Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

STUDY OF THE DIFFERENT ALTERNATIVES FOR THE COMMERCIAL CONSTRUCTION PROCESS OF FOWT CONCEPT WINDCRETE

Treball realitzat per:
Adrián Yagüe Martín

Dirigit per:
Climent Molins i Borell

Grau en:
Enginyeria Civil

Barcelona, 16 de Juny 2017

Departament d'Enginyeria Civil I Ambiental

TREBALL FINAL DE GRAU

STUDY OF THE DIFFERENT ALTERNATIVES FOR THE COMMERCIAL CONSTRUCTION PROCESS OF FOWT CONCEPT WINDCRETE

Adrián Yagüe Martín

My sincerest thanks to Professor Climent Molins for all his guidance, determination and for granting me the opportunity to participate in such a creative project in a prominent field of civil engineering. A special thank you the the lecturers and researchers at TU Delft for their knowledge and enthusiasm.

I would like to thank fellow students and friends, Pablo, Nacho and Álvaro for all their genuine feedback which always inspired me to aim further.

I would like to thank my dearest partner, for all her love and confidence, and her natural thrill that kept me going when spirits were low.

Finally, I would like to express my gratitude to my parents, Raquel and Agustín, who never ceased to offer their unconditional support, patience, and love. Without you, I wouldn't be who I am today.

Adrián Yagüe Martín
15th of June 2017

STUDY OF THE DIFFERENT ALTERNATIVES FOR THE COMMERCIAL CONSTRUCTION PROCESS OF FOWT CONCEPT WINDCRETE

GLOBAL INDEX

INTRODUCTION

MOTIVATION

The vast wind resources available at far-off deepwaters, together with the challenges encountered by traditional bottom fixed offshore wind turbines with increasing depth, have made evident the need for a new generation of solutions capable of harvesting the huge potential of offshore winds. To meet the industries demands and deploy offshore wind turbines at larger depths with lower costs, a whole new way of thinking may be the only solution.

Floating support structures have one immediate advantage –probably one of the most attractive–they are suitable for a wide range of depths which in turn allows the industry to expand to new countries and regions, such as the Mediterranean, Norway, the United States and East Asia.

As of today, cost reduction is the biggest challenge facing offshore wind. The possibilities of Floating Offshore Wind Turbines (FOWT) to bring down these costs are promising. These possibilities will be reasoned for a particular novel concept of FOWT, Windcrete.

Windcrete was born in UPC Barcelona from the mind of researcher and professor C. Molins and his team as an inherent reaction to the challenges encountered by the offshore wind industry. The concept was designed to counter two of the main cost-drivers that today constraint major deployment; expensive installation practices and excessive maintenance.

Windcrete is the first concept that incorporates tower, transition piece and floater in a single monolithic structure made out of concrete. By reducing the number of elements to just two single irreducible elements –turbine and support structure–, Windcrete hopes to bring offshore wind to its simplest expression.

For this reason, Windcrete should not be seen just as a spar-buoy, the particular floating concept it relies on to achieve stability, but as a completely new way of understanding FOWT support structures. Such a concept would ideally be produced in factory conditions as pre-fabricated high-quality elements ready-to-tow to final location.

If a cost-efficient construction process is defined, Windcrete could very well hold the key to achieving the major cost reduction the industry has been craving and contribute to unlocking unlimited carbon-free wind sources for many regions across the globe.

PROBLEM STATEMENT

The starting point of this thesis is the fixed design of Windcrete presented by C. Molins in *Spar concrete monolithic design for offshore wind turbines* (2016). The design, dimensions and other relevant details will be presented in **Chapter 3.** The characteristics of the structure will be mentioned but will not be discussed in depth. The aspects concerning construction constraints however will be treated thoroughly.

The conceptualization of Windcrete is at an advanced level, its ability to survive the harsh offshore conditions has already been proven, which means it is time to assess the feasibility of constructing such a concept. Each FOWT design will lead to differences in constraints during construction with regard to dimensions, geometry, preferred construction materials, installation procedure etc.

For our project, construction constraints are clear. A large concrete structure built in horizontal position, preferably in a single monolithic pour with high quality standards, and this within reasonable production time. Handling operations of the finished structure should be kept to a strict minimum, preferably avoided alltogether. Flooding of the dry- dock where construction takes place must allow a cost-effective transport to the final offshore location.

The construction possibilities that emerge from these constraints are incredibly different. Windcrete designers support construction using a slipform but the truth is many other possibilities exist or, at least, should be considered at preliminary stage.

It is common practice in Civil Engineering works to refer to similar projects successfully carried out in the past to gain insight. However, when it comes to defining a suitable construction procedure for Windcrete one quickly realizes current design trends see FOWT as made out of discrete elements and assembled in an outfitting yard, ready to be floated-out to the offshore location. One also finds that steel predominates in most of today's FOWT concepts, even though hybrid designs also exist (FOWT Nagasaki Demonstration project, Japan). Additionally, the different floater concepts actively been pursued (spar-buoy, semi-submersible & TLP) lead to a variety of geometries and different construction constraints.

The fact that few concepts have reached full-scale deployment leaves us with not many examples to seek inspiration. Statoil´s spar-buoy Hywind is perhaps one of the most advanced spar concepts yet, and the only one that at commercialization level. As of today, Hywind is made entirely out of steel even though the possibility of using concrete is still there (Sjur Bratland Asset Manager for Hywind at Statoil , 2010). Intrinsic differences between concrete and steel lead to radically different design paradigms for the construction process.

The singularity of Windcrete's construction must be recognized. As no prior construction method of Windcrete has been attempted, designers will have to look at existing technologies and beyond for inspiration. Construction proposals will certainly involve far-reaching adaptations of current construction technology from a variety of civil engineering fields to fit the particular needs of the Windcrete project. Creativity must also play a central role in elaborating cost-effective construction proposals.

Inspiring examples include, but are not limited to: cast in-situ tunnel lining methods, open-cut tunnelling practices, slipformed ConDeep structures such as Troll-A (developed by Norwegian Contractors AS, now Aker Marine Contractors AS), production of reinforced centrifugal concrete pipes, offshore caisson technology, and other relevant concrete technology. The aim is to assess the suitability of existing technologies to construct the Windcrete Towers.

The limitations and advantages derived from all relevant examples will serve as a basis to elaborate a series of more tailored solutions compatible with the specific requirements of Windcrete. The main cost drivers for each solution will be identified and some recommendations towards optimization will be done. The assessment and comparison of the proposals will be as rigorous as possible, keeping in mind that aspects like costs, execution risk and technological complexity can only be roughly estimated. More creative proposals will be even harder to assess due to the lack of information.
Even though at this stage the final results of this thesis remain uncertain, it appears reasonable to assume that the conclusion will not establish a unique construction method but rather a comparison of several possible methods. Nevertheless, some preferences may result from the research and some methods may be discarded for obvious reasons like economic or technical unfeasibility. The most promising alternatives will be further elaborated.

Difference will be made between the construction procedure for a single Windcrete tower -to serve as a full-scale prototype for instance- and the construction procedure for the chain-fabrication in a specifically-tailored plant. However, the focus of this report lies in defining suitable methods for the commercial serial production of such structures, industrializing the process as much as possible.

As mentioned earlier, it is not the goal of this paper to provide a unique solution but rather a comparison of different possibilities. The goal of this work may very well be to narrow down the several possibilities and eventually present some preferred methods that serve as starting point for further investigation.

Construction will be done in a dry dock or similar coastal facility. Particular attention will be paid to formwork -more precisely modular formwork engineered systems- a key driver of total construction costs.

We will see that formwork constitutes a major part of the overall investment and how optimization at this level is critical to the feasibility of the project.

Even though it is true that this paper will primarily focus on the construction process, one should keep in mind that this academic work hopes to find to find its place in a broader spectrum of documents and ongoing investigations that have one common goal: the successful implementation of Windcrete. For this reason, it seems negligent to directly address the constructability without first looking into all the phases of the planning process that precede construction. All phases essential to the successful outcome of the project will be duly described.

OBJECTIVES

The scope of this academic work is to assess the constructability of a monolithic concrete spar buoy concept –Windcrete- by comparing several proposed methods that will be duly described and confronted with each other.

To work towards this goal, an extensive overview of a broad range of civil engineering technologies will be carried out in search for an appropriate solution to constructing Windcrete. To achieve this, an open-minded exploratory mind-set will be adopted at early stage to come up with a wide range of candidate solutions

The main objective of this overview is to assess the suitability of diferent engineering practices, which will be understood as assessing the degree of adaptation they must undergo, if any, to become convenient for Windcrete tower production.

The suitability will be measured in terms of the degree of adaptation, and the most promising technologies will be used to elaborate a series of potentional contruction solutions which we will call *construction proposals*.

More specific requirements will include a detailed description for each of these proposals, establishing their main requirements, presenting their operative cycles and identifying the estimated cost-drivers ruling over the methods. The claimed advantages and disadvantages for each method will be discussed as well.

After generating several construction proposals with sufficient detail, the findings of this academic work will culminate in a Multi Criteria Analysis (MCA), where each proposal is appointed a score based on how well it satisfies all the desired requirements of Windcrete production. Horizontal construction, cost-effectiveness and serial production will be pivotal for the evaluation criteria of proposals.

Discussion and conclusions of the results of this MCA will help narrow down the list of candidate solutions. The optimal solution will only be obtained after multiple screenings, developping promising solutions with greater detail and future research. This academic works hopes to provide the first screening of potential solutions.

BACKGROUND

In the past decade, offshore wind turbines have witnessed an exceptional growth in the coasts of Europe. In 2005, the total installed offshore wind capacity in Europe was 804.5 MW, by the end of 2015 this figure increased to 11 027 MW of installed offshore wind capacity, an increase of 1270.67%.

Boosted by know-how gathered from European R&D and deployment activities, expansion towards the sea makes wind energy one of the most mature renewable energies, which continues to grow.

As of today, Europe now has a total installed capacity of 12,631 MW from 3,589 grid-connected wind turbines spread over 81 offshore farms in 10 countries. Northern Europe has been the setting in which these offshore structures have flourished and the remarkable prosperity of offshore wind turbines make it one of the fastest growing maritime sectors. As a result, the European Wind Energy Association (EWEA) expects offshore investment to overtake onshore in about 2023.

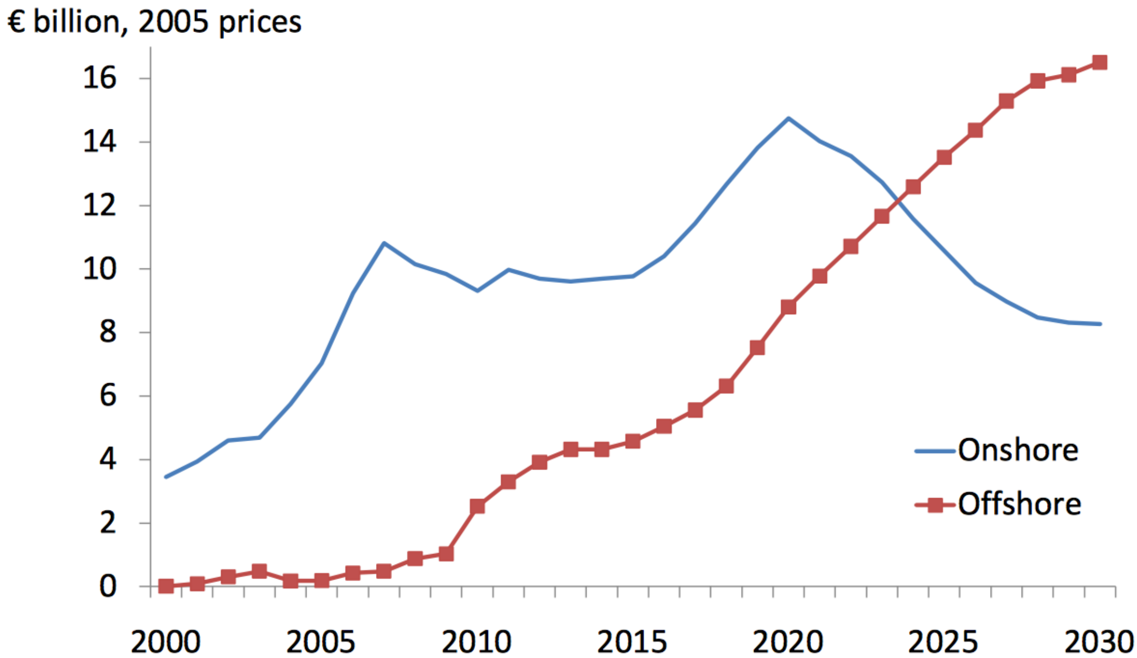


Figure 1. Predicted wind capacity investments in Europe. Source: EWEA (2009)

The commercial deployment of offshore wind turbines is impressive, especially if one looks back at the fast evolution from a technology still in its infancy, barely at demonstration stage, to a well-consolidated form of producing energy from wind. Offshore wind is an emerging and booming industry that has become a key player in the maritime economy, creating jobs and export opportunities by exporting European expertise, skills and technologies across the globe.

This rapid transition from R&D stage to serial production was possible thanks to the agency of the industry that has enthusiastically promoted new designs and cooperation between the research community. The idea to transfer energy producing wind turbines from land to offshore locations is not in itself new, however an inexperienced industry and inconceivable costs kept the idea at purely theoretical stage until the commercial wind industry was well established.

The first offshore wind farm in the world was commissioned on Danish waters in 1991, comprising 11×450 kW turbines. Since then, this rather young industry has been booming all across Northern Europe with major feats like the largest operational offshore wind farm in the world, London Array, completed in 2013 with an offshore area of 100 km^2 with 175×3.6MW turbines, generating enough power to supply as many as 500,000 homes.

The industry is rapidly maturing and is on the way to securing widespread acceptance by consumers, investors and politicians. Yet, the eye-catching proliferation of offshore turbines does not come without challenges. To name a few, towers and foundations and underwater cabling require higher investments than their onshore counterparts. As of now, offshore wind energy is estimated to be 1.5–2 times more expensive than onshore (Watson, et al., 2005). Offshore installation activities are weather tolerant and require expensive crane vessels. As the offshore environment can change by the hour, these activities can quickly become unreasonably expensive. Another set of challenges offshore wind farms face is related with trends displayed in more recent projects. The industry is moving to deeper waters in search of high-energy offshore winds, increasing foundation costs and complicating O&M operations. Together, these difficulties set the background for the development of existing and future concepts.

Other challenges also include non-technical aspects. The development of offshore wind depends on the reliability of regulation and the stability of political support. The young industry relies on public support schemes and successful offshore wind deployment will need a politically backed master plan at the national and European level. The financing of offshore wind projects must improve significantly by introducing financing instruments that reduce the risk for investors to facilitate private sector involvement. Therefore, technical aspects do represent a key challenge in unlocking the potential of offshore wind but the financing of projects must also be addressed and policy-makers will need to put in place a stable regulatory framework and define long-term policy schemes. The sector will need to overcome technical, economic and political challenges for a large-scale deployment.

Keeping in mind that non-technical aspects are as critical to enhance deployment of offshore turbines, the main challenges this academic paper would like to address are those related with the technical aspects that appear during the entire implementation process, ranging from construction to installation at the final offshore location.

Despite the unparalleled success of offshore wind, building offshore turbines still comes at great expense. Common practices used for erecting offshore wind turbines typically require the use of large floating cranes and expensive equipment as part of the assembly process is undertaken at the offshore site. Weather sensible installation and highly specialised equipment can quickly drive the project cost out of range in an uncertain offshore environment. The following diagram aims at emphasizing costs at sea. For now, the actual manufacturing costs are not presented, but rather the cost magnitude of the activities relative to their duration and where they are carried out. As depicted, activities carried out under offshore conditions, even for relatively short duration, amount to considerable costs.

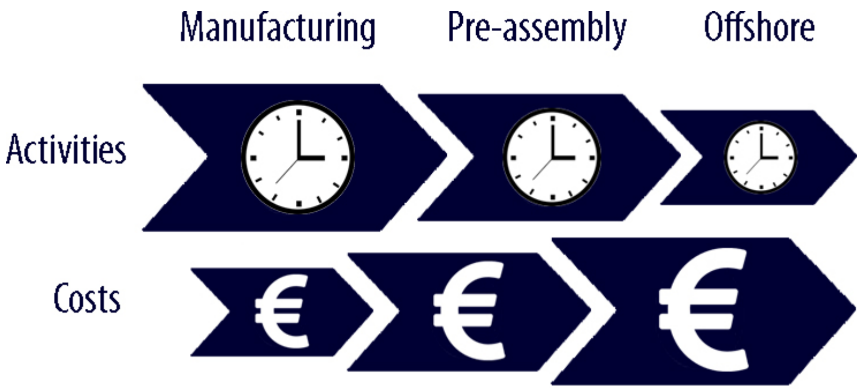


Figure 2. Costs at sea relative to duration of activities

Intuitively, one can deduce that clustering as many possible activities ashore will result in a considerable cost reduction. In fact, an ideal implementation process would avoid undertaking any activities offshore whatsoever and carry out all heavy construction activities at an onshore facility. Ideally, the offshore wind turbines would be fully manufactured and assembled on land and only then transported to the final destination and installed with minimum use of heavy floating cranes.

Before going any further in identifying the predominant challenges encountered by offshore wind turbines, let's have a look at why the wind industry has set eyes on maritime wind power.

