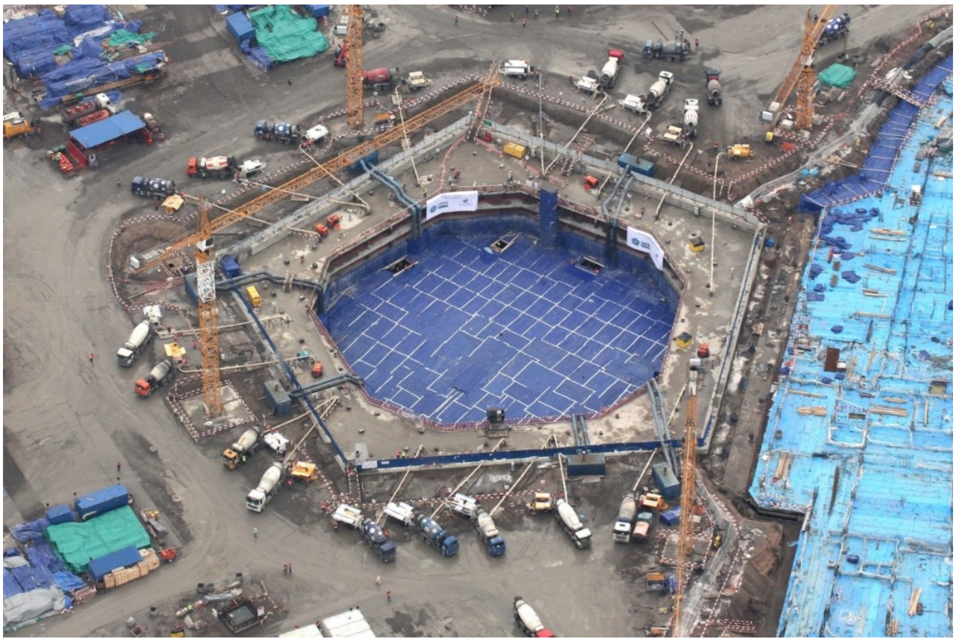


Figure 20. Pouring of the bottom slab of the box foundation (retrieved from https://lakhta.center/ru)

The bottom slab of the box foundation experiences a great stretching stress: axial tension about 2300 t/m, while the bending moment being 2150 tm/m.

The bottom cast-in-situ pentagonal reinforced concrete slab rests on a reinforced concrete bed at the elevation of –21.250 m. The slab was produced with compressive strength class B60 concrete, water tightness grade W8 and frost resistance grade F150.

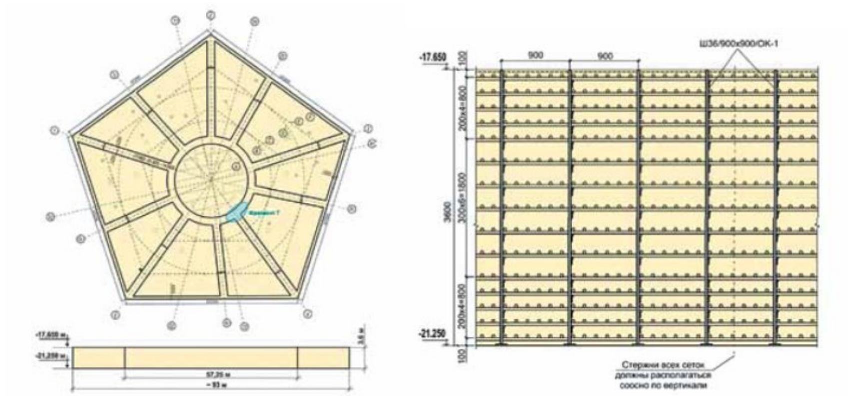


Figure 21. The bottom slab and its reinforcement (retrieved from Tall Buildings 1/2015)

The bottom slab is reinforced with steel rebars of A500C class 32 mm in diameter. The reinforcement cage consists of 15 horizontal grids with 150 mm spacing of the leading rods evenly distributed along the height of the slab. The thickness of concrete cover is 68 mm. An anti-shrinkage C-1 BP-1 grid with a 100 × 100 mm mesh is set in the concrete cover at 25 mm distance from the slab surface. (Travush & Shahvorostov, 2015, pp. 92-101)

4.4 **Burj Al Arab, Dubai, United Arab Emirates**

Figure 22. Burj Al Arab hotel (retrieved from www.jumeirah.com)

The building is a five-star sail-like hotel in Dubai. Being built in 1994-1999 on an island of reclaimed land 280 meters offshore, the structure accounts for 321 m in architectural height and represents the 110th tallest building in the world, although the vanity height is 124 m. (The Skyscraper Center web page profile, n.d.; CTBUH, 2013)

4.4.1 Architectural concept and structural design of superstructure

The tower was designed by Atkins consultancy led by architect Tom Wright (now WKK architects). Designed in the shape of a "billowing Arabian dhow sail" (Appendix 10), the skyscraper rests on the artificial island that was constructed in 3 years. The idea of such location was reasoned by the concept and protection of the beach from the hotel's shadow.

The façade is constructed from 'X' trusses. However, the main load path is exoskeleton that consists of diagonal trusses, mast and two legs.

The design considers seismic actions and windspeed of 45 m/s. After the tests 11 tune mass stampers were included in the design to balance the system and make it more stable under the seismic movement and vortex forces. To protect the structure from potential swaying, two tuned mass dampers, weighing about 2 tons each, limit vibrations in the tubular steel mast – the main load transfer element.

According to structural load analysis total dead-load is around 12 677 431.640 kN; total live-load is 383 258.775 kN; load acting on foundation - about 7182 kN/m2; maximum horizontal wind load is equal to 10 524.5 kN. (Shaktawat, Joshi, Gandhi & Chatterjee, n.d.)

4.4.2 Structural design solution of foundation and its construction process

Figure 23. Piles model and Figure 24. Basement excavation work (retrieved from CTBUH)

The solution of foundation is complex. It consists of the island itself and 250 reinforced concrete tubular piles (1.5 m in diameter) that go 45 metres under the sea and are held in place by the skin friction of the sand. The reinforced concrete raft is 3.7 meters thick and was poured utilizing C50 self-consolidating concrete, while reinforcement was installed every 300mm. Island rises 7.5 meters above the waves. (Jangam, Kudave, Kadage, Waghmare & Malu, 2017)

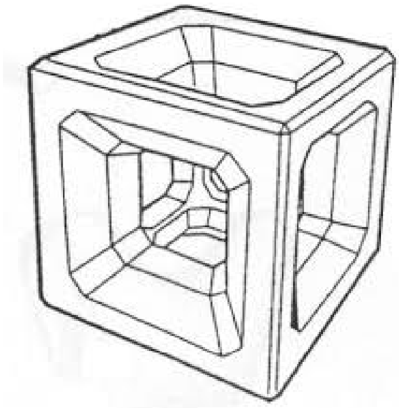


Figure 25. Cubic concrete armour and Figure 26 Shed armouring at Burj al Arab Hotel (retrieved from https://www.xbloc.com/sites/default/files/domain-671/documents/xbloc-2008-design-of-concrete-armour-layers-muttray-et-al-671-14585724381469179232.pdf)

The construction of the Island started with the installation of temporary tube piles into the seabed. Further, temporary sheet piles and tie rods were driven into the seabed to support boundary rocks. The process of construction of an artificial island is proceeded by the implementation of permanent boundary rock bunds with hydraulic fill layers deposited between bunds to displace seawater and island formation. The steep rock slopes were later covered with cubic concrete armor (Figures 25 and 26) to absorb the force of the waves. Cubes work like a sponge or mechanical barrier for waves vibrations: water passes inside the space and turns around on itself dissipating the force. After boundary had been formed, the island was dewatered and filled in by bulk. Finally, on the created land – dry island – the foundation could be easily installed (Figure 27).

Piles and then concrete raft slab were the initial part of the infrastructure. The final objects of the foundation – concrete retaining walls and basement floors complete the underground structure of the building. (Burj Al Arab Architecture Project, 2012)

Figure 27. Artificial island (retrieved from CTBUH)

4.5 CCTV Headquarters, Beijing, China

Figure 28. CCTV building in Beijing (retrieved from https://www.archdaily.com/236175/cctv-headquarters-oma)

CCTV applied for expansion and organized a contest to choose the best concept to proceed with. The international design competition was won in 2002 by OMA and Arup, which subsequently allied with the East China Design Institute (ECADI) to connect all processes of design in one project. Due to the purpose of the building and unique process of filming and TV production, the suggested design included all essential departments into one building. There are 54 floors and reaches 234 m in height. The construction of the building started in 2004 and was finished in 2012.

4.5.1 Architectural design and structural form

The structure consists of several parts: the nine-story base structure, the two leaning Towers inclined at 6° in each direction, and the nine- to thirteen-story connecting upper structure. It was decided to create one continuous ‘tube’ structural system to resist the huge bending forces generated by its form, as well as loads from wind and accidental earthquakes. That structure is performed by bracing that continuously follows the shape of the building, stiffens corners, and supports all building elements (Figure 29).