Deploying turbines at sea presumably comes with higher installation costs and a whole new set of executional obstacles that do not exist on land, yet the industry displays a persistent interest in expanding their market horizon to offshore winds. For the industry, the advantages of offshore wind turbines with respect to their on-shore counter parts are clear. To name a few:

- Over 75% of worldwide power demand comes from coastal areas.
- Vast offshore wind resources with higher and steadier wind speeds, generating more energy with fewer turbines.
- Un-limited space.
- Noise and visual impact are no longer a restriction and allow larger, higher and noisier turbines.
- Lower offshore wind turbulence.
- Availability of experience and knowledge gained from Oil and Gas offshore platforms.
- Scarcity of adequate space for the installation of onshore wind turbines.
- Avoid high property values in densely populated coastal regions.

These advantages explain why the wind industry has set eyes on maritime wind power and promotes a progressive shift from onshore to offshore turbines. The vast wind resources available offshore have offset the increased costs of deploying structures at sea. The industry is willing to assume greater implementation costs and tackle new challenges in exchange of generating more energy.

Nonetheless, the wind energy community has regularly welcomed new concepts in search for more cost-effective solutions. Everything seems to indicate that the industry is strongly committed to continue in its quest to unlock the full potential of offshore wind turbines but it is well aware a major cost reduction is in order. Plus, the benefits of offshore wind increase at further offshore locations, in line with the observable market trends within the industry: the main players are moving further from shore and into deeper waters. However, installation costs become unreasonably high for larger depths with current fixed-bottom technology.

As the industry looks for new options, the concept of floating wind turbines arrives as a promising alternative that may very well be at the heart of such solutions. It is in this context that new concepts are emerging, including the one that will be at the heart of this paper, Windcrete. Windcrete is a concept of floating offshore wind turbine (FOWT) born from the mind of researcher and professor C. Molins as a reaction to the current and future challenges faced by conventional bottom fixed turbines. This particular FOWT concept and all the challenges faced by bottom-fixed turbines will be discussed promptly.

Even though the term might appear inadequate for such a relatively new technology, bottom-fixed offshore turbines will often be referred to as conventional offshore turbines. Bottom fixed turbines are recent, but their rapid evolution and massive expansion has allowed the technology to reach a quick maturity in these past years. By referring to them as conventional, one implies that a new set of solutions is needed.

If floating structures could replace bottom fixed techniques, they could remove depth imposed restrictions and re-shape the entire construction and installation procedure resulting in a new design paradigm.

Their advantages with respect to conventional bottom-fixed turbines have yet to be clearly defined, yet the possibility of benefitting from an entirely different working principle for the installation process emerges with floating structures. These new possibilities should be thoroughly explored as any alternative solution to current installation techniques could lead to a much-needed cost reduction. Installation costs are a considerable part of the overall costs for bottom-fixed turbines any attempt to bring a cost-effective solution will need to optimize this aspect.

Everything seems to indicate that if a cost-efficient reliable solution able to meet all the requirements is presented to the offshore wind industry, it will be there to stay. Floating structures could lead the way in this quest but they also come with unexplored challenges that will need to be identified and tackled in a new design paradigm. The new and unique trade-offs that emerge with FOWT must be appropriately grasped and used advantageously if these offshore turbines are to become a promising cost-effective solution.

As the industry wishes to advance towards greater winds found at more distant sites, beyond the depth at which existing foundation technologies are commercially viable, new technologies become the only solution. FOWT could represent a major breakthrough for the world renewable energy production. Not only could they have a huge impact in the consolidation of renewable energies in the worlds energy production but it could represent a big leap forward for the overall sustainable green growth of the planet.

1. OVERVIEW OF OFFSHORE WIND

1.1. WIND TURBINE COMPONENTS

A turbine, which can also be referred to as Rotor-Nacelle Assembly (RNA), is composed of several elements. An overview of the main elements common to all wind turbines will now follow.

ROTOR: *Blades and hub together form the rotor*

NACELLE: *Contains the gear box, low and high speed shafts (for gearbox-operated turbines), generator, yaw system and brake. Some nacelles are large enough for a helicopter to land on.*

1.1.1. ROTOR ELEMENTS

BLADES: Wind lifts and rotates the blades, causing the rotor to spin. Blades are made of fiberglass composites and epoxies with carbon becoming more prevalent as blade sizes increase. Large turbines may have blades that are over 50 meters long meaning rotor diameters can be over 100 meters long. Each one has an in built electrical control system that allows each one to have their pitch angle easily adjusted.

Most turbines have three blades but there is a recent renewed interest in two-blade turbines. Blades can represent around 20% of the cost of a given turbine.

HUB: Load carrying structure typically made out of cast iron. Its design is optimized for low mass and its main function is to transfer the loads from the blades to the main shaft. The hub is protected by an aerodynamic cover typically made out of composite or an aluminium sheet.

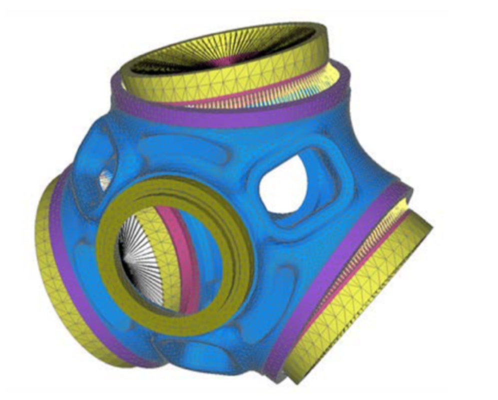


Figure 3. MODELLING OF HUB. Source: http://cepemax. de

Figure 4. HUB COVER. Source: http://technoplastimer.com

1.1.2. NACELLE ELEMENTS

Generator systems of wind turbines

There are two types of generator systems for wind turbines, gearbox systems that are extensively used, and direct drive systems gearless which engineers are exploring to install on upcoming offshore projects.

GEARBOX GENERATOR: This is the traditional design for wind turbines. The blades spin a low-speed shaft at about 30-60 rpm that is connected through a gearbox to the generator. The gearbox connects the low-speed shaft to the high-speed shaft and converts the lower turning speed of the blades into much faster 1000-1,800 rpm; the rotational speed required by the generator needs to produce electricity.

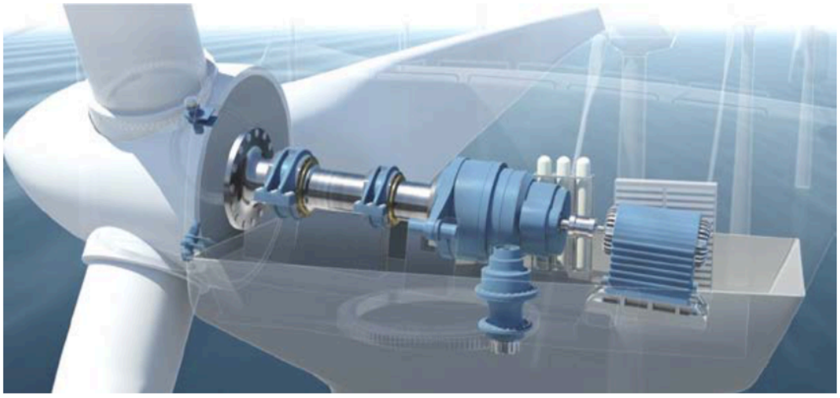


Figure 5. Drive train with gearbox, traditional wind turbine.
source: http://www.schaeffler.de/content.schaeffler.de/de/index.jsp

DIRECT-DRIVE GENERATOR: These turbines take the power coming from the blades without any reduction (such as a gearbox). Direct drive, or gearless systems, operate at lower rotational speeds by replacing conventional high-speed generators with a low-speed generator eliminating the need for a gearbox.

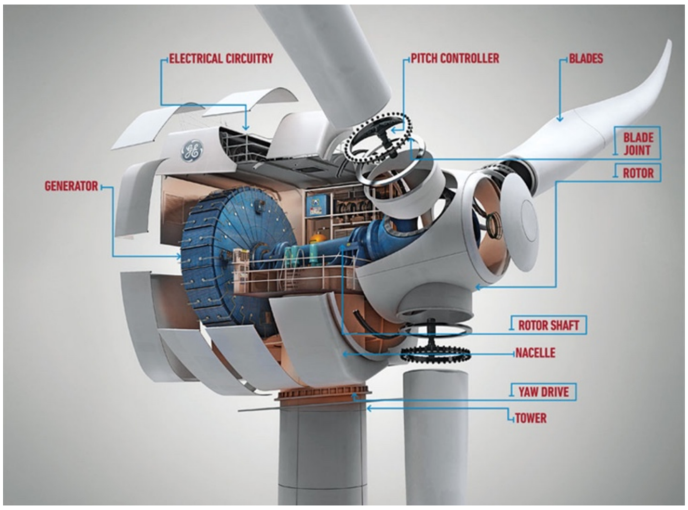


Figure 6. Direct-drive turbine. Created by Nick Kaloterakis

Direct drive technology has been praised for its design, which is less complex than gearbox technology, leading to easier operations and maintenance. (Morris, 2011) The most preferred direct drive wind turbine generator is the permanent magnet type generator, as it is lighter in weight and possesses high reliability for offshore applications. However, these generators require precious materials which are subject to political pricing as China is the main supplier. (Böhmeke, 2013)

BRAKE: stops the rotor mechanically, electrically or hydraulically in emergencies. An aerodynamic brake is also possible by enabling the blades to pitch to invert the aerodynamic torque.

YAW SYSTEM: Sensors allow the yaw system to orient upwind turbines to keep them facing the wind when the wind direction changes allowing maximum productivity.

1.1.3. SUPPORT STRUCTURE

The elements that constitute a Wind Turbine have now been introduced. The main physical difference between bottom/fixed and floating wind turbines is the absence of a foundation for FOWT, resulting in a completely different paradigm for the design of the support structure.

The Support has 2 main functions:

- Keep the RNA in place.
- Provide access to nacelle.

Besides complying with these 2 functions, support structures for offshore wind turbines shall also be designed to:

- Sustain loads liable to occur during the design life of the structure, including all temporary, operating, survival and damaged conditions.
- Ensure acceptable safety of structure during the design life of the structure
- Maintain acceptable safety for personnel and environment
- Have adequate durability against deterioration during the design life of the structure

As the main differences between conventional offshore turbines and floating concepts lies in the support structure they will be treated separately

SUPPORT STRUCTURE FOR BOTTOM-FIXED TURBINES

Support structure refers to the entire offshore structure spanning from the sea bed to the RNA (Rotor Nacelle Assembly). Generally speaking, it is composed of 3 different elements: tower, sub-structure and foundation. In reality each type of bottom-fixed solution has its owns particularities.

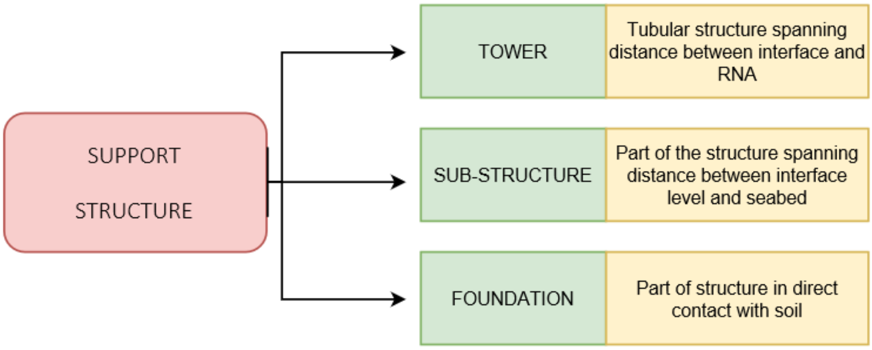


Figure 7. Definition of support structure

Hub height is defined as the elevation of hub above sea level.
The **interface level** is defined as the elevation of the bottom of the tower above sea level.

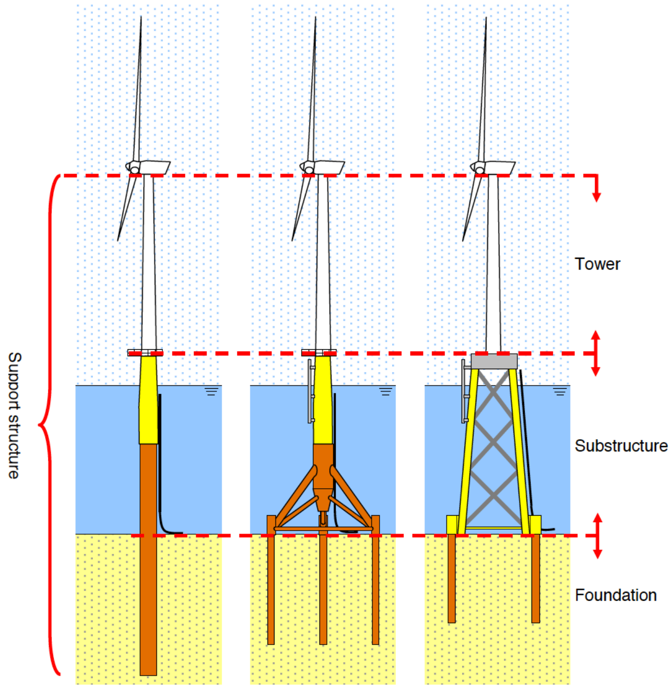


Figure 8. Definition of 'support structure' and main elements for 3 existing concepts.

FLOATING SUPPORT STRUCTURES

Floating support structures will be an integral part of this academic work, here only the outline is introduced. The main functions of the support structure are exactly the same as for bottom-fixed turbines, carry and provide access to the RNA. However, these will not be the only functions as they must also provide enough buoyancy to support the weight of the turbine and to restrain pitch, roll and heave motions within acceptable limits. (Butterfield, et al., 2005)

Before describing the several concepts that exist, a floating support structure can generally be broken down into the following systems:

- **Floater**: Part of the structure bellow water. Its primary function is to maintain buoyancy.

- **Tower**: Part of the structure above water. It must guarantee structural integrity and ensure vertical position of the turbine for maximum productivity.
- **Moorings**: connect the floater to the seabed.
- **Anchoring**: attach the mooring lines to the seabed.
- **Electrical cable**: export of power.

The geometry of the floating platform - the floater concept - will primarily be determined by the method through which the floating structures achieves stability. As these methods will be described with further detail in upcoming chapters, here they will only be briefly presented.

Three floater concepts exist today, and each can be associated to the particular method it relies on to gain stability.

Spar-buoys concepts mainly rely on ballast-stabilized floaters to resist the occurring moments at the top of the structure.

Barge-like floaters, commonly referred to semi-submersible or semi-sub, rely on buoyancy to achieve stability similar to ships.

Tension leg platforms are vertically moored to the seafloor by tensioned tendons which allow the system to move horizontally with wave disturbances, but does not permit vertical movement.

In practice, all floating concepts are actually hybrid designs that gain static stability from all three methods, although generally relying on one primary source for stability (Butterfield, et al., 2005). All of the above-mentioned concepts have flourished in the O&G industry and only recently have they started to be actively investigated for offshore wind applications.

Figure 9. 3 Existing Concepts Of 'Floating Support Structures': Spar-Buoy, Semi-Submersible and TLP. Source: https://www.dnvgl.com

1.2. AVAILABILITY AND ACCESS OF OFFSHORE WIND TURBINES

High availability is fundamental to the economics of offshore Windfarms. The costs of turbine downtime are often the greatest cost penalty, exceeding the direct cost of component or system replacement. The costs of loss of production are such that even expensive access can still be justified.

Several access methods include:

- **Helicopter access** to the nacelle top. Winds speeds should be less than 19 m/s. The helicopter cannot land but can lower personnel if the turbine is built for it. As a routine method, helicopter access is probably too expensive given current wind farm size and distance to shore. As distance to shore increases access by helicopter may become a reasonable way to access turbines.

- **Standard boat and ladder** principle with specialized service vessels, Catamarans generally provide safe personnel access for significant wave height Hs=1.5 m. This is generally possible during 50-80% of the time, which is insufficient for good overall wind farm availability. (European Wind Energy Association, 2009). Experience shows that standard boat transfers cannot –and should not- be attempted in sea states where the significant wave height is greater than 1.5 m.

Figure 10. Lowering of personnel on turbine at Horn Rev 1. Source: http://www.uni-fly.dk

Maintenance can only be undertaken effectively and safely during relatively calm atmospheric conditions. Due to their remote offshore locations, a safe working environment can sometimes be a rare privilege. Certain sites have very limited access rates for repair and maintenance, which may even be impossible during several weeks. For instance, it was estimated that for a site off the coast of Ireland turbines are reachable for repair only about 50-75% of the whole year. (Lönker, 2004)

Access impediments include icing (especially in the Baltic Sea), wind speeds higher than 12 m/s and high waves. It has been shown that access to turbine base by boat is already challenging in waves around 1 m height even for experienced skippers.

Accessibility is typically worst during the winter, when turbine failures are more frequent, and increasingly complicated with distance to shore, where conditions are harsher. Providing access in wave heights higher than 2.5 m is too challenging from a technical point of view and is considered unsafe. With some efforts, availability may increase slightly if access is made possible up to significant wave heights of 2.5 m but Improvements in availability of offshore wind turbines must be achieved through improved system reliability rather than increasing access.