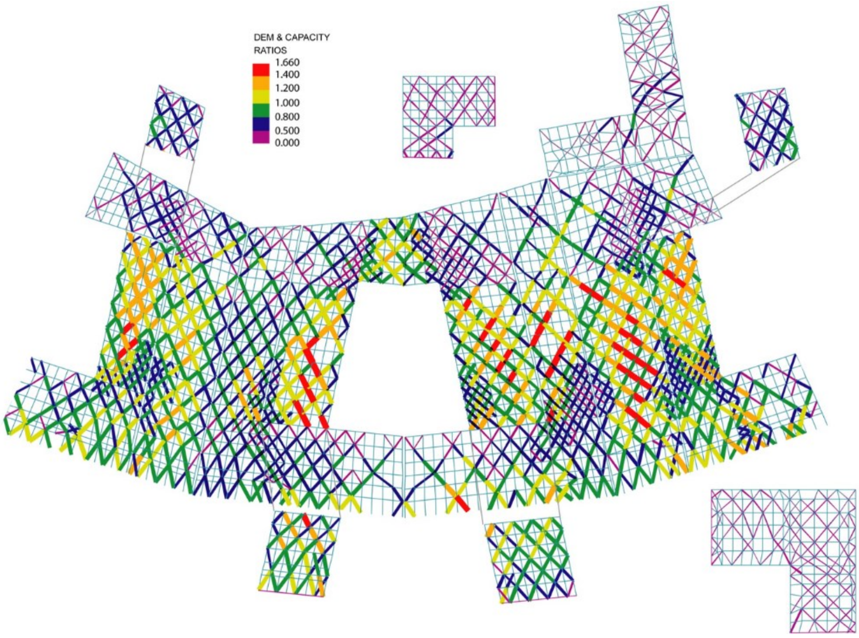


Figure 29. Unfolded view of final bracing structure (retrieved from https://www.archdaily.com/236175/cctv-headquarters-oma)

The versatile load-bearing structure allows to deal with permanent and temporary loading on the building, can bridge in bending and torsion between the Towers and deliver loads to the foundation in the most favorable distribution possible. Additionally, it provides alternative load paths in case of accidents and destruction of key elements. Nevertheless, gravity loads are also supported by vertical columns around the building's central cores. (Carroll, Gibbons, Ho, Kwok, Cross, Duan, Li, Lee, Luong, McGowan & Pope,2008)

4.5.2 Elastic analysis of structure, structural and seismic design

The elastic analysis and design were conducted by SAP2000 - a computer-based nonlinear structural analysis program, - and a custom-written Chinese steelwork code post-processor in Excel. This automatically took combined load cases for the limit state design.

The design team conducted project-specific rules and applied them in the performance-based design. "Appropriate linear and non-linear seismic response simulation methods were selected to verify the performance of the building… Inelastic deformation acceptance limits for the key structural brace members in the continuous tube were determined by non-linear numerical simulation of the post-buckling behavior". LS-DYNA was used for this purpose. (Carroll, Cross, Duan, Gibbons, Ho, Kwok, Lawson, Lee, Luong, McGowan & Pope, 2005)

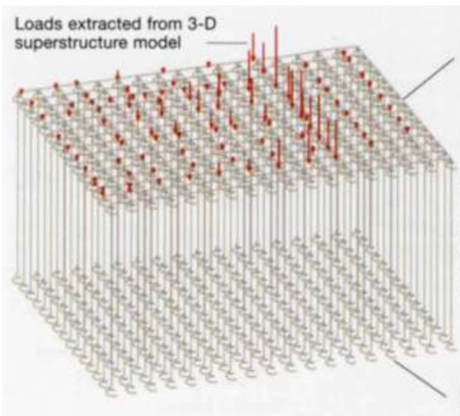
A shake table test of a building model in scale of 1:35 was conducted by the China Academy of Building Research (CABR) in Beijing to examine the structural performance under several seismic events including a severe design earthquake

Wind tunnel tests were performed by RWDI.

4.5.3 Geotechnical survey, foundation design and analysis

The soil profile of the building territory is very common for the Chaoyang area in Beijing. The fill consists of clay and silt, meanwhile the subsoil mostly includes sand and the combination of cobble with gravel. The deep layer analysis represents claystone, siltstone, and weathered rock.

Each of two towers sits on a piled raft foundation. The rafts (each contain up to 39 000 m^3 of concrete and 5000 tons of reinforcement) vary in thickness up to 7 meters and distribute forces evenly into piles. Beneath one separately taken tower there are up to 370 reinforced concrete bored piles typically 33 m long and 1.2 m in diameter. The piles are shaft- and toe-grouted. The foundation system is designed in a way in which the center of each raft is close to the center of load at the bottom of the tower. Thus, no permanent tension should be performed in piles during the service, although the seismic analysis indicated that several columns and foundation piles could experience tension during a severe design earthquake. Thus, some of the peripheral columns and their baseplates were embedded 6m into the rafts. Another part of the building stands on a traditional raft foundation with tension piles up to 20 m long and 0,6 m in diameter between column locations to resist uplift from water pressure acting on the deep basement. Additional 1.2 m diameter piles are installed under secondary cores and columns. More than 1200 piles were installed during the construction process. (Carroll, Gibbons, Ho, Kwok, Lawson, Lee, Li, Luong, McGowan & Pope,2008)



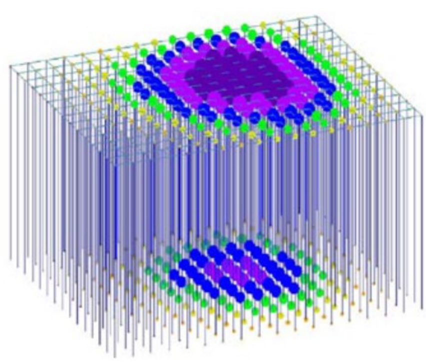


Figure 30. GSRaft model of the pile foundation and Figure 31. Foundation settlement analysis (retrieved from The Arup Journal)

To verify the load spread to the pile group, a complex analysis process was implemented adopting a non-linear soil model. All loads from superstructure were applied to a discrete model of the foundation (Figure 30). “Several hundred directional load case combinations were automated in a spreadsheet controlling the GSRaft soil-structure interaction solver” (Carroll, Cross, Duan, Gibbons, Ho, Kwok, Lawson, Lee, Luong, McGowan & Pope, 2005). The analysis was introduced by iterative process of changing input data and further modelling of the redistribution of load between piles when their safe working load was reached. Such procedure was repeated for each load case until the results converged and stress in piles was within the limits. Results of the analysis were reflected in the structural design of raft and its reinforcement. (Carroll et al., 2005)

4.6 Shihlien Group Offices, Huai'an City, Jiangsu, China

Figure 32. The Building on the Water, Huai'an City (retrieved from https://www.carlos-castanheira.pt/project/the-building-on-the-water/#)

Designed by two architects – Álvaro Siza and Carlos Castanheira, – the office building for the company Shihlien Chemical Industrial Group stands in the New Salt Industrial Park in the centre of an artificial lake. The motive of such location is explained by the need for water to ensure the constant production. It is one of the biggest combined soda ash and ammonium chloride production plant. The Building on the Water was built during 2010-2014 years. (Castanheira, n.d.)

4.6.1 Architectural concept and design of the building

The shape of the strip structure resembles a curved dragon or horseshoe with a total pristine length of 300 m (Appendices 14, 15). It is connected to the main ground by two perpendicular bridges. "Conceptually speaking, the building floats over the water, but constructively the structure is held by piles…" (Guerra, 2016) The superstructure consists of 2 floors above water and comprises 11 000 m^2. Built with white exposed concrete, the structure interplays with reflections, light, and the surrounding environment (ArchDaily, 2014).

4.6.2 Structural design of foundation

The weight of the building is held by 8 m long concrete piles and wall and transferred to the bottom of the pond (Figure 33). The foundation itself is covered by water and stays unnoticed from the outside. Due to that hidden construction, the building seems to float on water.

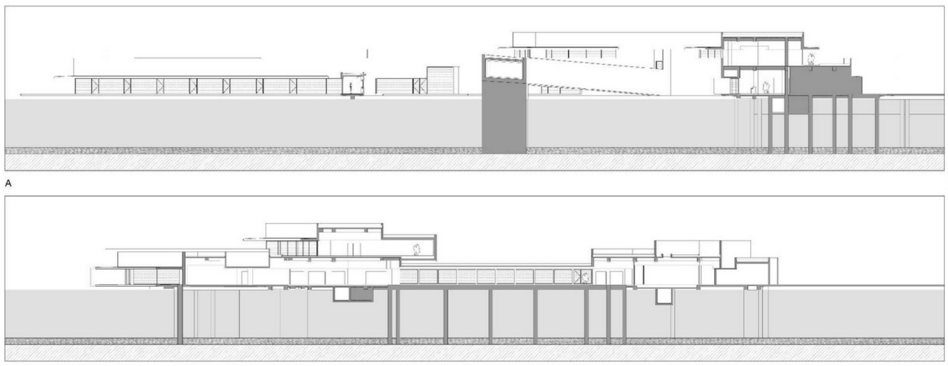


Figure 33. Cross-sections of the building (retrieved from https://magaceen.com/en/architecture/alvaro-siza-en-china/)

4.7 Trump International Hotel & Tower, Chicago, Illinois, USA

The tower is located at 401 North Wabash Avenue in the River North Gallery District. The building that was found at the same place previously was occupied by the Chicago Sun-Times. Constructed between 2005 and 2009, the 98-floor building reaches 423.2 m in architectural height.

4.7.1 Architectural concept and design

The building was designed by Adrian Smith from SOM (Skidmore, Owings, Merrill) Architectural department. The main desire was to harmoniously fit the structure into the architectural site of the surrounding district and highlight the neighboring buildings acting as the link between them. It was achieved by implementing the three-setback system, where each one reflects the height of a nearby building.

Figure 34. Trump International Hotel and Tower in Chicago (retrieved from http://www.skyscraper-center.com/building/trump-international-hotel-tower/203)

4.7.2 Soil profile

The soil profile consists of several layers and starts with sand layer up to 3-6 m in depth. The weak layer is proceeded by Chicago blue clay soil that gradually transfers to the Chicago hardpan at the approximate depth of 23 m. The last-mentioned layer is a very hard till consolidated by the glaciers more than 10 000 years ago. Deeper till becomes granular mixed with cobbles, boulders, and water under pressure. Bedrock lays at the depth of 30 meters and has a weathered surface with fracture sand clay seams with the compressive strengths of 7 kN/cm^2 to 14 kN/cm^2.

4.7.3 Foundation design

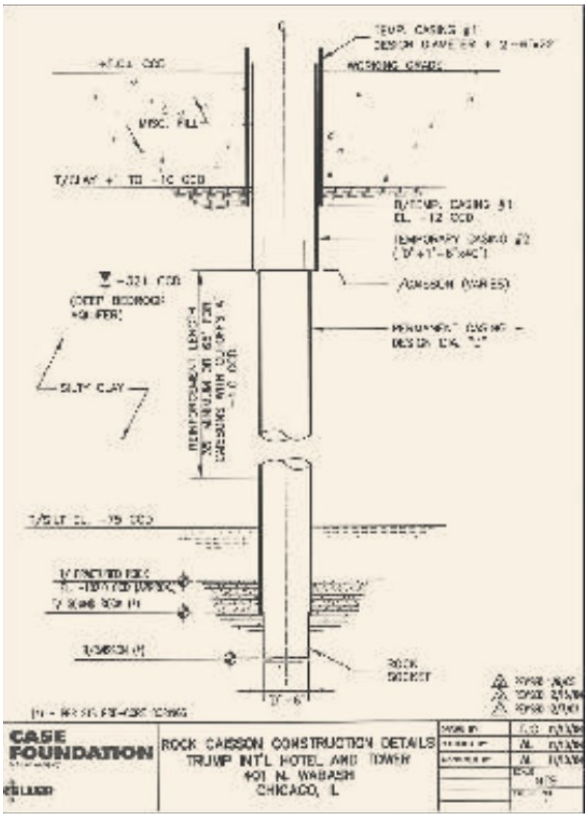


Figure 35. Typical rock socketed caisson construction procedure (retrieved from http://www.dfi.org/update/TrumpInternationalTower.pdf)

The foundation design met conflict in the very beginning of its construction with the old foundation system left by the previous structure. However, the issue was solved by the additional site work.

The foundation system consists of several parts: viaduct and pedestrian plaza, the tower foundation. The last one includes 35 cased caissons located along the perimeter of the building and 22 permanently cased caissons to support the core of the tower. Peripheral caissons are 1.2-2.7 m in diameter with 3 m socket piles 36.5 m below the ground and core elements with capacity of 177 000 kN are 3 m in diameter with 3 to 6 m deep rock socket bearing. (Deep foundations, 2009)

5 COMPARISON

All studied buildings included in this report were described in Table 1. According to the results, the main type of foundation or part of the infrastructure is piled raft foundation for on-ground structures, even in the case of reclaimed areas. On the contrary, offshore houses vary in their foundation types, although such structures are not so common.

It is noticeable, that unique high-rise structures are more spread in the world than marine buildings. It can be explained by the history of these types of structures and technical restrictions: it is hard to build offshore. Construction above the water is popular in wet regions or areas with a flood risk. Nevertheless, such structures can be built around the world regardless the soil profile and materials applied, whereas high-quality skyscrapers can be built only in developed and/or overpopulated countries.

However, according to the Table 1 pile foundation was implemented in the cases of weak soil profile, close location to water sources, unique shape of the building.

The shape of piles is usually circular. The most used materials for foundations are concrete and steel. The causes of such design are the load distribution factor and the weather and water resistance of the materials.

Table 1. Comparison table of researched buildings

Building	Soil	Problem	Solution for foundation
Turning Torso, Malmö, Sweden 2005	Sand, clay, bedrock	Close access of sea, entering of water to the site	Dewatering, sheet piles, **compensated piled raft foundation.** Concrete and steel.
Merenkulkijanranta, Helsinki, Finland 2015	Sea rock	Ice pressure, storm winds, stability, protection from moisture	Complex foundation; RD **piles** from steel and concrete, massive **caissons.**
Lakhta center, St. Petersburg, Russia 2019	Sand, Vendian clays, bedrock	Weak soil, absence of innovative machine	Deep **pile foundation** with the combination of **box-type structure** with diaphragms, excavation after the pile installation. Concrete and steel.
Burj Al Arab, Dubai, UAE 1999	Sea sand	Location in water basin, wind, and wave actions	Construction of artificial island, usage of cubic concrete armor, wind balance system implementation, consideration of sand skin friction, **piled raft foundation.** Concrete and steel.
CCTV Headquarters, Beijing, China 2012	Clay and silt, sand, cobble with gravel, claystone, siltstone, weathered rock	Unique and unsymmetrical shape of the building, earthquakes, groundwater level	Variation of foundation for different parts of the building; seismic design and analysis; dewatering. **Piled raft foundation,** application of tension piles. Concrete and steel.
Shihlien Group Offices, Huai'an City, China 2014	Artificial pond, concrete	Unique shape, the big volume, foundation covered with water	Artificial basin; **piled foundation**, concrete and steel.
Trump International Hotel & Tower, Chicago, USA	Sand, Chicago blue clay,	Old foundation from previous building; close	**Caissons with socket piles**, concrete and steel.

2009	Chicago hard-pan, bedrock	location to the water basin; weak and wet soil	

6 FURTHER DEVELOPMENT

6.1 Path of the future

Development is a constant and incessant process in every field, and construction is not an exception. Recently new type of materials and innovative strategies have gradually entered the world market and dramatically transformed the design and the construction. For instance, new high-strength steel or concrete additives have allowed to solve different issues and expand limits of plan implementation. Pile foundation can be developed as well: either materials or the structure itself. New alloys, reinforcement, concrete mix, or any invention can result in a more effective solution. Not only will high-rise buildings and offshore structures be developed in the near future, but the whole construction field will change a lot. However, it is safe to say that the main direction and at the same time the most important reason for such modification will be the desire of society to protect its members and the nature and prevent environmental disaster.

6.2 Interesting concepts

People should start to think about the fate of present and next generation: create concepts, generate ideas, and be constantly in search of solutions. Any interesting points about innovations or new design concepts must be discussed as a product and considered as a valuable content for further implementations. In this chapter I will share some interesting design concepts that were represented in the eVolo competition.

6.2.1 The Filtration Skyscraper, Honglin Li, 2019

"FILTRATION is a highly modularized prefabricated waste-management and waste-to-energy power plant megastructure that contains several Material Recovery Facilities (MRF) and Water Treatment Plants (WTP) to recycle the floating garbage continent and clean seawater…" (Honglin Li, 2019)

Figure 36. Filtration skyscraper model (retrieved from https://www.honglin-li.com/the-filtration)

The assumed location of such structure and its main foundation is abandoned oil platform. The tree truck core built on that platform can accommodate various plants and facilities such as plastic recycling or waste-to-energy power plant. These facilities have a modular structure which allows to replace elements as needed.

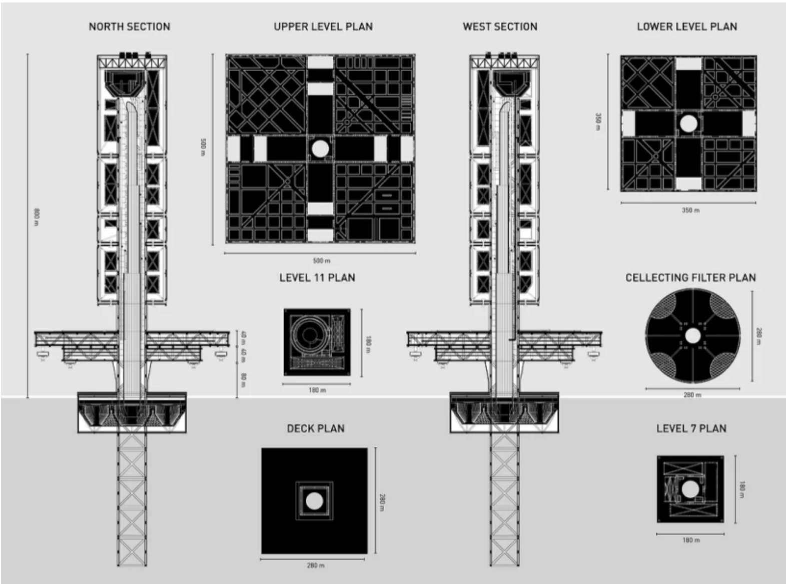


Figure 37. Structural drawings (retrieved from https://www.honglin-li.com/the-filtration)

The plant pumps garbage and polluted water along with seawater to the apex of the building; filters water, recycles material, and then lead them to the bottom. Meanwhile, non-recycled material will be transported away by tidal power.