Repairs and maintenance operations are so weather sensible and difficult to plan that in the case of Horns Rev 2 -an offshore wind farm located 30 km off Denmark- it was deemed more economical to build an accommodation platform (the first for an offshore wind farm) named Poseidon. It is connected by walkway to the transformer platform. It has 3 decks, weighs 422 tons and is manned year-round by up to 24 workers

On-site accommodation was estimated to be cheaper and more efficient than transporting service personnel by boat. As projects move further away, transit times by vessel will be too impractical for day-workers and constructing accommodation platforms or using helicopters will become a credible alternative.

*Figure 11. Poseidon (right), the first offshore wind farm accommodation platform in the world.
Source: (Maritime Denmark, 2013)*

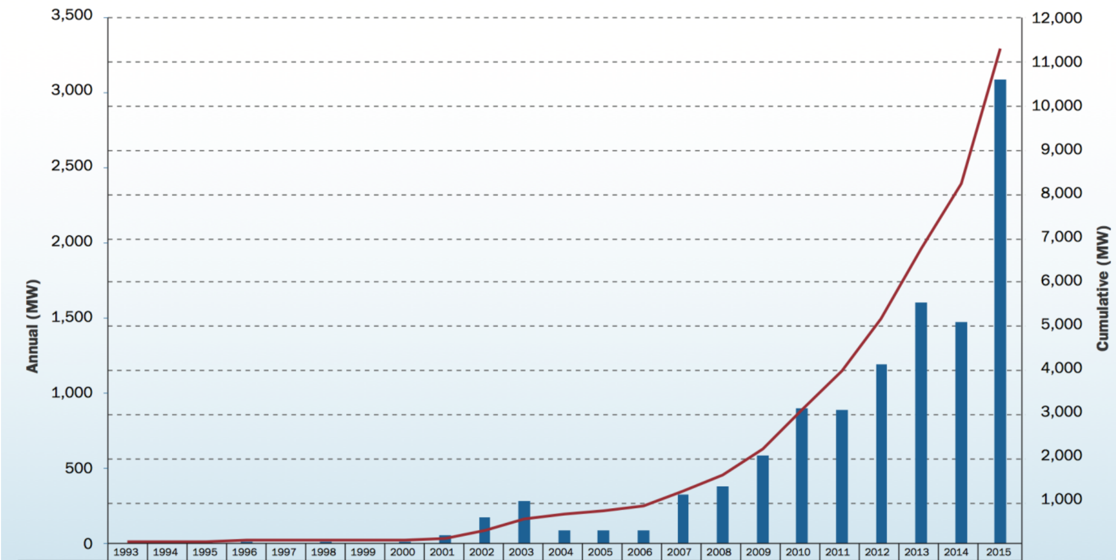
Limited access calls for a design based on reliability. Turbine manufacturers have already put the accent on new, more reliable turbines. Logically, the support structures must also be designed according to this principle. What can be established is, even if accessibility plays a strong role, maximizing availability should focus on increasing the reliability of all the elements to minimise maintenance operations.

1.3. CURRENT STATUS OF THE EUROPEAN OFFSHORE ENERGY MARKET

The introduction kicked-off by boasting the recent merits of the off-shore wind turbine industry. Let's start off by having a look at the current state of the offshore energy market in Europe.

Europe currently ranks first with 11 GW of installed capacity, more than 90% of the world's offshore wind power. This is due to a welcoming political environment and public awareness of man-made climate change. Logically, available strong wind resources also explain why Europe is pioneer in the installation of off-shore wind turbines and todays undisputed global leader.

Ever since the year 2000 new offshore wind turbines are being commissioned and between 2005-2015 the cumulative installed capacity in MW of offshore wind has grown by a factor 15. With an installed capacity of 5 GW at the end of 2012, Europe's cumulative installed capacity has more than doubled in 3 years reaching 11 GW by the end of 2015. Offshore wind turbines have witnessed an eye-catching prosperity in recent years and is one of the fastest growing maritime sectors. The European Wind Energy Association (EWEA now) provides figures that speak for themselves.



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Annual	-	2.00	5.00	16.8	-	2.80	-	4.00	50.5	170.	276.	89.7	90.0	92.5	318.4	373.5	576.9	882.7	873.5	1165	1567	1446	3018
Cumulative	4.95	6.95	11.9	28.7	28.7	31.5	31.5	35.5	86.0	256.1	532.3	622.0	712.0	804.5	1122	1496	2073	2955	3829	4994	6561	8008	11027

Figure 12. Number of grid-connected offshore turbines and cumulative and annual capacity (MW) 2015. Source: (EWEA, 2015)

In 2007, the annual capacity of offshore wind was more than tripled with regard to the previous year, escalating from just over 90 MW in 2006 to more than 300 MW of installed power by the same date in 2007. From 2007 to 2014 the cumulative capacity increased by a factor 4.

Only in 2015, 14 offshore wind farms were completed and fully grid-connected representing 3,019 MW of new offshore wind power connected to the grid, 108.3% increase over the previous year and marks the highest yearly addition to date. Works are ongoing in 6 other offshore projects contributing a further 1.9 GW that once completed will increase the total cumulative capacity in Europe to 12.9 GW.

There are currently 11 European countries, with different degrees of experience, willing to harvest the free, unlimited and vast resources offered by offshore winds. The following table shows the number of wind farms, total number of turbines and installed capacity for each of these 11 countries. Only wind farms fully connected to the grid at the end of 2015 are included.

Table 1. Number of wind farms with grid-connected turbines, no. of turbines connected and no. of MW fully connected to the grid at the end of 2015 per country

Country	BE	DE	DK	ES	FI	IE	NL	NO	PT	SE	UK	Total
No. of farms	5	18	13	1	2	1	6	1	1	5	27	**80**
No. of turbines	182	792	513	1	9	7	184	1	1	86	1,454	**3,230**
Capacity installed (MW)	712	3,295	1,271	5	26	25	427	2	2	202	5,061	**11,027**

At the time of writing, the UK is leading and will presumably continue to do so with an installed offshore wind capacity of more than 5 GW representing 45.9% of all installations. Germany ranks second with 3.294 MW (30%) and Denmark follows with the third largest amount slightly over 1200 MW, 11.5% of total European installations. Belgium and the Netherlands together supply 1.100MW of offshore wind power, just over 10% of all installations. Sweden has 5 farms with 86 offshore turbines accounting for 200 MW of installed capacity. The remaining 5 countries (Finland, Ireland, Spain, Norway and Portugal) barely represent 0.5% of the installed wind capacity. Norway, Portugal and Spain all have one wind turbine each.

1.3.1. UNEVEN DEPLOYMENT & GEOGRAPHIC REALITY

Development of offshore technology throughout Europe appears uneven. This should not be seen simply as a lack of interest of other countries to deploy offshore wind turbines. Other underlying factors could help explain this uneven development.

For instance, the current financial distress of several European economies or the fact that offshore wind technology is still in its infancy and comes with very high costs, or a combination of the two, could help explain restricted access and expansion of offshore wind turbines. Notice that it is mainly healthy economies that are currently leading in the offshore wind industry.

Another factor may be a literally non-existing framework in most of the European countries. Regulatory uncertainty is the main non-technological barrier restraining offshore wind deployment. The lack of permitting and licensing procedures does not build the necessary confidence for industry and financial players. EU member countries should reach consensus, elaborate policies and define dedicated areas to promote a generalized development offshore wind technology.

Another possible cause for this uneven expansion of offshore wind turbines could be a certain reluctance to change, do not recognize man-made climate change and oppose the long-term decarbonisation promoted with renewable energies. However, for the EU at least, this seems unlikely to be the leading cause for various reasons. All member states have traditional wind turbines in their territory and are well aware wind is a reliable and competitive source of energy that generates net benefits and contributes to energy security. A poll in 2010 also suggested that about 80% of EU citizens supported wind power and several member states have implemented ambitious renewable energy policies showing that they have accepted a new energy paradigm and the need for a greater share of renewables in the energy mix.

In reality, what is strongly driving the uneven expansion of offshore wind technology is the geographical differences between regions, specifically the differences in water depths. Differences in the geological situation across the globe result in a diversity of water depths depending on the region, even for a same distance to shore. The unequal water depth is explained by the irregular presence of a continental shelf.

A Continental shelf is a geological term that refers to a broad, relatively shallow submarine terrace of continental crust forming the edge of a continental landmass. The geology of continental shelves is often similar to that of the adjacent exposed portion of the continent.

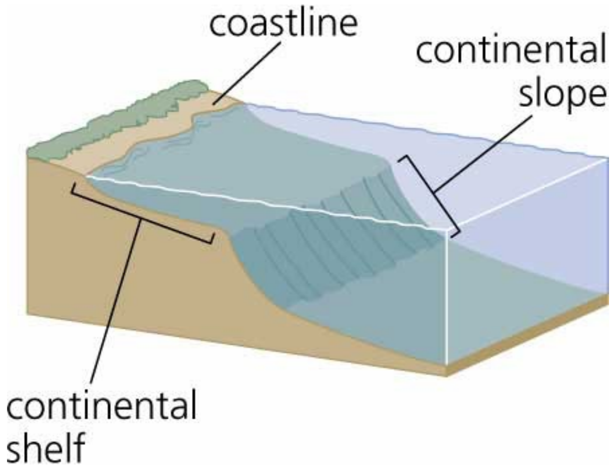


Figure 13. Continental Shelf.
Source: The American Heritage Dictionary of The English Language.

Some regions are characterized by smaller and narrower continental shelfs. It is not uncommon for an area to have virtually no shelf at all which means that the water depth drops suddenly and this fairly close to the shore.

This geological factor alone has a direct impact on designing the foundations for bottom fixed offshore turbines and often translates in unpractical locations to deploy offshore wind turbines. It is interesting to realize that continental shelves only make up an estimated 8 percent of the entire area covered by oceans. This implies that many regions which have no shelf include heavily populated countries like USA, Japan and Korea (see figures 3 & 4). These countries are surrounded by large water depths and for that matter are excluded by current offshore wind practices. This fully justifies developing new concepts for offshore turbines that could lift depth related limitations and enhance unrestricted deployment of offshore wind turbines independently to their geographic reality.

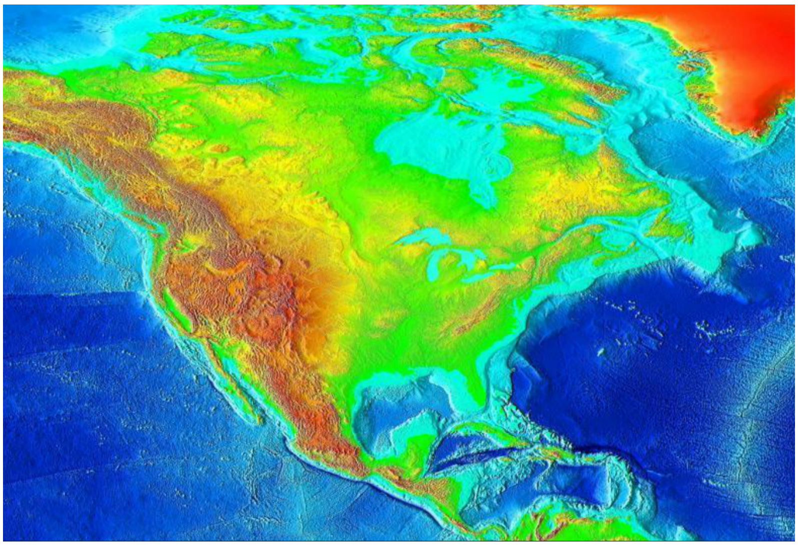


Figure 14. Seafloor topography map of North America. Provided by the National Oceanic and Atmospheric Administration (NOAA). Source: https://www.ngdc.noaa.gov

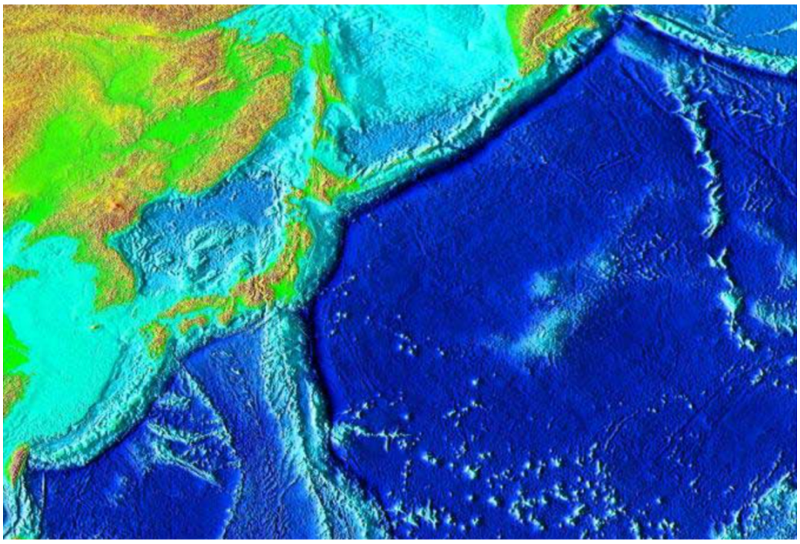


Figure 15. Seafloor topography of the Sea of Japan and Pacific Ocean Source: https://www.ngdc.noaa.gov

The impact of the geology on offshore turbine deployment becomes evident when one looks at the geographic distribution of today's Windfarms in Europe. This uneven distribution conceals one of the main challenges that needs to be addressed by future solutions.

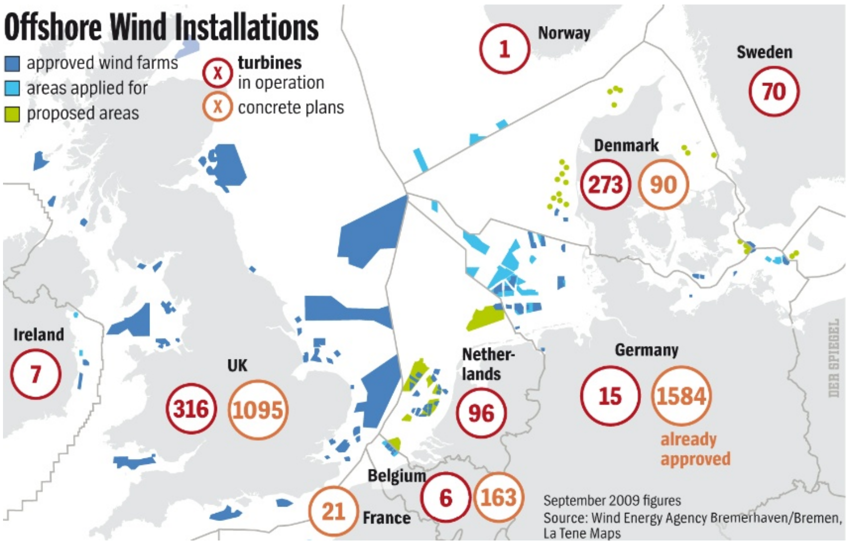


Figure 16. Status of European Wind Farms and Projects By Country.
Source: Wind Energy Agency Bremerhaven.

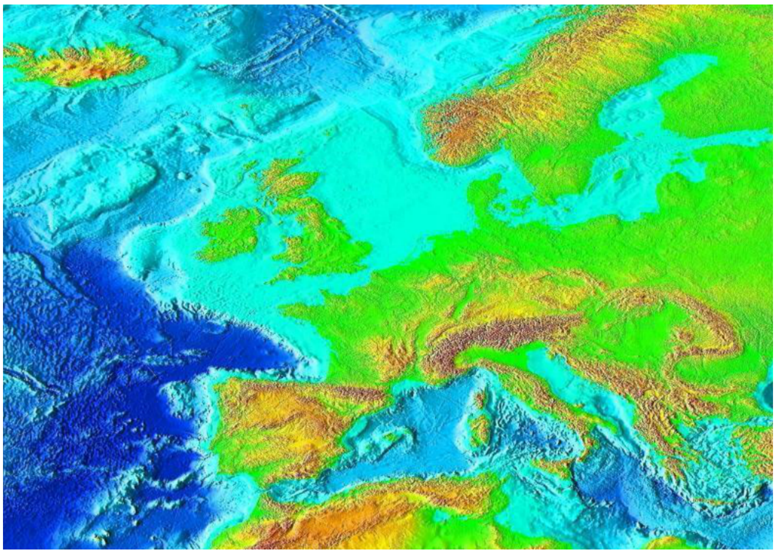


Figure 17. Seafloor elevation map in Europe. Source: NOAA

As can be seen, Wind farms are unevenly distributed across Europe. Note the strong correlation between wind farm deployment and presence of continental shelf highlighted in cyan.

It should come as no surprise that the North of Europe -North Sea, Irish Sea and Baltic Sea-clusters the gross of European offshore farms.

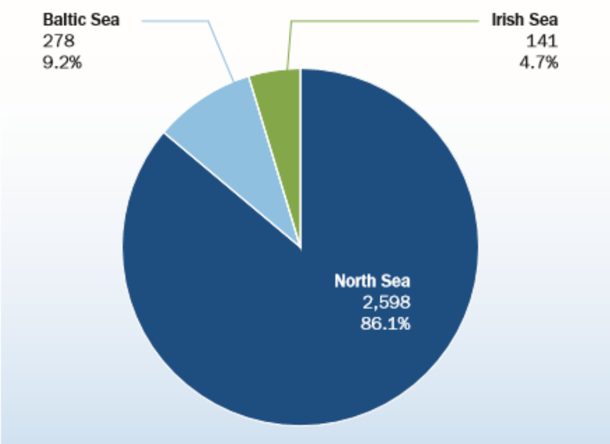


Figure 18. Sea basin share of turbines installed in 2015.