6.2.2 Bamboo Forest, Thibaut Deprez, 2014

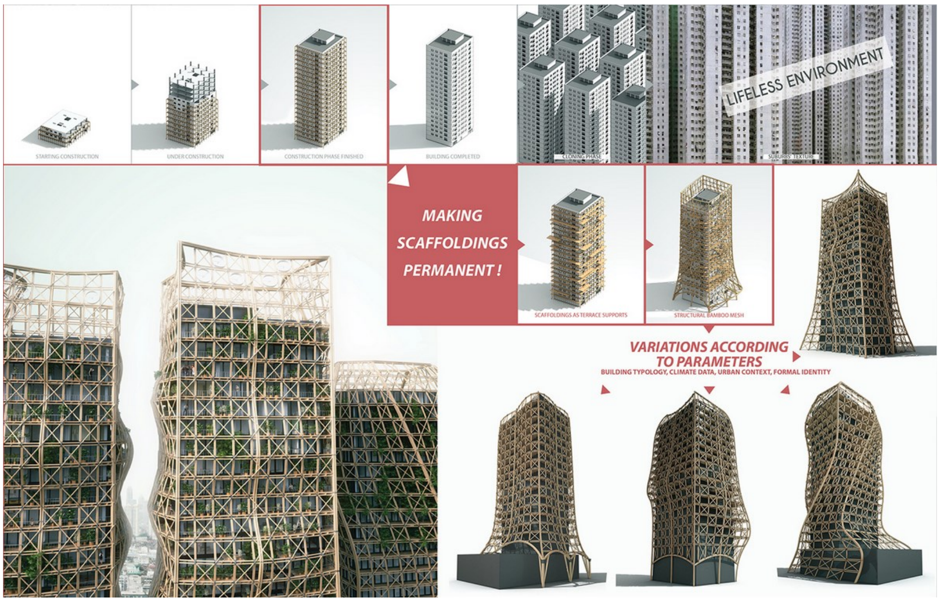


Figure 38. Bamboo Forest scaffolding (retrieved from https://www.evolo.us/bamboo-forest-sky-scrapers-and-scaffoldings-in-symbiosis/)

The concept is based on the idea to give the ordinary typical high-rise structures a unique look and enhance the envelop with customized wooden or bamboo frame against wind action. The project aims to modify existing and future buildings to more environmental-friendly sites. (eVolo, 2014)

6.2.3 Coast Breakwater, Charles Tzu Wei Chiang, Alejandro Moreno Guerrero, 2020

Figure 39. Modular Coast Breakwater structure (retrieved from eVolo, 2020)

The project of vertical communities in Senegal for rising sea level combines the traditional wooden architecture of Taiwan and innovative modular structures. Standing on pillars, the building is protected from rising level of water and gives the access to sea. The modularity allows to move apartments higher or add more levels to existing structures. (Appendix 16; eVolo, 2019)

6.2.4 Airscraper, Klaudia Gołaszewska, Marek Grodzicki, 2019

The structure represents the apartment complex with embedded facility to clean the air in urban area.

Figure 40. Airscraper (retrieved from http://www.evolo.us/airscraper/)

It consists of three main parts: air-intake, solar-gain, and green-garden modules. The hollow core element connects all modules, takes part in filtration process, and acts as a main bearing structure at the same time. (Appendix 17, eVolo, 2019)

6.2.5 The Urban Lung, Ryan Gormley, 2018

The design concept reflects the balance of proper material sourcing, structural performance, environment, and digital design. Built from wood the building performs reduced carbon emissions and acts as a showcase of the modern green architecture. (eVolo, 2018)

Figure 41. The Urban Lung Timber Skyscraper (retrieved from http://www.evolo.us/the-urban-lung-timber-skyscraper/)

7 CONCLUSION

The variety of architectural concepts and designs were investigated during the research process. The initial idea of the survey was to understand the major tendencies in construction of high-rise and offshore buildings in different parts of the world: Europe, Asia, Russia, America.

The main discoveries were:

- **The most common foundations are piled raft foundation and box-type foundation with piles.**

  These infrastructures are the most effective solutions nowadays. Piles are usually composed of concrete with steel reinforcement and sometimes with steel profiles. Nevertheless, the material and design depend a lot on the site and economical constituent. Pile foundation is generally implemented in weak or wet soils. Thus, the combination of concrete and steel, as the most effective materials in such cases, is an appropriate solution in different projects.

- **The diversity of small, local offshore buildings and scarceness of such regional or big scale projects.**

  The trend can be noticed in different countries such as USA and The Netherlands. Different country houses and family buildings are located next to the water or above it. It is a reasonable solution due to the density of population, geological features, and historically established traditions. However, big scale projects are avoidable because of the technical and executive difficulties during the foundation construction.

- **The main share of piled high-rise construction belongs to Asia.**

  This feature is explained by the density of population and cultural heritage and worldview. However, high-rise objects are complex and expensive structures: they are affordable only in developed countries. Nevertheless, USA and Canada prefer spread foundations over the piled infrastructure. In projects with weak soil engineers from North America they use caissons or apply slab with a huge thickness.

- **Europe only begins to develop high-rise and offshore city construction fields and implement interesting solutions for foundations.**

> The majority of such structures has been erected recently. New complexes have already been built or are ongoing projects (Tripla, Redi) in Finland. The construction of these buildings is controversial in many cities due to the historical and cultural components. Different sites are included in the UNESCO World Heritage list, and unordinary buildings can interfere with the overall look of a city centre or heritage sites.

These tendencies can describe the condition of the construction field at the moment. Erection of high-rise structures and offshore buildings is unavoidable nowadays. Additionally, people may be tired of the typical urban development. They may want to have changes and diversity: it is rooted in the human psychology.

The current generation stands at the beginning of a new path: innovations in green technologies and rethinking of traditions and foundations. The results of different contests in construction and architectural design determine and represent the direction of future developments. High-rise and offshore structures are part of the future that can help to protect the environment and encourage the evolutions of other parts in our live. All produced concepts and designs bring valuable content for further implementation in different fields. People should learn know about such innovations and structures to be able to adapt fast in the near future.

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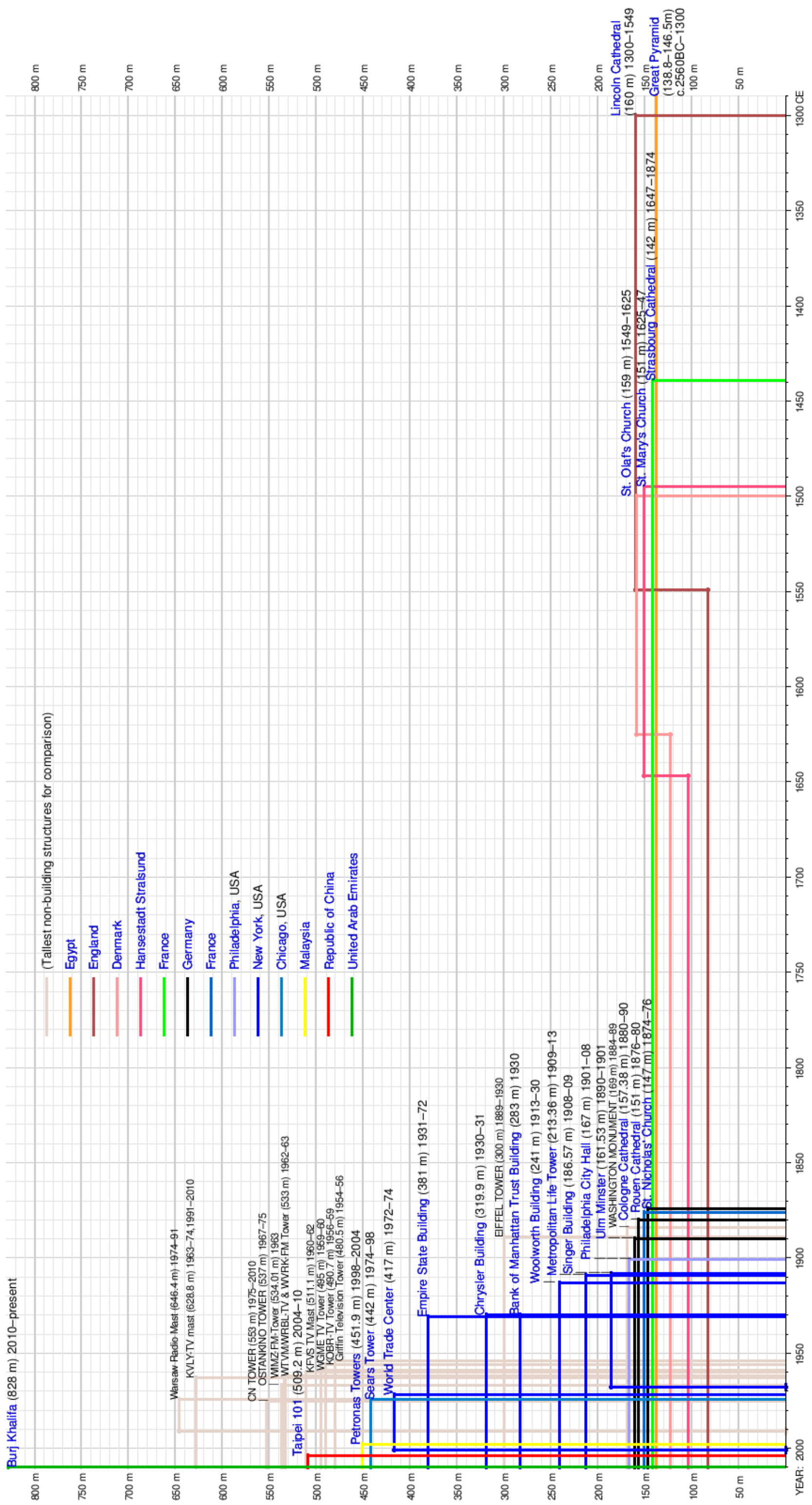
Appendix 1

Timeline of the tallest buildings from 1300-present
Derived 9th of June from
https://en.wikipedia.org/wiki/History_of_the_world%27s_tallest_buildings



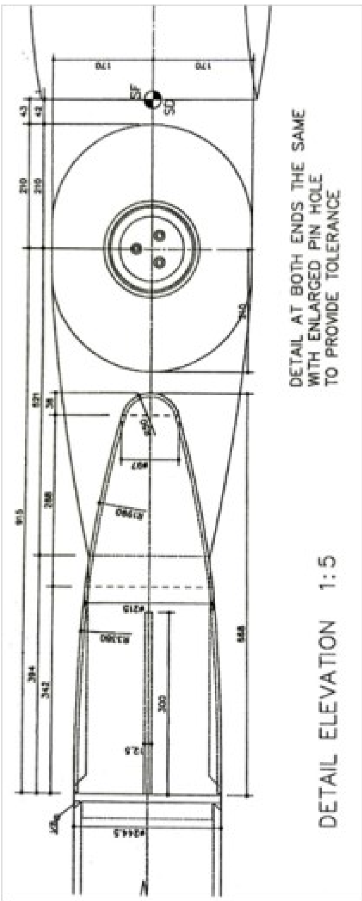
Appendix 2

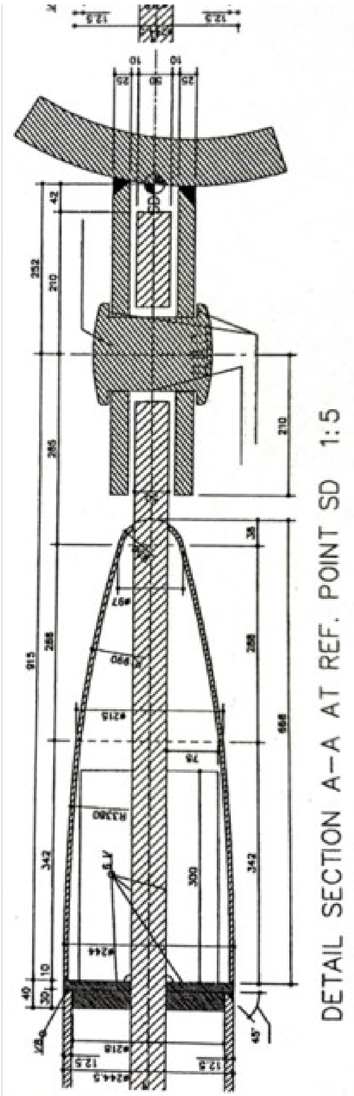
The tallest buildings in Finland
Derived 9th of June from
https://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Finland

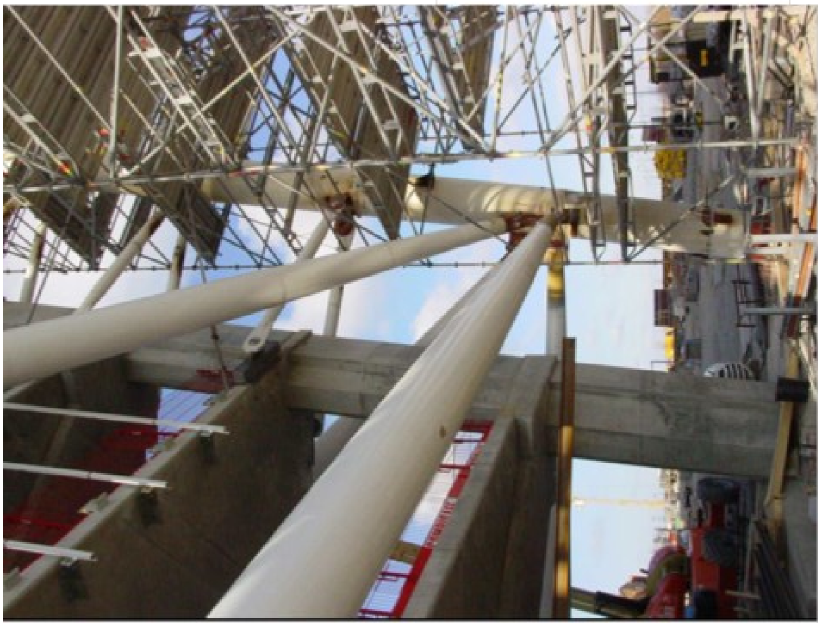
Building	City	Height	Floors	Built
Majakka	Helsinki	134 m (440 ft)	34	2019
Cirrus	Helsinki	86 m (282 ft)	26	2006
Hotel Torni Tampere	Tampere	88 m (289 ft)	25	2014
Niittyhuippu	Espoo	85 m (279 ft)	24	2017
Meritorni	Espoo	70 m (230 ft)	22	1999
Leppävaaran Torni	Espoo	68 m (223 ft)	21	2010
Luminary	Tampere	71 m (233 ft)	21	2018
Accountor Tower	Espoo	84 m (276 ft)	20	1976
Sellonhuippu	Espoo	61 m (200 ft)	19	1986
Haapaniemenkatu 7-9	Helsinki	65 m (213 ft)	19	1975
Clarion Hotel Helsinki	Helsinki	78 m (256 ft)	19	2016
Itäkeskuksen maamerkki	Helsinki	82 m (269 ft)	19	1987
Reimantorni	Espoo	63 m (207 ft)	18	2007
Hotel Ilves	Tampere	63 m (207 ft)	18	1986
Reimarintorni	Espoo	66 m (217 ft)	18	1990
Itämerentorni	Helsinki	66 m (217 ft)	18	2000
Pitäjänmäki Tower	Helsinki	70 m (230 ft)	18	2001
Kone Building	Espoo	73 m (240 ft)	18	2001

Appendix 3

Connection detail of the external steel element of the Turning Torso
Derived 30th of September from https://artchist.blogspot.com/2015/10/turning-torso-in-sweden-by-santiago.html







Celosía Exterior

Appendix 4

Merenkulkijanranta site plan
Derived 19th of September from Betoni lehti 4/2013

Appendix 5

The tallest buildings in the world
Derived 25th of August from
https://en.wikipedia.org/wiki/List_of_tallest_buildings

Rank	Building	City	Country	Height		Floors	Built
1	Burj Khalifa†	Dubai	United Arab Emirates	829.8 m	2,722 ft	163	2010
2	Shanghai Tower	Shanghai	China	632 m	2,073 ft	128	2015
3	Abraj Al-Bait Towers	Mecca	Saudi Arabia	601 m	1,971 ft	120	2012
4	Ping An Finance Center	Shenzhen	China	599 m	1,965 ft	115	2016
5	Lotte World Tower†	Seoul	South Korea	555.7 m	1,823 ft	123	2016
6	One World Trade Center†	New York City	United States	546.2 m	1,792 ft	104	2014
7	Guangzhou CTF Finance Centre	Guangzhou	China	530 m	1,739 ft	111	2016
7	Tianjin CTF Finance Centre	Tianjin	China	530 m	1,739 ft	98	2018
9	China Zun	Beijing	China	528 m	1,732 ft	108	2018
10	Willis Tower†	Chicago	United States	527 m	1,729 ft	108	1974
11	Taipei 101	Taipei	Taiwan	508 m	1,667 ft	101	2004
12	Shanghai World Financial Center†	Shanghai	China	494.3 m	1,622 ft	101	2008
13	International Commerce Centre	Hong Kong	China	484 m	1,588 ft	118	2010
15	Central Park Tower	New York City	United States	472.4 m	1,550 ft	103	2020
16	Landmark 81†	Ho Chi Minh City	Vietnam	469.5 m	1,540 ft	81	2018
17	Lakhta Center	St. Petersburg	Russia	462 m	1,516 ft	86	2018
18	John Hancock Center†	Chicago	United States	456.9 m	1,499 ft	100	1969
19	Changsha IFS Tower T1	Changsha	China	452 m	1,483 ft	94	2017
20	Petronas Tower 1	Kuala Lumpur	Malaysia	451.9 m	1,483 ft	88	1998
20	Petronas Tower 2	Kuala Lumpur	Malaysia	451.9 m	1,483 ft	88	1998

Appendix 6

LEED Certification of Lakhta center
Derived 26th of August from
https://lakhta.center/en/article/?id=1328

LEADERSHIP IN ENERGY & ENVIRONMENTAL DESIGN
LEED
PLATINUM

LAKHTA CENTER
TOWER BUILDING

Saint Petersburg, Russian Federation

HAS FULFILLED THE REQUIREMENTS OF THE LEED GREEN BUILDING RATING SYSTEM CERTIFICATION ESTABLISHED BY THE U.S. GREEN BUILDING COUNCIL AND VERIFIED BY GREEN BUSINESS CERTIFICATION INC.