In 2015, just over 3000 MW of wind power were connected to the grid distributed in 14 fully completed Windfarms. Only considering these new offshore wind farms in European waters, 86.1% of the installed capacity is in the North Sea, 9.2% in the Baltic Sea and 4.7% in the Irish Sea. Work continued on seven other wind farms all of which are found in the same region.

As of 2016, of the total 11,000 MW of connected European offshore wind power 69.4% were in the North Sea, 12.9% in the Baltic Sea and 17.6% in the Irish Sea, all within the region of northern Europe presenting a continental shelf.

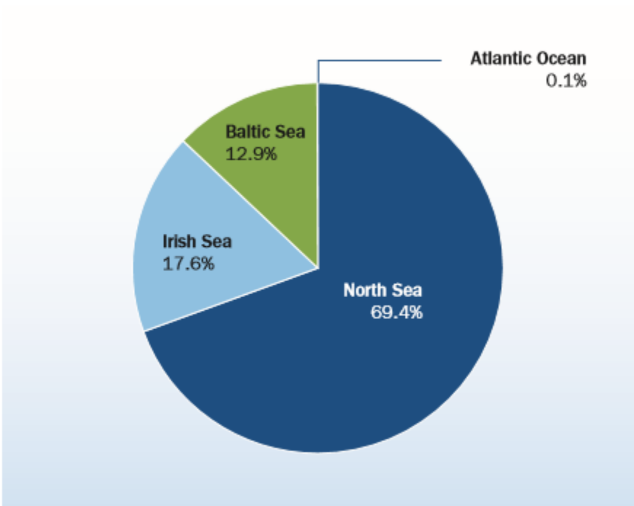


Figure 19. Share of cumulative installed capacity by Sea basin. (EWEA, 2015)

To show the potential of wind resources at larger depths, EWEA presents an interesting scenario. Consider only the North Sea sites with water depths over 50m (66% of the North Sea) and for illustration purposes only, consider 6 MW wind turbines deployed in this area with some kind of floating mechanism.

This hypothetic scenario found that the energy produced in this area alone could meet today's EU electricity consumption four times over.

This estimate only considered deep waters found in the North Sea. If floating turbines in the North Sea alone can exceed Europe's demand by this amount, by including the deep waters of the Atlantic and Mediterranean seas, the potential is many times greater.

This scenario truly shows how much can be gained from new deep offshore designs. Floating offshore designs are necessary to unlock the promising offshore market potential in the Atlantic and Mediterranean, and deep North Sea waters. Plus, these deep-water designs represent an extraordinary export opportunity to any region of the globe with deep waters like Japan and the US.

1.3.2. Market trends

To understand the desired features that future offshore wind turbines should include, one must have a look at market trends. Current market trends fall into three observations, an increase in wind turbine capacity and windfarm size, an increase in water depth and an increase in distance to shore. To present a competitive solution, especially in the long run, it is essential to integrate these trends in a future-tolerant design. A few intuitive consequences that appear from each of these three trends will also be mentioned.

Turbine rating and wind farm size

The first turbines, installed in 1991 had a capacity of 450kW. By the year 2000, the average capacity of installed wind turbines had increased to 2 MW and to 3 MW by 2010. From 2010 to 2015, wind turbine capacity has grown 41.1%. In 2015, the average capacity of new wind turbines installed was 4.2 MW, a significant increase from 3.0 MW in 2010.

The most recent deployment of turbines seen in 2015 had a rating capacity of 4-6 MW. Clearly the industry promotes a continuous development in turbine technology to increase energy production and will presumably continue to do so (see *Figure 20*). Towards 2018, the first 6-8 MW turbines are expected to be introduced in the offshore energy market.

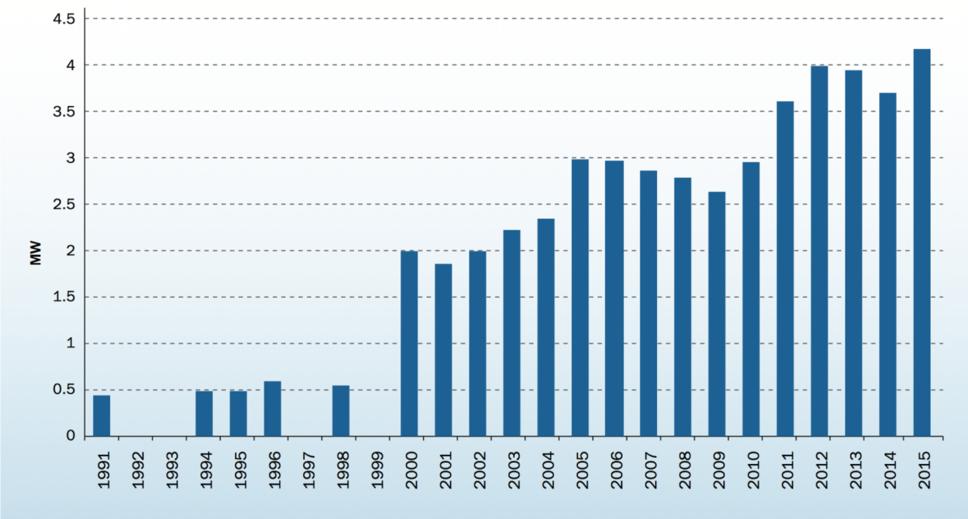


Figure 20. Average capacity of installed wind turbines by year. Source: EWEA report 2015 (EWEA, 2015)

The fact that average capacity of new wind turbines is growing has direct consequences on the average wind farm size, which has more than doubled, from 155.3 MW in 2010 to 337.9 MW in 2015.

INCREASE IN WATER DEPTH

Offshore wind farms are moving into deeper waters. The average water depth of offshore wind farms commissioned in 2015 was 27.2 m, slightly more than in 2014 (22.4 m). Vast wind resources can be found at greater depths but remain mostly untapped by current day bottom-fixed practices.

This trend alone is a main obstacle to large-scale deployment with the available techniques. Increasing water depth is the main reason why re-thinking current fixed-bottom technology is in order. To satisfy this trend, a whole new design paradigm is a necessary step for offshore wind.

DISTANCE TO SHORE

Offshore wind farms have moved further from shore by the end of 2015, the average distance to shore was 43.3 km.

The following graphic see (*Figure 21*). illustrates both these trends. The arrows show that new projects (consented and under construction) are shifting to deeper waters and further away from the shore.

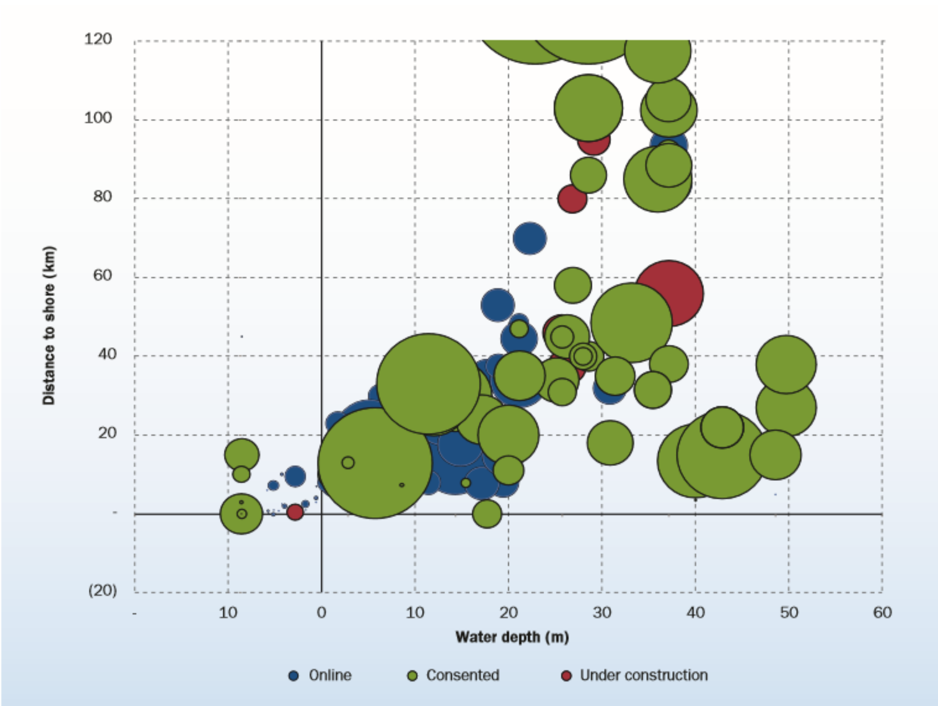


Figure 21. Water depth and distance to shore for current and consented offshore windfarms. Source: EWEA report 2015 (EWEA, 2015)

As distance to shore increases access becomes more difficult. Logistics and maintenance operations will need careful planning. As distance increases, so will transfer time of personnel and equipment. For large distances alternatives to transport by boat will become more relevant, such as helicopters or designing permanent accommodation facilities within the wind farms.

As the industry evolves, market trends show that offshore wind farms are moving further from the coast into deeper waters. Another noticeable trend is an increased turbine size. The underlying ideas behind these trends is achieving an optimal balance between power production and implementation costs. The industry is well aware that the economic advantages of higher energy production could pay-off higher costs. The current trend of increasing project size, cost, and distance from the shore all aim at lowering costs.

Up-scaling turbines is essential to off-shore wind economy and continuity, and as such should be anticipated by designers. Therefore, all conceptualization work should integrate these trends in future designs as they are the key to achieving future-proof turbines that respond to the industries needs to remain competitive. The desired offshore wind turbine will need to remain flexible with increasing depth and distance to shore while accommodating larger turbines and fulfilling all the structural requirements.

Note that FOWT have the potential to incorporate all these market trends in their design. As they require no foundation, FOWT could remain relatively "unaffected" by water depth. The same cannot be said about the installation procedure - yet to be defined- which may be influenced by water depth and should remain as flexible as possible to allow installation in a wide range of depths. FOWT should have no problem accommodating larger and heavier turbines if the support structure is properly designed. The impact of increased distance to shore on FOWT is still uncertain and will be strongly related to the required equipment for transport of the structure.

1.4. STATE OF THE ART OF CONVENTIONAL OFFSHORE TURBINE TECHNOLOGY

1.4.1. *OVERVIEW* OF CONVENTIONAL BOTTOM FIXED FOUNDATIONS

Offshore wind energy is divided into two main categories: shallow water and deep-water. Bottom fixed turbines are deployed in shallow waters. There are also transitional depth foundations, but as they are similar to shallow water, the two technologies will be grouped together. Deepwater is usually defined as over 60 meters.

First let's examine the main offshore foundation technologies in shallow water, and then describe in greater detail the most common type of foundation, monopiles. The construction procedure to erect a bottom-fixed offshore turbine with monopile foundation is mainly carried out at the final location, and will be developed to illustrate the difficulties that arise from building at sea.

Bottom-fixed offshore wind turbines are proven technology and are already operating in water depths of up to 40m and within 40km of the UK shore line. One of the most common foundation structures are monopile foundations, which require large piles driven into the seabed. This practice is severely penalized by increasing depth. To truly grasp this, let's take a closer look at the most common practices employed to construct offshore wind turbines today. By looking at these techniques, we can understand why the industry is currently restrained from moving into deeper waters.

Foundations offshore wind towers can be categorized by their configuration, solutions that have been used up to now mainly fall in the following types:

- Monopile
- Tripod foundation
- Jacket foundation
- Tripile
- Gravity foundation

There are currently 3,313 foundations installed in the seas of North Europe, monopile foundations, gravity based and jacket foundations together represent 89% of all the installed turbines. Monopile substructures remain by far the most popular substructure type. In 2015, of the total offshore turbines that were grid-connected, 97% used monopiles, amounting to 385 new monopile turbines.

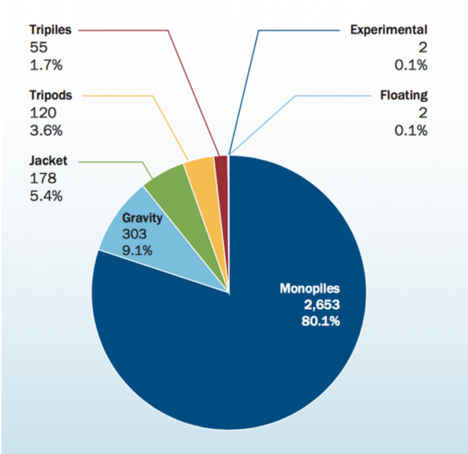


Figure 22. Share of substructure types (EWEA, 2015)

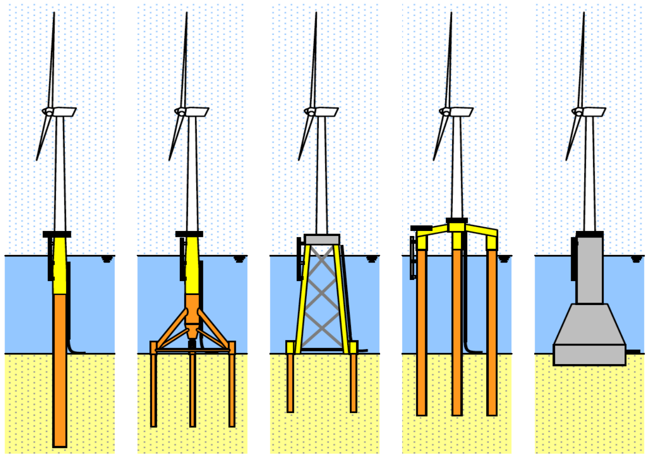


Figure 23. Monopile, tripod, jacket, tripile and gravity based support structures. (Vries, 2011)

MONOPILE FOUNDATIONS

Table 2. Specifications of Monopile Foundations

Foundation Type	MONOPILE
Status	Proven design
Share (*)	80.1%
Number of foundations (*)	2.653
Depth range	0-30m
Construction sequence	(a) Place pile (b) Drive pile

*by the end of 2015 including those awaiting turbine installations or grid connections

Mono pile foundations consist of a single large diameter hollow steel pipe which is embedded into the sea bed. Friction and bearing forces are used to support the structure. How far the pile goes into the sea bed, and the pile diameter and wall thickness will be determined by the maximum water depth and rated capacity of the wind turbine. The pile can be up to 6 m in dimeter with a thickness of 150 mm. Typical diameters range from 3.5 to 4.5 meters with wall thickness of around 5cm. The length of a monopile varies, depending on the seabed, but is normally around 30 to 50 meters long.

Depending on the seabed characteristics the pile is typically driven into the seabed by impact or vibratory hammers. After installing the piles at the design depth into the seabed, they are connected to a transition piece and fixed with grout in a special concrete casting process. The transition piece incudes ducts for the submarine cables, flanges to bolt the turbine tower and sometimes a place to moore a boat. The upper part of the transition piece provides the interface to the wind turbine tower. Some seabed preparation might be required, such as the laying of gravel for scour protection.

Monopile are relatively slender structures have low stiffness. They are suitable for water depths of up to 25 m. The use of Mono pile in deeper waters is limited by excessive deflection. As they become less stable in deeper waters, larger diameters reducing the monopiles' flexibility could become a solution but would require an increase in size of installation equipment and up-scaling manufacturing capabilities. These are the single most common foundations for water depths less than 25m.

GRAVITY BASED FOUNDATIONS

Table 3. Specifications of GB Foundations

Foundation Type	GRAVITY BASE
Status	Proven design
Share (*)	9.1%
Number of foundations (*)	303
Depth range	0-15m
Construction sequence	*(a) Prepare seabed* *(b) Placement* *(c) Infill ballast*

*by the end of 2015 including those awaiting turbine installations or grid connections

Gravity foundations were the first type of foundation used by the offshore wind energy industry. Gravity foundation use a similar working principle to caissons. The foundations are built onshore, then transported and lowered to their final location using cranes. Once in place, the foundation is ballasted with sand or gravel. Sea bed must be smooth and silt removed before the foundations can be lowered. These foundations are cost-effective when the environmental loads are relatively low, and the dead load is significant. Gravity Structures resist the overturning loads solely by means of gravity. Stability is achieved by the dead load and the weight of the ballast. These foundations are used in shallow waters, where driving piles in the underlying seabed is difficult, such as on a hard rock ledge. If a competent soil is available relatively close to the surface, gravity caissons also provide a cost-effective solution. Gravity base foundation are suitable for shallow waters, the become too heavy and expensive to install at depths greater than 15 m.

Figure 24.Gravity base foundation waiting to be installed.
Source: http://scotsrenewables.com/blog/offshorewind/no-tiree-array-group-visit-an-offshore-windfarm/

TRIPOD

Table 4. Specifications of Tripod Foundations

Foundation Type	TRIPOD
Status	Proven design
Share (*)	3.6%
Number of foundations (*)	120
Depth range	20-40m
Construction sequence	*(a) Prepare frame* *(b) Insert pile* *(c) Drive pile*

*by the end of 2015 including those awaiting turbine installations or grid connections

In a tripod foundation, the turbine tower rests upon a steel pile, similar to a monopile foundation. A steel frame is attached to the pile which distributes the loads from the tower onto three steel piles, which are driven into the seabed. The embedded depth depends on water depth and seabed geology. The design of the tripod foundation gives it sufficient strength to be places in deeper waters, with minimal sea bed preparation.