LEED 2009
CORE AND SHELL DEVELOPMENT

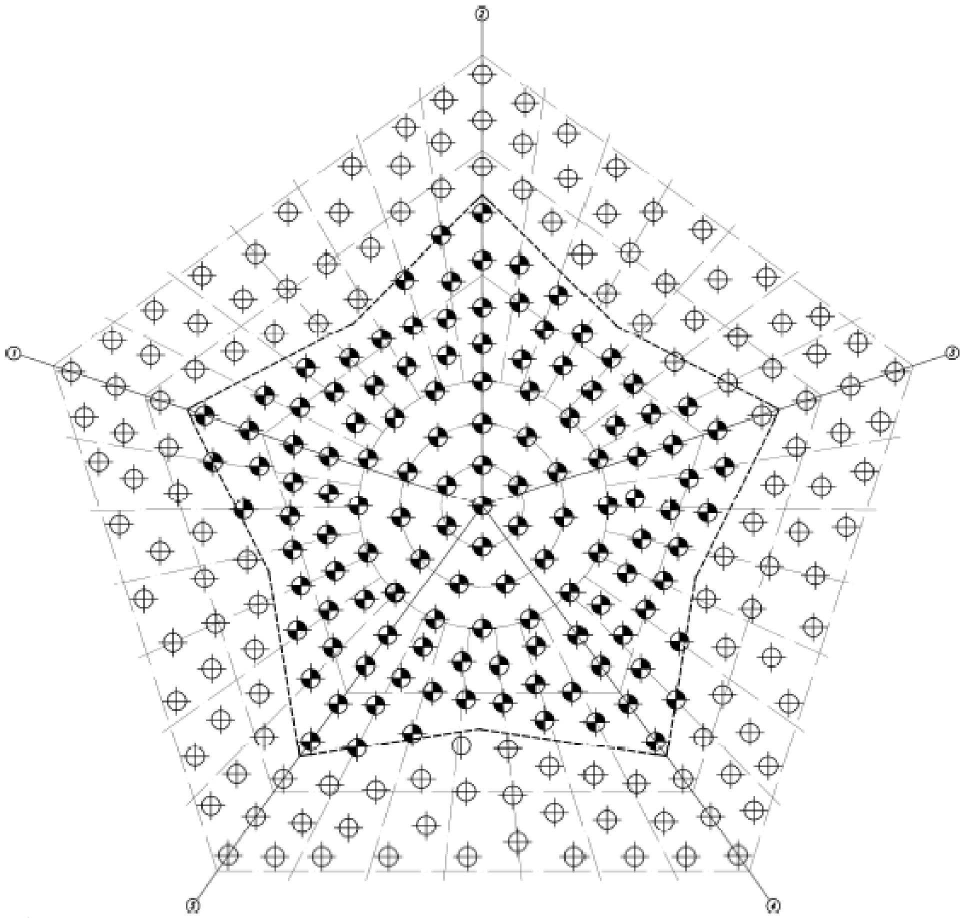
PLATINUM

December 2018

MAHESH RAMANUJAM, PRESIDENT & CEO, U.S. GREEN BUILDING COUNCIL,
PRESIDENT & CEO, GREEN BUSINESS CERTIFICATION INC.

Appendix 7

Pile foundation layout of Lakhta center
Derived 31st of August from INFORCE project library



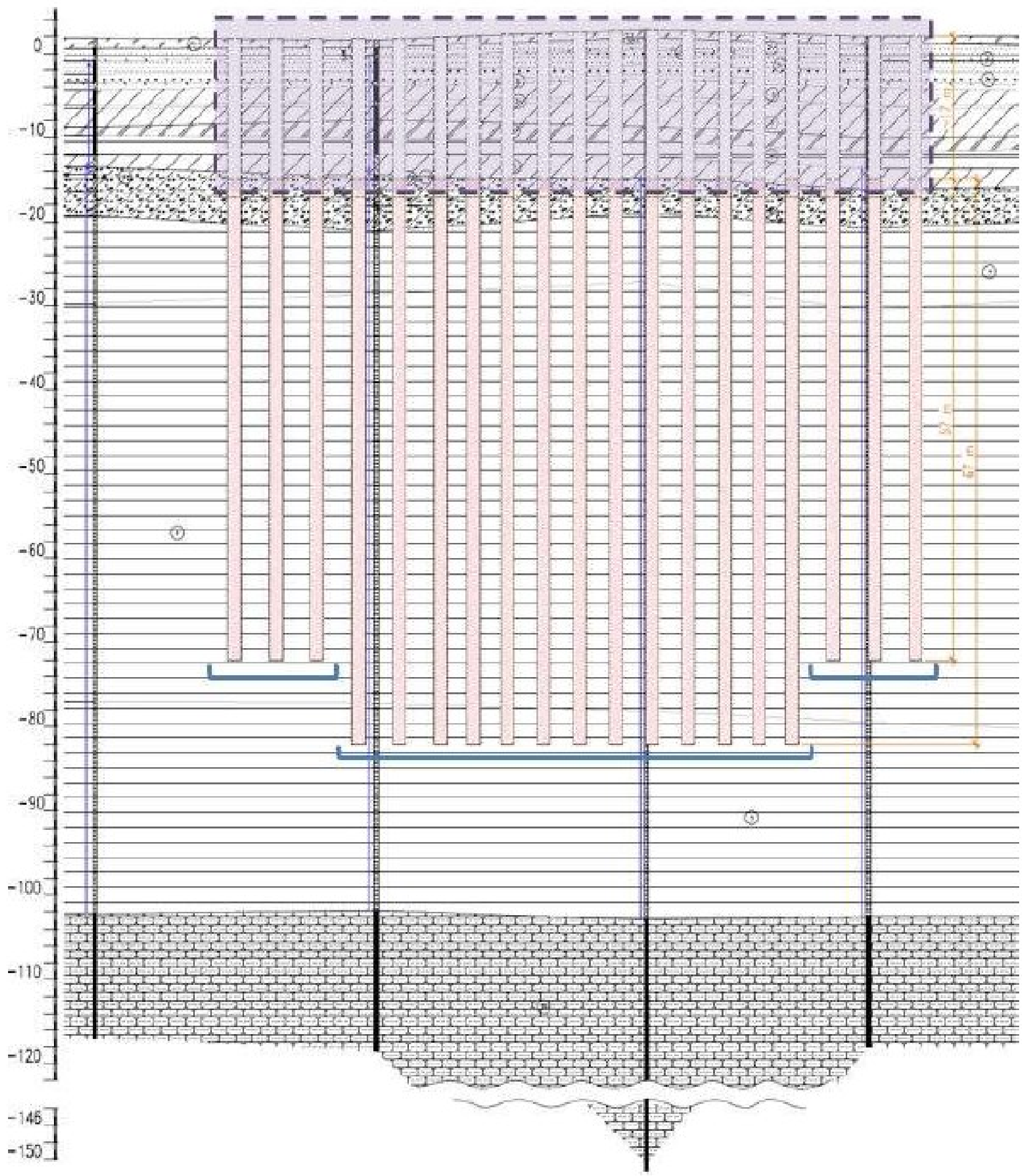
Сваи длиной 65метров от дна котлована

Сваи длиной 55метров от дна котлована

План свайного основания башни Лахта Центр

Appendix 8

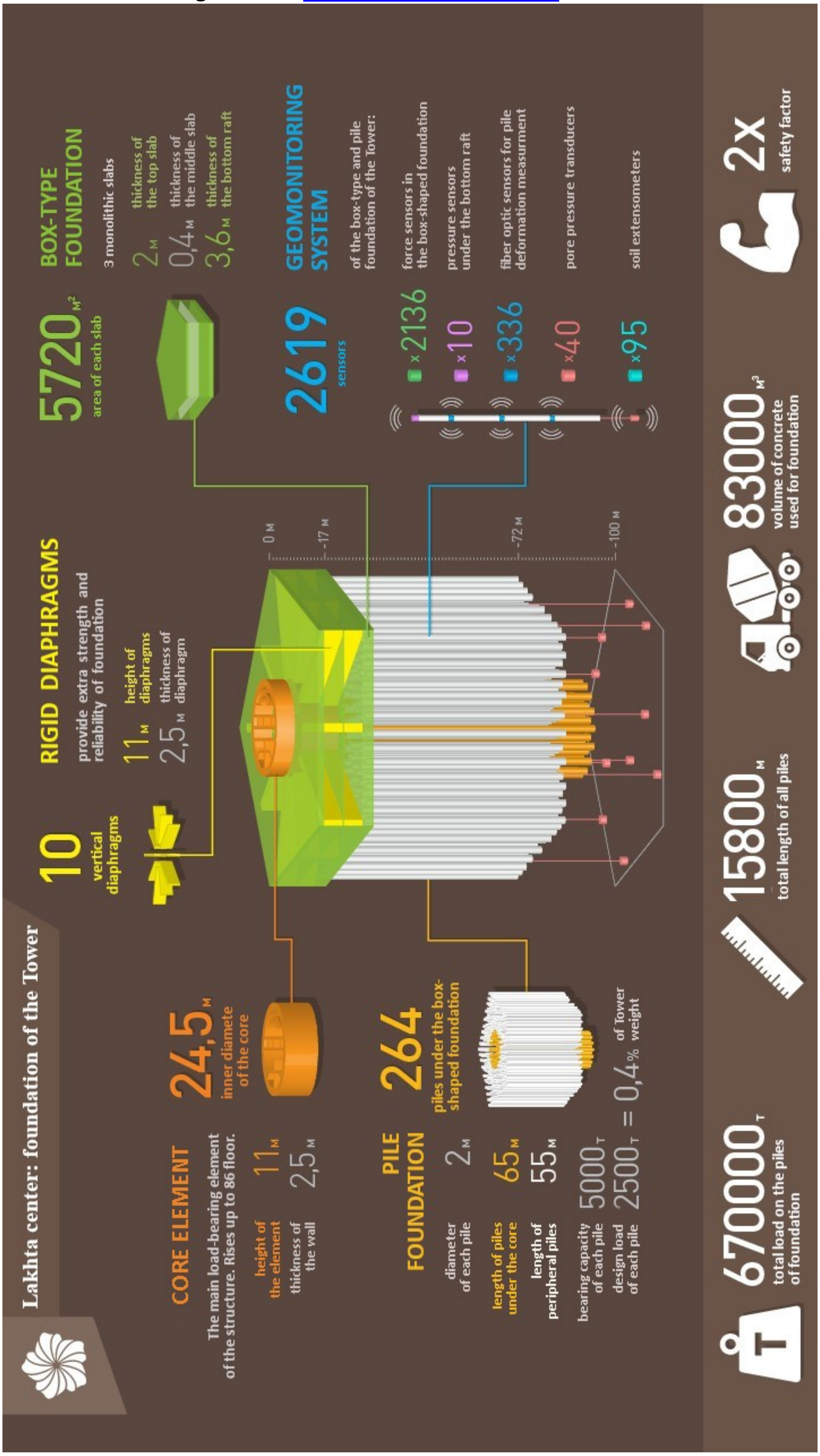
Pile foundation cross-section
Derived 31st of August from Inforceproject library



Appendix 9

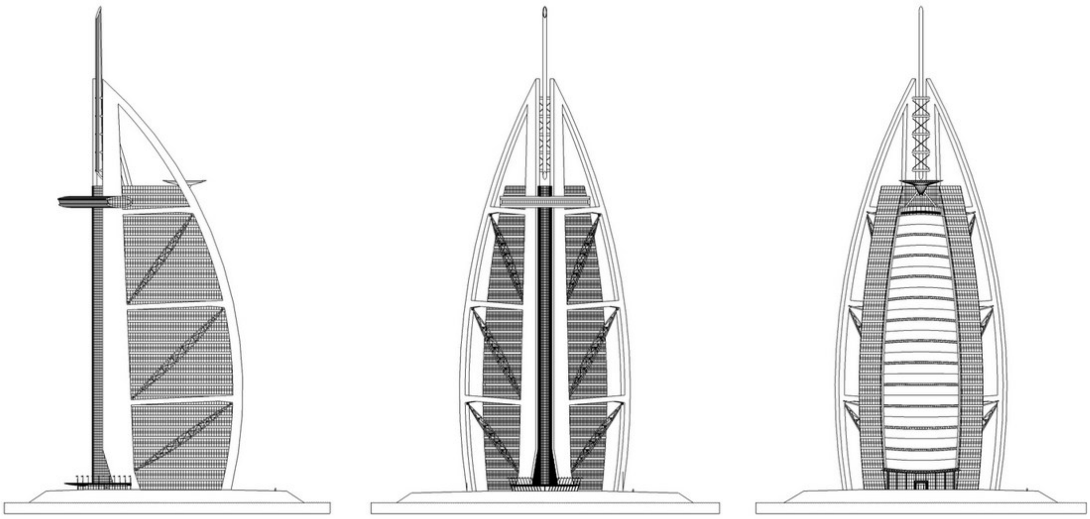
Lakhta Center: foundation of the Tower

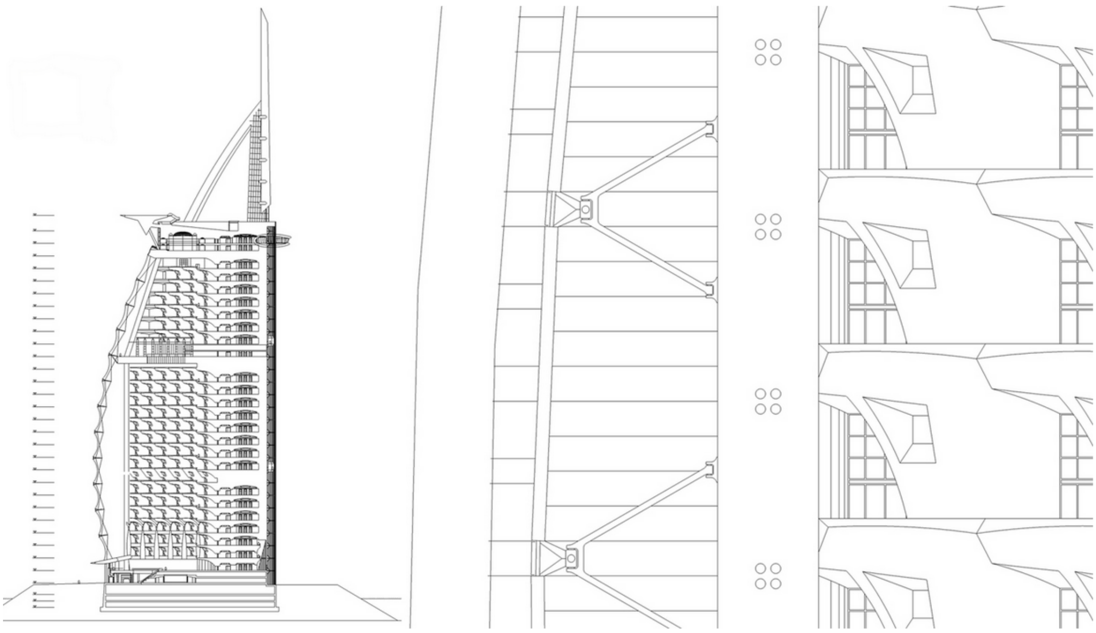
Derived 25th of August from https://lakhta.center/ru



Appendix 10

Architectural drawings of Burj Al Arab
Derived 19th of September from https://wkkarchitects.com/aburj-al-arab-dubai-2

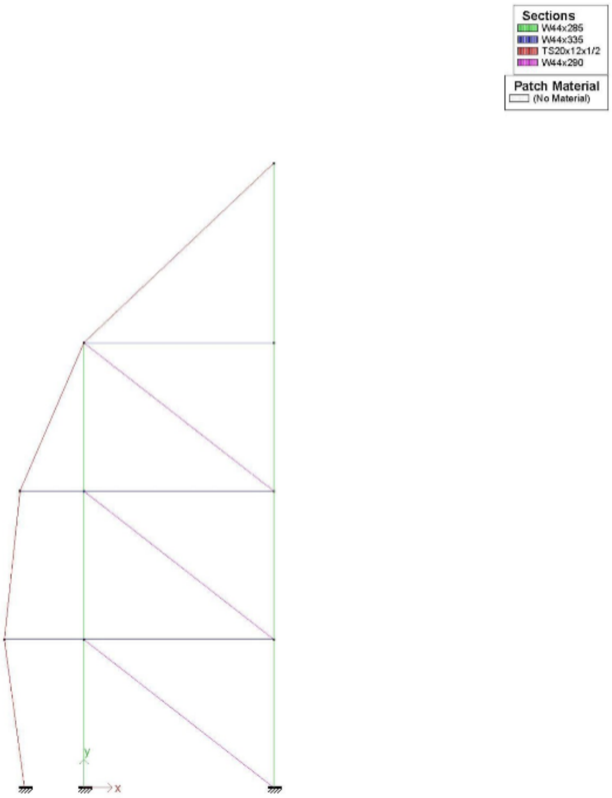




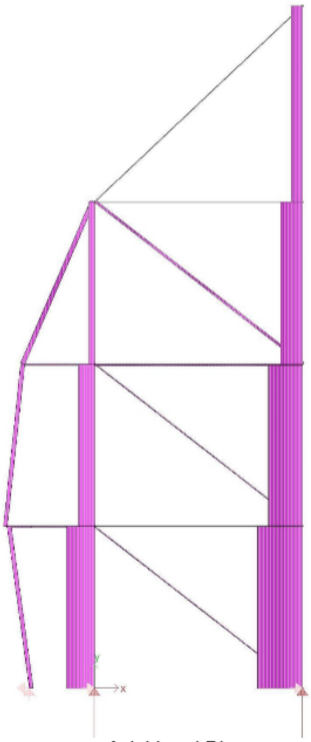
Appendix 11

Structural Load Analysis of Burj Al Arab

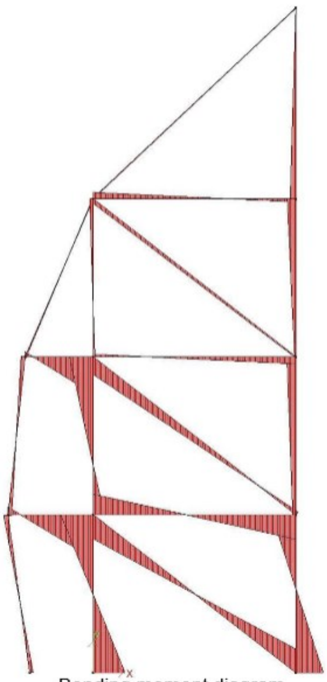
Derived 19th of September from https://docplayer.net/47292762-Case-study-burj-al-arab-dubai-by-chetna-shaktawat-deeksha-joshi-sakshi-gandhi-prodipta-chatter-jee.html