Tripods allow installation at greater depths but they come with another advantage that could benefit the wind industry. As turbines become larger, monopile diameters may become sufficiently large to be uneconomic, and an alternative structure founded on three or four smaller foundations a “tripod” or “tetrapod” may be a cost-effective solution.

The bulky frame below the surface difficult the approach of service vessels, making tripods unsuitable for shallow waters. Tripod foundations are typically used in the oil and gas industry. Tripod foundations for offshore turbines were used for the first time in 6 of the 12 turbines at Alpha Ventus in Germany in 2010. This project will provide valuable information about the viability of offshore wind farms using tripod foundations. From an installation point of view, the tripod poses challenges as it cannot be transported as easily as a monopile foundation (Vries, 2011).
They are suitable for transitional water depths between 20 and 40m.

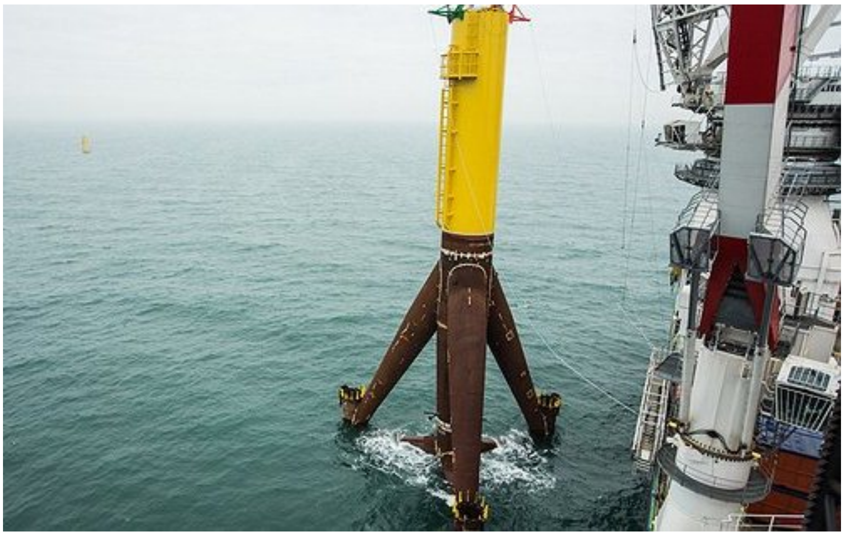


Figure 25. Tripod during installation. Source: http://www.offshorewind.biz/tag/i/page/2/

JACKET

Table 5. Specifications of Jacket Foundation

Foundation Type	JACKET
Status	Proven design
Share (*)	5.4%
Number of foundations (*)	178
Depth range	20-40m
Construction sequence	*(a) Prepare frame* *(b) Insert pile* *(c) Drive pile*

*by the end of 2015 including those awaiting turbine installations or grid connections

A jacket foundation is a very large multi-chord base formed of structural tubular pipes that are welded together. Jacket type structures use a number of smaller piles, often 3, to provide support in deeper water. It is a semi-submerged structure, with a small portion of the jacket extending above the surface of the water in which the turbine tower is mounted. The jacket is prefabricated onshore and placed upon a large transport barge to be transported to the installation site. Jackets are considerably lighter than monopiles, reducing transport and installation costs. They are usually used in the range of 30 to 40 metres. However, jacket structures can be installed in waters as far as 60 meters and with minimal seabed preparation. The jacket foundation structure is an adaptation from the oil and gas industry.

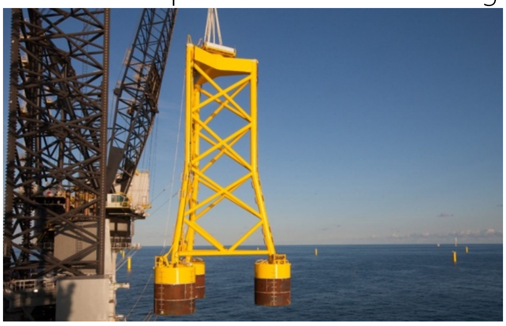


Figure 26. Jacket foundation.
Source:https://marineoffshoreconsultants.com/

TRIPILE

Table 6. Specifications of Tripile Foundations

Foundation Type	JACKET
Status	Proven design
Share *)	1.7%
Number of foundations (*)	178
Depth range	25-40m
Construction sequence	*(a) Place piles* *(b) Drive piles* *(c) Connection of transition piece*

*by the end of 2015 including those awaiting turbine installations or grid connections

The concept was patented by BARD Engineering. BARD claims that this type of structure is suitable for water depths between 25 and 40 m.

It comprises three foundation piles which extend above the sea surface and are connected by a crosspiece with three struts.

The main advantage of tripod foundation is that it can easily be adjusted to accommodate water depth variations, as the transition piece dimensions can be maintained and the pile dimensions can be adjusted to suit the site. The transition piece is relatively complex to manufacture and the installation requires the precision of a purpose-built vessel as the transition piece struts must fit inside the piles. However mass production of transition pieces in adequate near-shore facilities decreases costs.

Figure 27. Tripile foundation for 5 MW Engineerd by Bard

As the piles are arranged away from the centre of the tower, smaller diameter piles can be used to achieve sufficient stiffness, leading to lower hydrodynamic loading. (Vries, 2011)

1.4.2. COMPARISON OF CONVENTIONAL BOTTOM FIXED FOUNDATIONS

Table 7. Construction Phase requirements for each foundation.

CONSTRUCTION PHASE	GRAVITY BASE	MONOPILE	TRIPOD
Onshore Fabrication	*On land and close to site to be economical*	*No constraint*	*On land and close to site to be economical*
Transport Offshore	*Float to site or barge*	*Float to site or barge*	*On barge*
Pre-placement activities	*Seabed preparation required*	*Minimal Seabed preparation*	*None*
Placement	*Lift or float over*	*Lift and sink*	*Lift and sink*
Fixing tower to substructure	*Bolt to structure*	*Grout to pilling*	*Grout to tripod central member*
Installation of tower and turbine	*Several liftings*	*Several liftings*	*Several liftings*

1.4.3. Suction caisson, an alternative to conventional methods

Certain alternatives to the foundations mentioned above are being considered, one of the most promising is the use of suction caissons.

Suction caissons foundations have already been demonstrated in a number of offshore oil and gas projects. They are simple steel fabrications resembling upturned buckets, that are installed into the ground using a suction technique, namely pumping water out of the compartment to create a pressure differential, sinking deeper into the seabed.

Suction caissons would require less steel than that required for an equivalent pile foundation resulting in lower material costs. Due to a decrease in weight and an entirely different installation principle, suction caissons could avoid the mobilisation of crane barges and other expensive equipment like pile driving hammer spreads and grouting spreads, yielding considerable savings. Another attractive cost-benefit is a simplified and quicker installation method, that would practically be unaffected by weather conditions. Finally, at the end of the turbine's life, a suction caisson can be removed completely from the sea bed by reattaching the pumps and applying pressure inside the caisson leaving little trace that it was ever there.

Figure 28. Jacket-structure equipped with suction buckets for Aberdeen Offshore Windfarm, Scotland. Source: http://www.indepthnrg.com/aberdeen-offshore-wind-farm/ /Figure 2 with suction.

On must admit that suction caissons could provide an economically attractive alternative to pile foundations. Lowering installation costs, replacing highly specialized floating equipment by pumps, reduced risk of weather delay are all advantages worth researching. As such, the industry should consider them as worthy alternatives to monopiles and investigate them further. However, suction caissons only address the manner in which the foundation is fixed to the seabed and do not solve the issue of oversized substructures that would be required for very deep waters. By reallocating the money saved by the use of suction caissons instead of pile-driving, wind turbines could be deployed into somewhat deeper waters but would eventually become uneconomical at a certain water depth. Offshore wind turbines could advance into slightly deeper waters, but suction caisson foundations would end up facing similar economic restraints and technical challenges (excessive deflection of substructure).

The current practices used to install conventional bottom-fixed wind turbines in shallow and transitional water depths has been described. For deep waters, the limits of these practices become evident. Efforts to reduce costs, like those presented by suction caissons, are insufficient to allow unrestricted deployment the industry needs.

1.5. MAIN COST DRIVERS DURING INSTALLATION BOTTOM-FIXED TECHNOLOGY

The implementation cycle of a typical bottom-fixed offshore turbine consists of several distinct steps: foundation construction, pre-assembly, transport, installation and commissioning.

Foundations are considerably expensive for offshore turbines. The costs depend on both the sea depth and the type of foundation being built. For current offshore projects, foundation costs represent typically more than 21 per cent. Despite the fact that considerable experience will be gained and further optimisation of foundations can be expected, foundation costs will continue to be high if the industry moves towards deeper sites in the future. The previous construction sequence allowed us to visualize the main cost drivers of a standard procedures today. Identifying these drivers is the first step to defining cost-efficiency. The will now be stated.

1.5.1. Heavy lifting at sea

Current day practice for installing offshore turbines requires heavy lifting operations, both for the foundations and the remainder of the elements.

Apart from driving the monopoles into the seabed, turbine installation requires eight additional offshore lifts all of which yields costs:

1) Transition piece
2) First half of the tower
3) Second half of the tower
4) Nacelle
5) Hub
6) Blade 1
7) Blade 2
8) Blade 3

Note that optimizing installation, the number of offshore lifts could be decreased to seven if a one part tower is used, and even further by using a pre-assembled rotor.

Figure 29. Hochtief jack-up vessel Vidar during lifting operation of second blade.
Source: http://www.offshorewindindustry.com/news/jan-de-nul-acquires-jack-vessel-vidar

1.5.2. OFFSHORE WIND VESSELS

These offshore lifts require highly specialized vessels. These vessels are necessary not only for lifting operations but also other stages of the cycle like laying the electrical cables or maintenance operations. Vessel costs account for the majority of the total installation costs. A list of the most commonly mobilized vessels follows.

a) A dynamically positioned heavy-lift cargo vessel is used to ferry the components from the pre-assembly harbour to the offshore location.

b) Foundation and turbine manufacturers may be located at some distance from the pre-assembly harbour, and even in different countries requiring additional mobilisation of heavy-lift cargo vessel.

c) Offshore barges and seagoing tugs to transport foundations and components
d) A jack-up vessel is used to install the wind turbines, transporting and hoisting of large components

e) Diving support vessel for underwater inspections and repairs

f) Cable-laying vessel installs the electrical cabling with the assistance of a remotely operated vehicle (ROV).

Of the total vessel costs during installation, the largest cost is that of the cable-laying vessel, but is followed closely by the heavy-lift vessel, and the jack-up vessel.

There are three main chartering strategies for offshore wind projects:

- Spot market

- Short term charter

- Long term charter

Y. Dalgic, I. Lazakis & O. Turan extensively studied vessel charter rates for offshore wind and presented the following comparison of vessel chartering strategies for offshore wind projects.

Table 8. Chartering strategies. Source: (Dalgic, et al., 2013))

Strategy	Advantages	Disadvantages
Spot market Min: ~1 month Max: ~3 months	- Use vessel only after a failure of wind turbine occurs - Select optimal vessel for each turbine failure - Only use vessel when required - Maximum utilisation of vessel	- Potential limited certainty in vessel availability - High uncertainty in mobilisation time and costs - Day rates and mobilisation costs likely to be very high- Due to last minute arrangements, potential delays in mobilisation time and subsequently increased downtimes and loss of revenue
Short term charter Min: ~3 month Max: ~1 year	- Reduces risk of weather effect (if performed during summer) - Reduces number of vessel being chartered - Can be used across multiple sites	- Risk of low utilisation in winter - In case of maintenance/supply delays, risk of uncompleted/imperfect repairs
Long term charter Min: ~1 year Max: ~20 years	- Reduced mobilisation time and costs - Eliminated risk of vessel unavailability - Increased operational control/planning for the offshore wind farm operators operator - Costs vary less over lifetime - Can use across multiple sites - Better planning - Stable costs	- Paying for vessel even when not being used - High initial investment - Vessel not optimised for individual sites - A management team required to operate the vessel - Repair and maintenance expenses potentially be added - A port needed for the vessel mooring

Note that the availability vessels and the length of the chartering period are vital for estimating the costs. For instance, during the installation period of The Alpha Ventus offshore wind farm, operators had to charter a vessel much larger and extremely expensive than originally planned due to the unavailability (Dalgic, et al., 2013). Planning phase of any offshore wind project should carefully assess the availability beforehand and plan installation and maintenance operations accordingly to keep costs under control.

The chartering period also plays a fundamental role in the economics of an offshore wind project. This aspect will be shown by referring to a study that estimated the charter rates for 6 types of jack-up vessels (#1 to #6) depending on the charter period. The technical specifications of these 6 jack-up vessels is readily available in *Vessel charter rate estimation for offshore wind O&M activities*. (Dalgic, et al., 2013)

(Dalgic, et al., 2013) presented the following daily rate for each vessel and type of chartering strategy.

Table 9. Vessel charter rate estimation for offshore wind O&M activities. Source: (Dalgic, et al., 2013)

Vessel no	Year built	CAPEX	Daily rates for a spot market	Daily rates for a period of 20-years	Daily rates for a period of 1 year
		£ MM	£	£	£
1	2012	102	160,400	67,800	117,200
2	2009	86	133,000	58,200	96,400
3	2011	176	287,400	112,200	213,400
4	2003	64	95,300	45,000	67,800
5	2012	141	227,300	91,200	167,900
6	2012	160	259,900	102,600	192,600

In accordance with this research on vessel charter rate estimation, there is great advantage to hire the vessels for longer periods of time.

In addition to the variation of rates depending on the chosen chartering strategy, it is well known that the charter rates have a strong seasonal component. Harsher offshore conditions in winter restrict the maintenance operations decreasing the demand when charter rates are usually at the lowest level. Therefore, it is not uncommon for offshore vessel owners to distinguish daily charter rates for summer and winter.

Vessel chartering should be planned ahead by operators, and maintenance operations should be carefully scheduled to mobilise the optimal vessel during the required amount of time to reduce the chances of facing unexpected costs. Large projects should definitively consider hiring vessels for longer periods or even consider ownership as a solution to high utilization.

1.5.3. ENVIRONMENTAL UNCERTAINTY

Offshore is a challenging and unpredictable environment which changes by the hour and the installation is weather-sensible. Working in such an uncertain environment also yields great costs. Even if the planning phase was carried out carefully, unpractical wave heights or high wind speeds can hold-off installation activities during several hours or even more. Weather conditions frequently cause delays in installation process costing standby fees and idle installation crews.

1.5.4. LOGISTICS

Working offshore means logistics in bringing the spare parts and the necessary equipment, which is always a challenge that requires time and vessels to ferry on an around-the-clock basis. Logistics functions include transporting equipment, transporting people and enabling installation

Unforeseen environmental conditions can also hinder the supply chain of the project as logistic difficulties can be expected under bad weather and increase with distance to shore.

DETAILED INSTALLATION PROCESS: *CONSTRUCTION SEQUENCE OF ENECO LUCHTERDUINEN*

Monopile foundations are currently the most popular technique used to construct offshore turbines, for this reason it has been chosen to depict the stages of a full implementation cycle of monopile bottom-fixed offshore wind turbines. Here the construction sequence of Eneco Luchterduinen will be described.

Eneco Luchterduinen is an offshore wind farm finished in 2015. This Wind farm is located 25 km off the coast of the Netherlands, in a depth range of 18-24m. The building costs amounted to 450 million.

The main contractor was Dutch company Van Oord NV. In this project, Van Oord NV installed 43 Vestas V112 turbines with rated power of 3.45 MW and was responsible for the engineering, procurement and installation of foundations, the complete electrical infrastructure including the offshore high voltage station and installation of the wind turbines (4C Offshore, 2015). This project was chosen as it illustrates well the entire implementation process which is already highly optimized.

Figure 30. Brand-new installation vessel Aeolus started its first job at the Eneco Luchterduinen Source: http://www.offshorewindindustry.com.

Installing wind turbines offshore takes place in several distinct steps, all of which require many months of planning and preparation.

I. FOUNDATION AND TRANSITION PIECE INSTALLATION

Monopiles up to 80 meters long are fabricated in a factory close to the feeder port. The 43 monopiles were designed, ordered and built within approximately 10 months. These monopiles weigh up to 1000 t each. They are transported to the pre-assembly harbour and uploaded onto a sea-a vessel with a crane that can handle 1,500 tonnes.

Once the vessel arrives at the offshore location, the vessel will position itself independently with no tugs or external assistance with dynamic positioning technology. The vessels then jacks-up to a working height of up to 24 metres. Previously the jack up-vessel is preloaded and the sea bed is tested to ensure there is no penetration.

After the vessel jacks-up, driving of monopiles to target depth begins. Each pile-driving operation takes about 24 hours, including driving through the previously laid scour protection. At this stage, noise mitigation measures are used to reduce environmental hindrance and keep noise to an agreed limit. Note that for each monopile, the target depth may vary depending on the sea-bed conditions at that particular location.

Next, the transition pieces, 30 m long and with a weight of up to 300 t, are transported from the feeder port to the offshore site.

Vessel jacks up-again. The vessels crane then places the transition piece. Bolting and grouting of the transition piece to the top of the monopile follows. The crane may include laser precision to accurately place, bolt and grout the transition piece. Note that monopiles and transition pieces may be loaded together on the same vessel if space allows it.

II. Pre-assembly phase

The first critical step is pre-assembly of the main components. MHI Vestas has a pre-assembly site-harbour, on the south wester n coast of Denmark, where turbine components are delivered from the factory before a specialized crew starts the pre-assembly (placing fibre glass shells, mounting the cooler tops). The aim of the pre-assembly harbour is to guarantee turbines are in prime condition before going offshore as there can be no room for surprises at sea.

The towers are fully erected, the nacelles are equipped and tested as fully functioning turbines before they leave the pre-assembly harbour. This process ensures time spent offshore is minimized, significantly reducing installation costs. Checking the configuration of the nacelles is essential to delivering the project in a timely and efficient manner.

Being able to pre-assemble wind turbines to this extent is possible by cutting edge transport technology, allowing towers to be transported upright standing more than 60 metres tall. Hundreds of metric tonnes of steel are loaded on the vessel and safely secured on the deck.

III. Transport of towers, nacelle and blades

When the components are lifted off the ground at the pre-assembly harbour on to the sea going vessel, the crew responsible for the final installation takes over. The nacelles are 12.87m long 6.8 m high and 4 m wide weighing 165 tonnes. The turbine components are bolted and strapped to the deck of the installation vessel with special sea fastenings. The vessel can hold total components for 8 complete wind turbines. This loading operation is carried out whether at day or night, what is paramount is the right weather window. Operating at high winds risks damaging components and compromises the safety of the crew. While sailing the crew checks the fastening lashes for the elements are in the right position. The vessel is heading to sight no matter what time of the day.

IV. OFFSHORE INSTALLATION OF TOWERS, NACELLE AND BLADES

When the vessel arrives at the site, the installation process begins. Vessel jacks-up and the vessel crane installs the components one by one. The vessel needs to jack out of the water to be free from the external influence of the waves, in this stage, precision is paramount, and the process can't afford any motion on the crane.

The tower is lifted on to the foundation followed by the nacelle and then the 3 blades are installed. Here too laser precision is often used. Nacelle installation is less than 2 hours and a complete turbine can be installed within a day if weather allows it.

V. COMMISSIONING

Before the V112 turbines begin to produce power, other offshore activities need to be completed including mechanical and electrical completion, as well as cold and hot commissioning. The completion work ensures all bolts are torqued and all cables are connected.

During cold commissioning, high and low voltage system are tested to make the turbine ready for grid connection.

Once the sea cables are energized, hot commissioning will complete the turbine which is now ready to supply power to the grid. One of the last steps in commissioning is taking the turbines for a final test run to ensure quality of the wind farm. The offshore substation is completed and collects and transmits energy to onshore grid.

2. FLOATING DEEPWATER TECHNOLOGIES

2.1 THE NEED FOR FLOATING DEEP-WATER TECHNOLOGIES

Many high-energy offshore wind sites can be found up to 100km of the shoreline, where water depths range from 50 m to over 100 m, beyond the depth at which existing foundation technologies are commercially viable. Thus, an exponential growth is only achievable through the deployment of turbines in deep waters and FOWT designs could hold the key.

Current offshore farms have been developed at a series of locations with relatively shallow waters and using expensive floating equipment normally mounted on highly-specialized vessels. It is in under these specific conditions that the offshore wind technology has matured. Today, a noticeable shift towards deeper water represents perhaps the biggest obstacle to pursue continuous expansion.

The fact that most existing concepts have been designed for shallow waters often makes them incompatible with larger water depths present in numerous regions. This clearly marks the limit of present day practices and calls for a novel methodology to address the industries demands.

Up until now we have identified 3 key reasons to justify the need for a new generation of solutions:

I. Prohibitively high implementation costs of conventional solutions beyond depths of 60 m.

II. Unsuitability of conventional solutions for regions with no continental shelf, heavily restricting geographical expansion.

III. Market trends show noticeable shift to deeper waters, aggravating the two previous points.

For a cost competitive foundation, designers must look beyond existing technologies.

The above-mentioned reasons motivate looking for new solutions capable of reducing costs whilst advancing to deeper waters, as well as unlocking offshore wind for many economies across the globe.

The massive deployment the wind industry so strongly desires may only be truly possible through the development of floating designs. These will contribute to unlocking carbon-free wind sources for many regions and could additionally bypass the need of some of the most expensive installation vessels, which is one of the most promising advantages that come with FOWT.

It is in this context that alternative schools of design for support structures should be defined. FOWT will play a central role in new solutions and could really hold the key to the future of offshore wind.

2.2 DIFFERENCES IN CONSTRAINTS OF FOWT W.R.T BOTTOM-FIXED

2.2.1 CHANGE OF CONSTRAINTS AND NEW TRADE-OFFS

New challenges and benefits arise with the development of floating concepts with regard to conventional offshore turbines. Some of the major differences will concern:

- Support structure design.
- Environmental loading.
- Access, maintenance and reliability.
- Turbine design.
- Installation process.

When considering floating structures in deeper waters, one must recognize changes in constraints w.r.t. to onshore wind turbines. Many trade-offs lead to intuitive requisites for a new generation solutions. To name a few:

- Lower visual & noise restrictions → larger and noisier turbines
- Higher investments → Optimize for offshore environment, upscale turbine productivity
- Difficult access → More reliable turbines
- Less space restriction → unrestricted deployment
- Larger water depths → eliminate the need for jack-up vessels and other offshore installation equipment; turbines that are easier to install
- Harsher offshore environment → Higher hydrodynamic and ice loading. Other material deterioration

The major challenge of designing an offshore wind farm is not to get something that works and meets the constraints, but something that works better with increased reliability as a main design driver. Reliability is all that more important for floating wind farms located further into the sea.

The following table presents the main differences in constraints and the new challenges and trade-offs that emerge.

Table 10. Difference in constraints of floating concepts w.r.t Bottom fixed

Design	- New design tools and methods required - Accurate modelling of harsher offshore loads - Dynamic analysis of FOWT under stochastic loading - Complex coupled analysis and interactions between RNA and floating structure
Support structure	- Proven concepts (O&G) but little wind experience. - Floating concepts with a wide variety of geometries, characteristics and materials - To date no commercial deployment - Increased importance of water tightness for certain designs - New designs, new materials
Environment	- Larger water depth and distance to shore - Harsher conditions and higher loads, increased wind speeds and wave loads. - Increased risk of ice - Lower turbulence
Turbine	- No "marinization" of onshore turbines, instead new designs operating at higher wind speeds and lower turbulence - Lighter and easier to install turbines - Simplified turbine drivetrains and development of new generators with lower maintenance. - Renewed interest for 2 blade turbines as opposed to 3 blades
Access, maintenance and Reliability	- Decrease of accessibility due to remote location. - Increased reliability of support structure required - Increased reliability of RNA required
Installation	- Float-out of the structure to offshore location as opposed to offshore construction - Potentially lower installation costs thanks to new paradigms - Installation will vary for each FOWT concept, most remain to be demonstrated - Minor or no use of specialized vessels (claimed) - Mainly prototypes with little utility-scale FOWT installed - Development of deep-water mooring cables and anchors

2.2.2 NEW TRADE- OFFS

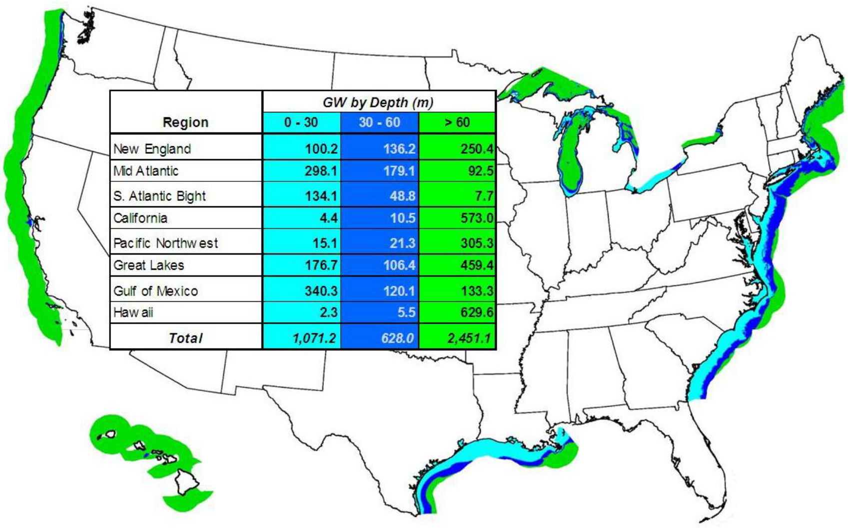
FOWT must identify and take advantage of the many trade-offs that emerge as they hold the key to ensuring a competitive alternative to conventional offshore turbines. This part discusses in more detail some of the most promising features of new floating designs.

INSTALLATION SIMPLICITY

Floating structures offer an innovative approach to the installation process. FOWT can by their very nature be floated directly in a fully or partially commissioned condition from the fabrication and out-fitting yard to the offshore site. This is precisely one of the most promising features that come with floating concepts. This difference may hold the key to reducing the considerable cost of constructing and installing turbines at sea.
If the structure is stable during float-out, high cost of special purpose ships can be avoided and replaced by low-cost tugboats. This cost reduction will be even more considerable if the towed structure carries a fully assembled turbine (Butterfield, et al., 2005).

HIGHER WIND SPEEDS

Most of the benefits of offshore wind improve as distance to shore increases (often closely related to water depth). This is particularly true for wind speeds, which tend to be faster and steadier. Faster wind speeds offshore mean much more energy can be generated, whereas a steadier supply of wind means a more reliable source of energy (Gilman, et al., 2016).



Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

Figure 31. United States offshore wind resources in GW by region and depth at 90 m elevation (NREL)

WATER DEPTH INDEPENDENCE

Floating structures can overcome depth imposed restrictions, leading to a much-needed cost reduction for deploying turbines into deep waters.

A truly flexible FOWT should be independent of water depth during all relevant stages of the implementation process, like transport and installation phases.

Lifting depth limitations has another major advantage, namely deploying turbines across the globe independently of their geographic reality. This results in unparalleled export potential covering a huge market.

Durability and resistance to the offshore environment

New concepts should always consider new ways to address previous problems. For offshore turbines, high corrosion and costly yearly maintenance operations is a major cost-driver. FOWT have the potential to re-assess the choice of preferred construction materials and should see it as an advantage over conventional solutions. Floating concepts design should make room for non-corrosive materials like concrete. By replacing steel and using concrete where possible, FOWT will have a better chance at being a cost-effective alternative. Favouring concrete over steel will also save costs on corrosion resistant coatings and cathodic protection.

Reduced sensitivity to seabed conditions

FOWT will theoretically involve minor interaction with only mooring lines anchored to the seabed. If anchor systems are designed to meet a broad range of soil conditions, FOWT can be deployed independently on soil conditions. Floating concepts will also decrease the need for expensive and time consuming geotechnical surveys. Floating concepts also minimise seabed preparation such as the laying of gravel for scour protection.

Decommissioning and maintainability

FOWT can be decommissioned in a similar way they were installed, effectively reducing costs. Maintenance will remain a challenge as the sea state is the main hinder to access, however if large maintenance operations are required, floating structures can be towed back to port for proper repair which is an interesting feature. Additionally, given the new geometry of some floating concepts, these may include easier access for crew and equipment during poor weather.

Floating concepts with a low draft like semi-submersibles will be easier to transport back to port than concepts with large drafts like spar-buoys.

Lower environmental impact

Floating concepts induce minimum footprint and are likely to be suitable even for environmentally sensitive regions. The environmental impact of FOWT is much lower than that of bottom fixed turbines. The only real physical impact of FOWT will be the anchored moorings in the seabed. Another advantage is that FOWT can be decommissioned leaving no trace they were ever there.

2.2.3 NEW CHALLENGES

FOWT designers must also be well aware of the challenges to overcome as the technology is still at its infancy and demonstration stage is ongoing. Challenges in design are to be expected and can only be addressed by gaining experience and detailed characterization of environmental loads. Environmental conditions of interest over a project's lifetime include wind, wave, current, water depth, soil, seabed characteristics, and ecological conditions

The design phase for FOWT is no easy task. One will need to assess the structural behaviour of a FOWT through the duration of its lifetime. The lack of design tools and accurate modelling tools is one of the first challenges that FOWT design will encounter. This is due to the fact that wind turbines must be designed to operate in a very stochastic environment usually for at least 20 years, during which the structural response of these turbines is still largely unknown.

The designer of FOWT is faced with estimating the fatigue life and peak loads over 20 years, which would require 20 years of real time computer simulations which is obviously not practical. (Veers & Butterfield, 2000)

Analysts must have other tools that are able to simulate these offshore conditions. New design load estimation procedures for offshore wind turbines will have to be developed to accurately treat the statistical nature of offshore loads and to fully grasp the response of the structure.

Note that different types of floating concepts will require different modelling tools. In his Conference paper presented in 2005 at the Copenhagen Offshore Wind Conference, MIT professor P. Sclavounos estimated that TLP would require the simplest analytical tools as opposed to spar-buoy and barge types which are more subject to nonlinear wave forces and require more advanced tools.

2.3 CURRENT STATUS OF FOWT

Floating wind turbine technology is in its infancy stages and currently, no deep-water floating wind farms exist in the world. The concept for floating platforms was adapted from the offshore drilling industry and other marine technologies. Floating platforms are well used, but the idea of combining them with turbines is still currently under investigation.

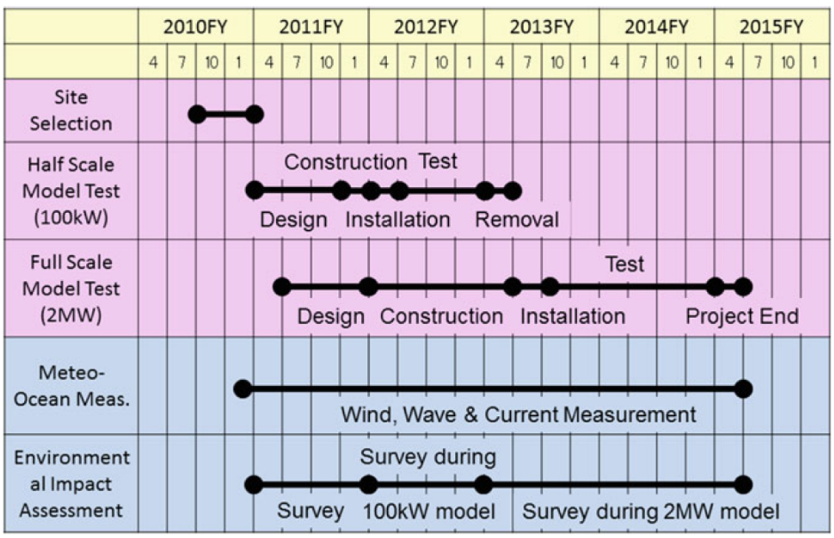
Similar to the bottom-fixed case, there is not a single solution but rather a wide range of candidate types of floating foundations. Proof of this is the variety of full-scale prototype units in operation or under construction today, in Norway, Portugal and Japan to name a few. However, the majority of work completed to-date is at research and development phase with very few tangible large scale FOWT in the water and none at commercial deployment level.

Actually, the path that takes FOWT concepts from a simple sketch to a large-scale project is comprised of several successive phases that candidate concepts will need to successfully overcome if they aspire to convince the wind industry.

FOWT must undergo a long demonstration process, starting from model testing, design and testing of a small scale floating turbine prototype, followed by the design and deployment of a full-scale turbine prototype and culmination with the construction of a number of commercial floating wind farms. Prototype testing is common practice to demonstrate the feasibility of offshore structures, which is even more true for novel FOWT concepts. Floating technology is not in itself unproven as the O&G industry already accumulates interesting experience, however it will need to be demonstrated for wind energy applications.

Although the installation/operation of a multi-megawatt FOWT is the main target of a demonstration project, a step-by-step approach is generally required in order to prove the technology and gain acceptance and financial support from stakeholders. The following figure illustrates a typical schedule of a demonstration project. This schedule corresponds to the one followed for the implementation and testing of 2 FOWT in Nagasaki (Japan), a half-scale model with a rated capacity of 100 kW and a full-scale model with a capacity of 2MW.

Table 11. Master schedule of Nagasaki FOWT demonstration project. Source: (Utsunomiya, et al., 2015)



2.4 MOVEMENTS, STABILITY AND FORCES ON FOWT

Floating support structures must have enough buoyancy to support the weight of the turbine and to restrain pitch, roll, and heave motions within acceptable limits. A key challenge is to ensure that the rotor plane stays as vertical as possible to maximize energy production and minimize down-time.

A FOWT is susceptible to translational movements and rotations in all the three directions when loads are applied, therefore it has six degrees of freedom, namely:

- **Surge**: translation in the x -direction (forward and backward)
- **Sway**: translation in the y -direction (side to side)
- **Heave**: translation in the z -direction (up and down)
- **Roll**: rotation about longitudinal x -axis
- **Pitch**: rotation about transverse y -axis
- **Yaw**: rotation about vertical z -axis.