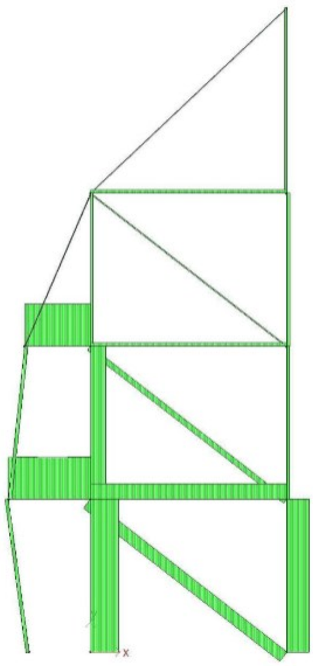
Multiframe 2D Model of Building section



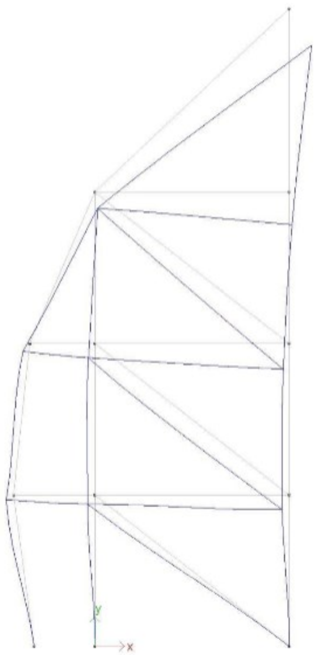
Axial Load Diagram



Bending moment diagram



Shear force diagram



Deflection diagram

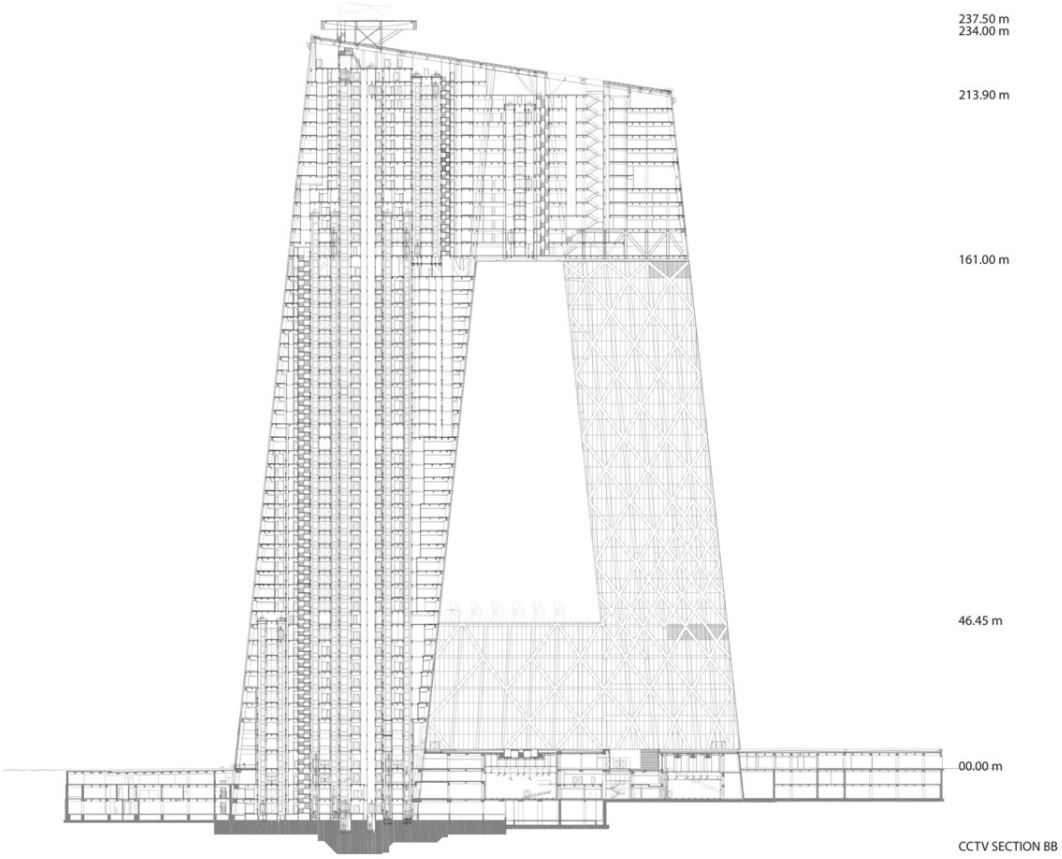
Appendix 12

Site plan of CCTV Headquarters

Derived 19th of September from https://www.archdaily.com/236175/cctv-headquarters-oma

Appendix 13

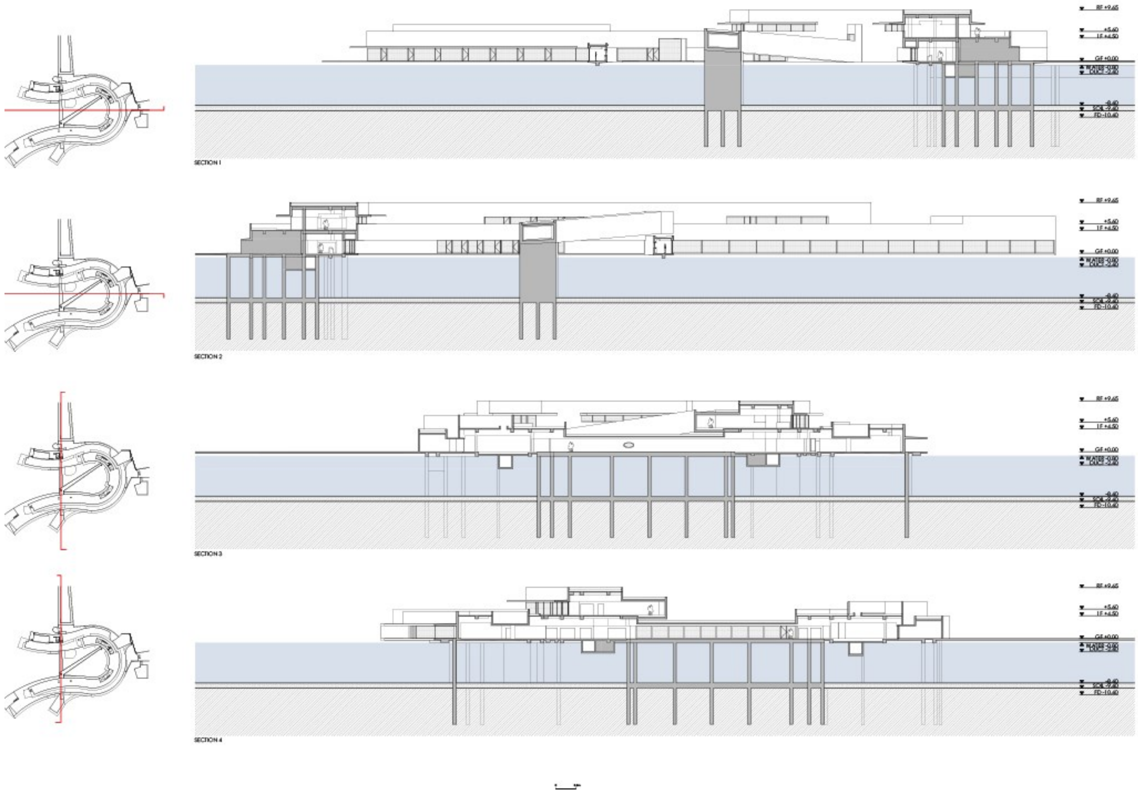
Cross-section of CCTV Headquarters
Derived 19th of September from https://www.archdaily.com/236175/cctv-headquarters-oma



Appendix 14

Cross-sections of Shihlien Group Offices

Derived 26th of September from http://habitarportugal.org/EN/projecto/edificio-de-escritorios-da-fabrica-shihlien-chemical-industrial-jiangsu-co/



Appendix 15

1st floor plan of Shihlien Group Offices

Derived 26th of September from http://habitarportugal.org/EN/projecto/edificio-de-escritorios-da-fabrica-shihlien-chemical-industrial-jiangsu-co/

Appendix 16

Coast Breakwater

Derived 27th of September from http://www.evolo.us/coast-breakwater-vertical-community-in-senegal-for-rising-sea-levels/

Appendix 17

Airscraper modules
Derived 27th of September from http://www.evolo.us/airscraper/