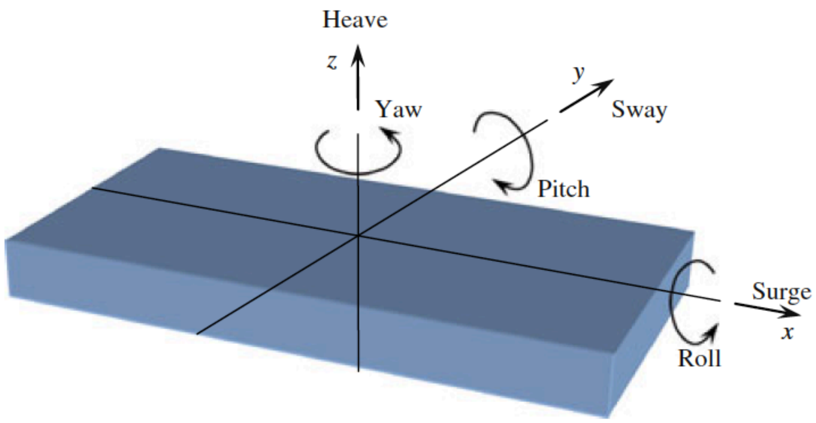


Figure 32. Types of motions of a floating structure. Source: Large floating structures: technological advances (Wang & Wang, 2015)

These degrees of freedom may be restricted by appropriate mooring. Where a floating structure is moored, the sway, surge and yaw of the structure can often be effectively neglected (Wang & Wang, 2015).

Floating offshore wind Concepts, similar to bottom-fixed offshore projects, are highly site specific. To successfully design a FOWT for the offshore environment, an appropriate site will have to be selected with good wind resources an all the desired features like sufficient water depth and acceptable access from on-shore facilities.

Characterization of the offshore environment is the very first step in defining the design requirements.

Meteorological and oceanographic (together abbreviated to *metocean*) conditions are an important factor in governing the mechanical actions that affect the behaviour of offshore structures. All offshore structures are exposed to environmental actions of wind, current and

waves. These conditions produce substantial environmental loadings on the structure that always needs to be carefully considered and accounted by the designer.
The main environmental factors to consider when designing offshore structures are:

- Wind velocity and its variation in time and space (particularly over height)
- Water depth
- Tides
- Storm surge
- Current velocity and its variation in time and space (particularly over height)
- Marine growth
- Air and water temperature (normally only for material selection)
- Ice and snow

The air and water temperature are important for material selection as the properties of steel and most materials such as yield strength and brittleness depend on temperature. For instance, low temperature can lead to sudden brittle fracture of low carbon steel which caused some of the so-called Liberty ships to sink during WWII (Okumoto, et al., 2009). A relatively high water temperature increases corrosion rates, thus having influence on corrosion protection requirements. Warm water is also more oxygen rich than cold water, which promotes marine growth.

FOWT are subject to hydrodynamic and aerodynamic loading which can be of steady, periodic and random fluctuating type. The most important loads to consider in the design are wind turbine thrust, wave loads, wind turbine torque and drift forces. These lead to eccentric loading and/or moments than can cause roll and pitch movements in the floating structure. These loads will not be described further.

The floating structure must be able to withstand extreme environmental loads during its entire design. The buoyancy force acting from below the structure stabilises heaving movements and oscillations caused by gravity and dynamic loads. In the case of FOWT, loads are primarily wind-driven overturning moments.

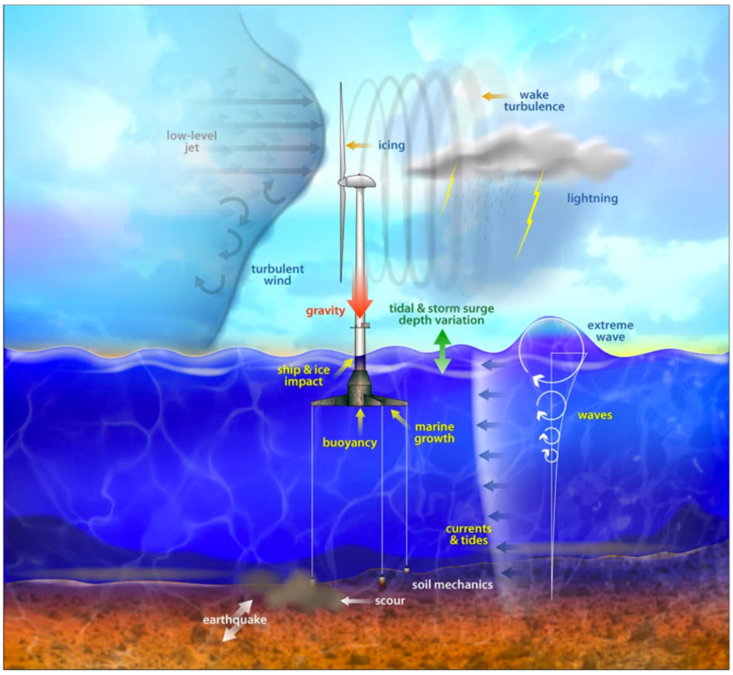


Figure 33. Aerodynamics and hydrodynamics associated with floating platform (mini-TLP type).
Source: (Matha, et al., 2009) NREL

2.5 STATE OF THE ART FLOATING DEEPWATER CONCEPTS

There is a wide variety of solutions under consideration. As Floating concepts for wind turbines are still in their infancy, there are few proven concepts and still a large gap for innovation. Relatively unexplored possibilities lead to number of choices for the floater. However, the geometry of the floating platform will depend on which method is chosen to counter the acting loads and the overturning thrust load. The methods through which floating structures achieve stability are:

- **Buoyancy**: through hydrostatics, using a restoring moment via water plane area. A large surface structure is preferred, rather than a deeper one. It is the same working principle used by ships. The structure must be sufficiently large to achieve the desired degree of stability.

- **Ballast**: uses a very large weight under water to counteract the loads. The deeper located this weight is, the larger the stabilizing moment it provides. This results in a slender structure with a large draft.

- **Tensioned-moorings**: uses tension in cables to keep the attached structure stable. Results in a highly-loaded slender structure, but smaller than the above-mentioned.

All the above mechanisms efficiently grant stability to the floater. The main mechanism used for stability will determine the design and geometry of the floater. See the floating platform stability triangle:

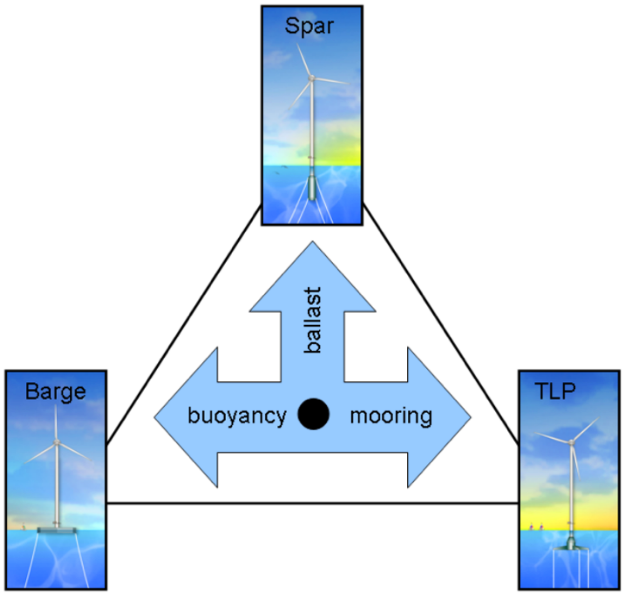


Figure 34. Stability mechanism and corresponding floater design. Source: NREL (Butterfield, et al., 2005)

2.5.1 BALLAST STABILISED FLOATERS

Ballast stabilised floaters will require a slender vertical structure with a concentrated mass at the bottom. This ballast is used to get the centre of gravity well below the centre of buoyancy, providing stability This leads to a spar concept which provides a large submerged volume to generate sufficient buoyancy and a low centre of gravity to maintain stability.

2.5.2 BUOYANCY-STABILISED FLOATERS

Buoyancy-stabilised floaters need a large part of the structure at the water's surface, to provide enough buoyancy to remain stable. Due to the large waterplane area at the surface barges have been found to be susceptible to excessive pitching in extreme wave conditions and are less stable than other concepts. In reality, FOWT concepts will achieve static stability by combining the three stability mechanisms. A preferred solution that uses ballast in addition to buoyancy is the so called semi-submersible type floater, which usually results in a floating jacket or space-frame.

2.5.3 TENSIONED LEG PLATFORM (TLP)

TLPs are barge floaters stabilized with unextendable tensioned mooring lines.

Unlike the TLP concept, the semi-submersible and spar-buoy types can be anchored to the seabed with slack catenary.

For developing deep water wind energy, all these approaches are being actively researched by academia and the offshore wind industry. Each concept has its challenges and advantages with regard to motion behaviour, characteristics, fabrication, transport and installation opportunities.

	Spar	TLP	Semi-Sub
			
Stability	Ballast	Moorings	Hydrostatics
Min depth [a]	Deeper	Shallower	Shallower
Periods	Good	Good	Acceptable
Cost	Uncertain	Uncertain	Uncertain
Yaw and torque	Acceptable	Probably good	Good
Fabrication	Potentially simple structure	More complex structure	More complex structure
Installation	More complex operation	More complex operation	Good

[a]However greater depths will typically allow a better performing and lower cost design to be deployed

Figure 35. Assessment of floating platform classes. Source: Floating Offshore Wind Energy (Cruz & Atcheson, 2016)

For spar-buoys the key installation challenge is transporting a deep-draft platform from a shallow assembly harbour. The deep Norwegian fjords located very close to shore are a unique exception worldwide.

2.6 EXISTING FOWT

The first multi-megawatt floating wind turbine that existed was is Norway's Hywind, built in 2010. The second multi-megawatt floating wind turbine, WindFloat–a semisubmersible-type floating wind turbine was installed in Portugal in June 2012. Currently, Japan's Ministry of the Environment is financing extensive research on FOWT in two major demonstration projects: GOTO Island project and Fukushima demonstration project (also called Fukushima Forward Project).

Although the list of promising FOWT projects is long, it is the abovementioned existing FOWT that have been chosen to be briefly discussed.

2.6.1 HYWIND

The Hywind floating offshore wind concept is a slender steel cylindrical structure, making it a spar-type platform. It is currently the most advanced spar concept and the world's first floating full-scale wind turbine Hywind Demo, installed in 2009, 10km off the coasts of Norway in a water depth of 200 m. It was developed by Norwegian Statoil ASA, a company with background in and experience with design, installation and operation of floating offshore oil and gas platforms. Thus, Hywind combines known offshore technologies with the specific requirements of wind turbines.

The Hywind technology was first conceptualised in 2001 and a scale model was used to test the concept in 2005 before the full-scale demonstration project was constructed. This depicts the typical pathway floating wind turbine concepts must undergo prior to commercialisation.

Figure 36. The world's first full-scale floating wind turbine. Source: Statoil

The substructure, also known as floater, is indicated in yellow. The rest of the structure includes the tower, nacelle and rotor.

The structure is ballast-stabilised with water and rocks, and anchored to the seabed with three mooring lines and anchors suited to the seabed conditions on site. The two extra mooring lines have adequate reserve strength to prevent the structure from drifting off in the event of failure of the main mooring lines. The electrical cables have expansion loops on the seabed to prevent damage in this event.

For the installation process, the spar structure is filled with water to raise it from horizontal to vertical position, then the other components were assembled and the completed unit was towed to the final offshore location where anchors had been pre-installed. Note that this installation method is not suitable for shallow waters.

The Hywind model was equipped with more than 200 sensors to measure the platform motions and loading, which allowed the technology to be verified through operational testing. It performed beyond expectations producing in 5 years approximately 41 GWh of electricity. It is interesting to note that Hywind Demo turbine experienced several storms with maximal wave height of up to 19 m and wind speeds of 44 m/s without any consequence to the structure during almost six years of operation.

Hywind Demo was successfully tested and has undergone all the necessary demonstration steps to become a proven design. Statoil now plans to scale up this technology to larger applications. Hywind is due to be deployed in a pilot park in Scotland using higher rated wind turbine of 6 MW. It is worth noting that this project- Hywind Scotland Pilot Park- will be the first floating wind farm in the world. This makes it arguably one of the most –if not the most– developed FOWT concept.

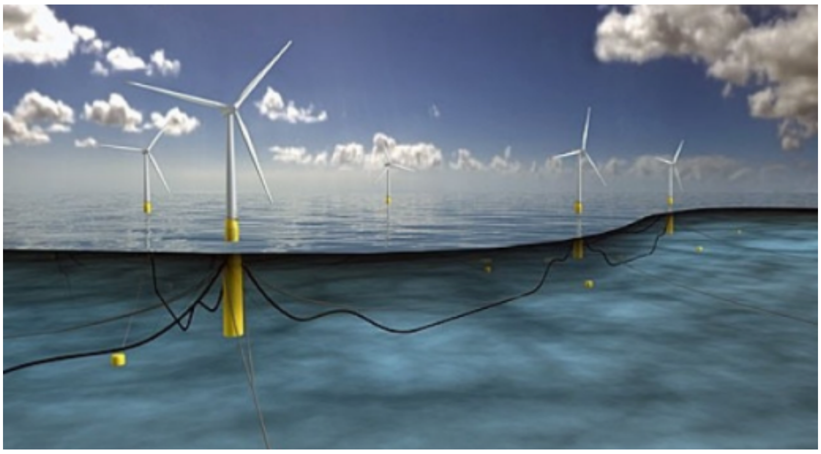


Figure 37: Hywind Scotland Pilot Park, production scheduled to start in 2017. Source: Statoil.

2.6.2 WINDFLOAT

WindFloat is a semi-submersible three-legged platform designed and patented by Principle Power. Windfloat came to life in 2011 as a full-scale prototype equipped with a 2 MW Vestas V-80 turbine. Windfloat1 prototype (WF1) was installed in Aguçadoura, Portugal. The turbine is mounted asymmetrically on one of the legs.

Under each of the three legs, WindFloat includes water-entrapment plates, or heave plates, that increase the hydrodynamic mass and add significant viscous damping, stabilizing the structure. The water entrapment plates efficiently reduce platform motions instead of having to increase hull dimensions and overall weight of the structure.

The hull is made of ballast tanks, one at each of the three legs, that are interconnected in a closed-loop system that allows ballast water to actively move around in response to changes in wind velocity and direction. It is a real-time self-corrective active ballasting system that keeps the tower vertical, improving turbine efficiency.

Design philosophy of WindFloat focuses on optimisation of power to weight ratio by reducing the structural weight. However, ease of fabrication was a primary design driver, meaning that instead of choosing the lightest structure, a balance between fabrication difficulty and weight of the overall structure weight was sought.

It is the first offshore full-scale wind turbine to be installed using a semi-submersible floating foundation worldwide as well as the first offshore wind turbine to be installed without the use of any heavy-lift jack-up vessels or floating cranes, fully assembled at the quayside.

Two key features of WindFloat make it relevant for the future of offshore floating wind.

EASY INSTALLATION PROCESS

The major achievement is that Winfloat is the first FOWT to be deployed with no use of any offshore heavy lift turbines. Up to date it is the only solution that can be fully completed on-shore: final assembly, erection and commissioning of the wind turbine is completed onshore at the quayside, where the wave environment is not a constraint. It can be wet-towed whilst supporting a fully assembled and commissioned wind turbine. The same working principle that keeps WindFloat stable during operation keeps it stable during transport. This provides significant cost savings opportunities by eliminating transport and installation challenges, currently constraining the industry.

SHALLOW DRAFT

Another promising feature of Windfloat is its minimal draft. This allows the structure to be towed directly from the assembly harbour to the offshore site in standing position. Once out of the harbour, the hull is ballasted to its operational draft through a fully reversible ballasting operation. This represents an advantage over larger floating concepts, such as a spar type platform, that need to be towed to site in the horizontal direction.

Figure 38. WindFloat 1 prototype.

Figure 39. Wet tow of fully assembled and commissioned WF1 to installation site. Source: http://www.rechargenews.com

2.6.3 FOWT DEMONSTRATION PROJECTS IN JAPAN

Japan has huge offshore wind energy resources and is located in relatively deep waters, with water depth ranging from 50 metres to 300 metres. Even though Japan has extensive experience on floating platforms (Tokyo bay's Megafloat), it was the Fukushima disaster that triggered further investigation on FOWT. Japan is now probably one of the global leaders in floating wind developments and some experts state Japan is likely to be the place where floating wind first will be fully commercialised (Utsunomiya, et al., 2015)

Here, 2 projects involving several FOWT concepts will be discussed:

- Fukushima demonstration project (Fukusima FORWARD)
- Goto island demonstration project

FUKUSHIMA FORWARD

The Fukushima offshore wind consortium was formed in March 2012 to develop the Fukushima demonstration project, also known as Fukushima FORWARD. The consortium comprises University of Tokyo, ten companies and is funded by the Ministry of Economy, Trade and Industry.

The Fukushima demonstration project is perhaps one of the most ambitious projects undertaken as it tested 3 different FOWT concepts. In this project, three floating wind turbines and one floating power sub-station have been installed off the coast of Fukushima. Phase I of the project (2011-2013) consists of one 2MW semi-submersible FOWT and the world first 25MVA floating substation. During the second phase (2014-2015) a 5MW advanced spar and a 7MW V-shape semi-submersible FOWT were installed. The latter is as of today the world's largest turbine.

The goal of the project was the development and verification of a new V-Shape semi-submersible floater as well a compact semi-sub floater, but also to assess marine navigation safety, environmental impact and set the ground for collaboration with the fishery industry. The economic feasibility of each concept was also studied as part of the project was to establish a business-model for floating wind farms.

Figure 40. Phase I & Phase II of Fukushima FORWARD project.
Source: http://www.fukushima-forward.jp/

GOTO ISLAND DEMONSTRATION PROJECT

Goto-Nada is the name of the sea where this project took place, 1.7km southwest offshore from Goto City, Nagasaki Prefecture. Funded by the Ministry of the Environment and with the collaboration of Tokyo University and Fuji Heavy Industries Ltd., the Goto FOWT demonstration project is yet another spar-buoy concept. However, what makes this particular FOWT interesting is that it is a hybrid spar that uses both pre-stressed concrete (PC) rings at the bottom part and steel cylindrical shells at the upper part. This concept is a clear example of the industry's belief that a different choice of material can have a favourable impact on reducing costs. Using a hybrid design will be beneficial for reducing the CAPEX and could potentially also reduce OPEX.

With this project, it can be observed that the premises of using steel as the main material for FOWT are being reconsidered.

The project consists on the design, construction and testing of two models in a depth range of 91-96m. The first model was a half-scale model that was designed, constructed, installed, operated, and finally removed. Following the half-scale model test, the full-scale model was designed, built and installed, and is now in operation. The project will take 6 years beginning from September 2010 to March 2016. (Utsunomiya, et al., 2015)

The first FOWT mounts a 100kW wind turbine and the second FOWT mounts a 2MW turbine, both of downwind type. The dimensions of the full-scale model are almost double of the half-scale model, hence the name.

The half scale model was installed at the site on 11th June, 2012 and the opening ceremony of the full-scale model was held on 28th October, 2013.

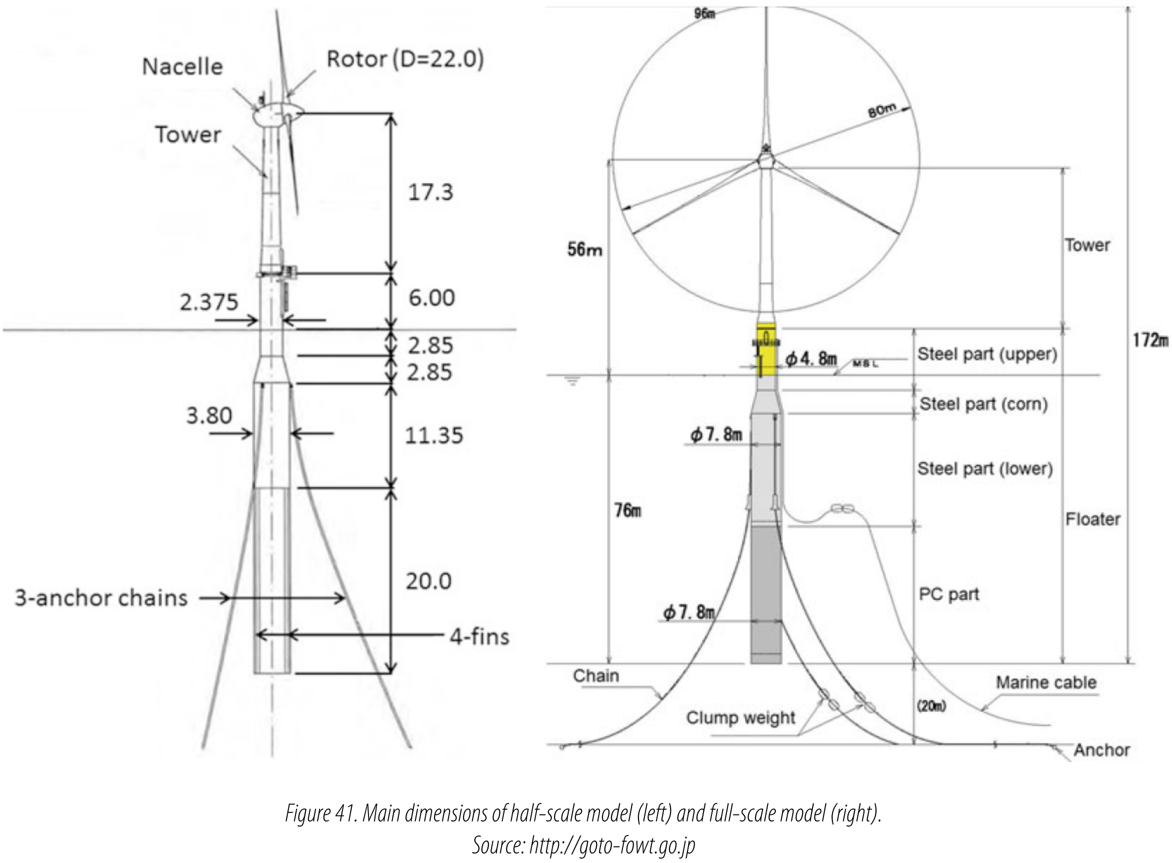


Figure 41. Main dimensions of half-scale model (left) and full-scale model (right).
Source: http://goto-fowt.go.jp

The Goto project is a spar buoy concept and one of the first to integrate concrete in the floater design. Given these similarities with Windcrete the construction and installation of both half-scale and full-scale models are briefly presented.

CONSTRUCTION

The PC part and the steel part of the floating body were constructed separately by different manufacturers. For the half-scale model, the ring segments had an outer diameter of 3.8 m and length 2.0 m. They were produced through a centrifuge manufacturing process (shown in figure 24). All the concrete elements were fabricated at the shipyard, close- by to the quay yard where they were assembled in horizontal position.

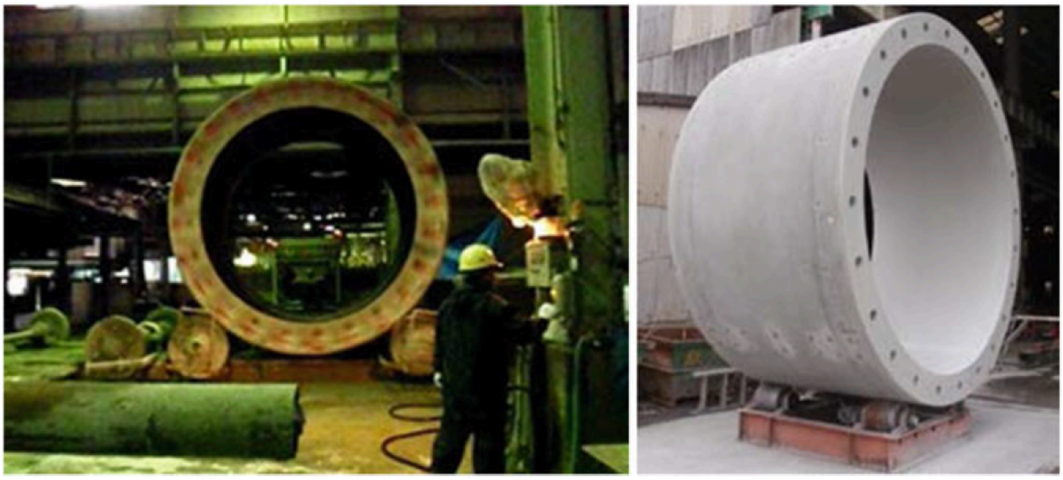


Figure 42. Manufacturing of the centrifugal PC precast segments by centrifugation. Source: (Utsunomiya, et al., 2015)

Figure 43: Manufacturing of the steel part. Source: (Utsunomiya, et al., 2015)

INSTALLATION PROCESS OF HALF-SCALE NAGASAKI FOWT

Installation of half-scale model as described in *Floating Offshore Wind Turbine, Nagasaki, Japan*, (Utsunomiya, et al., 2015)

a) Stowage to barge
b) Upending
c) Towing to the site
d) Hook-up of mooring chains

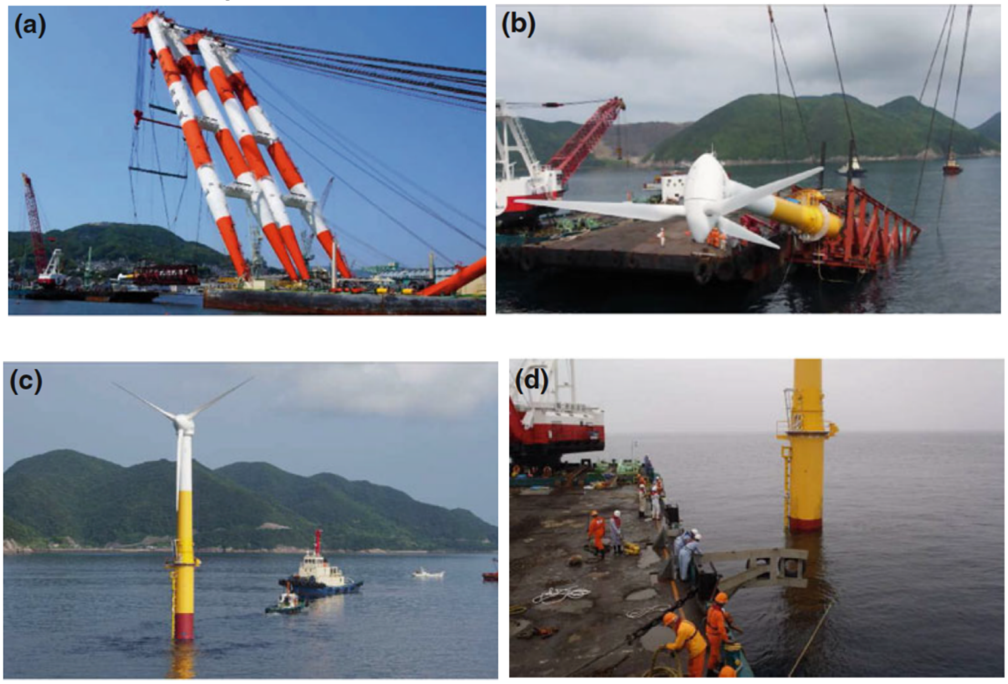


Figure 44. Installation of half-scale Nagasaki FOWT. Source: (Utsunomiya, et al., 2015)

INSTALLATION PROCESS OF FULL-SCALE NAGASAKI FOWT

Installation of full-scale model as described in *Floating Offshore Wind Turbine, Nagasaki, Japan*,

a) PC and steel part being connected at a quay yard in the horizontal position.

b) The completed hybrid spar floater was towed to the northern part of the Kabashima Island using a barge.

c) The floater was then upended by using a large floating crane. The procedure is basically the same as the half-scale model.

d) The tower (in two pieces), the nacelle, and the rotor were assembled to the floating body.

e) After completion of the floating wind turbine, it was towed to the southern part of Kabashima Island.

f) Finally, the anchor chains were hooked-up to the floating body. Here, the anchor chains had been pre-laid. The final hook-up was completed on 18 October 2013.

Figure 45. Installation of full-scale Nagasaki FOWT. Source: (Utsunomiya, et al., 2015)

The full-scale model was installed successfully and today demonstrates the feasibility of a hybrid spar-type FOWT in Japan, which combines a lower PC precast segments and upper steel part. (Utsunomiya, et al., 2015)

2.7 DESIRABLE FEATURES OF A FLOATING WIND TURBINE PLATFORM

A promising solution will take into consideration all the new trade-offs that come with FOWT with respect to conventional bottom-fixed technology. There is a vast number of possible floating offshore wind turbine concepts actively being pursued by researchers. However, the preferred configuration remains unclear as the industry encourages further research and awaits results for current prototypes deployed around the world. This part aims at defining the more desirable features that any FOWT should include if it hopes to become a cost-effective solution, regardless of the floater concept.

2.7.1 FLEXIBLE INSTALLATION

Installation process must be flexible, low cost and weather tolerant. A Flexible installation process means:

- Full assembly at a coastal facility.
- Floater size independent of water depth.
- Tow floating structures to offshore location.
- FOWT movable for major maintenance.

Mobilising highly specialized purpose ships must be avoided as much as possible. An optimal solution will require no heavy lifting operations during the installation and would preferably be transported fully assembled with the turbine and blades.

2.7.2 CONSTRUCTION ON A NEAR-SHORE FACILITY

Floating systems offer the opportunity to perform most of the assembly process onshore in production facilities that can maximize the advantage of series production. Through high production floating, systems may become cheaper than fixed bottom systems, which must be constructed at sea. (Butterfield, et al., 2005). Another advantage of achieving production through an industrialized process is the possibility to build complex designs while maintaining high quality standards, only truly possible at an onshore construction site.

2.7.3 INCREASED TURBINE RELIABILITY

Increasing number of large offshore farms will require turbines be specially designed for the offshore environment. The use of "marinized" onshore wind turbines must be abandoned and replaced by a new generation of turbines, designed to extract energy from greater winds and withstand harsh offshore environment while making reliability a priority.

Gearboxes in offshore turbines, which face faster wind speeds, are more vulnerable than those in onshore turbines. This is expected to become even more true for FOWT located at more remote offshore locations.

Various independent studies have concluded that malfunctioning of gearboxes is the main cause of downtime (EWT, sd). Removing the gearbox from the wind turbine eliminates the technically most complicated part of the machine, therefore improving reliability and leading to easier and lower maintenance (Butterfield, 2013). The industry's shift to direct-drive is a response to gearbox failures and very high maintenance costs for offshore turbines. The economy of floating concepts, located further offshore, will benefit from gearless generators and calls for further research to make direct-drive systems more affordable. The fact that they are raw-material intensive remains an issue today.

2.7.4 DECREASED MAINTENANCE OF SUPPORT STRUCTURE

O&M costs (OPEX) can amount to as much as 20 to 30% of the overall project costs making it a great area to drastically cut down costs. Whereas designing more reliable turbines is a good start to lowering costs, FOWT must efficiently decrease maintenance requirements for the support structure itself. Re-thinking the standard choice of materials may lead to improvements in maintenance costs and slower deterioration rate. It is also safe to assume that OPEX will decrease further in a support structure presenting fewer joints.

Everything seems to indicate that if a reliable and cost-efficient alternative to bottom-fixed turbines is presented to the offshore wind industry, it will be there to stay. Floating structures could lead the way in the quest of unlocking deep water wind energy but new designs must take advantages of all the above-mentioned features.
The new and unique trade-offs that emerge with FOWT must be appropriately grasped and used advantageously if these offshore turbines are to become a promising cost-effective solution.

Now that the possibilities of FOWT to bring down costs have been presented, they will be reasoned further for a particular concept of FOWT: Windcrete.

3. WINDCRETE: AN OPTIMIZED SPAR-BUOY CONCEPT

3.1 Concept

Windcrete is a novel deep water concrete floating spar-buoy. The structure consists of three parts –floater, transition part and tower- built as a continuous single piece. The monolithic nature of the concrete structure is precisely what makes Windcrete a truly novel concept.

The floater achieves stability by adding a concentrated mass at the bottom to lower the centre of gravity well below the centre of buoyancy. Thanks to this ballast the floater can resist the overturning moment occurring at the top of the structure. The ballast specific weight is set to 25 kn/m3, corresponding to black slag from electrical furnaces.

The choice of material –concrete as main construction material- is perhaps one of the most innovative features of Windcrete. Concrete is readily available just about anywhere and there is deep knowledge and consensus of the enhanced mechanical and durability properties of concrete in marine environments. This preference clearly indicates that designers understood that a major cost reduction would only be possible by addressing maintenance costs.

3.2 Motivation

Windcrete was born in UPC Barcelona from the mind of researcher and professor C. Molins and his team as a 'natural reaction' to the current challenges faced by conventional bottom fixed turbines. As such, Windcrete has been designed to tackle two of the areas of the supply chain where cost reductions are most likely to be realised: installation costs and maintenance costs. Just how Windcrete hopes to achieve these cost-reductions will be the obect of the upcoming part.

Another feature that highlights the potential of Windcrete is the possibility of extending the lifetime with little additional costs that can be expected from concrete structures.

The IEC 61400 is an International Standard published by the International Electrotechnical Commission regarding wind turbines. According to IEC 61400, wind turbines must be designed for at least 20 years lifetime, which is currently the governing practice.

However, –if properly constructed- Windcrete has a chance at extending the lifetime of floating support structures to new limits, beyond 20 years and up to 6o years or more. By extending the lifetime these support structures can be reused when the wind turbine lifetime is exhausted.
If enhancing durability is at the core of design and construction efforts, the design lifetime could be more than doubled giving Windcrete an exceptional advantage over its competitors.

3.3 Dimensions of the design

The geometry of Windcrete is fairly simple and practically constant.

As previously mentioned Windcrete is the first FOWT concept that considers floater, transition part and tower as a single continuous piece. The structure dimensions are as follows:

The tower height is 87·6 m above MSL and has been selected to be the same as in the OC3 NREL prototype. The tower is in the shape of truncated cone with diameters of 10 m and 4 m. The thickness of the tower is 40 cm.

The transition which connects the tower and the floater between the tower and the floater is 10 m long. The shape is a truncated cone with lower radius of 13 m and upper radius of 10 m offering a smooth connection between floater and tower. The thickness of the transition part is 50 cm.

The floater is a 113·5 m long cylinder and its diameter is 13 m. It is estimated that no internal stiffeners will be required for diameters up to 20 m. The thickness of the cylinder is 50 cm.

The length of the overall structure is around 220 m.

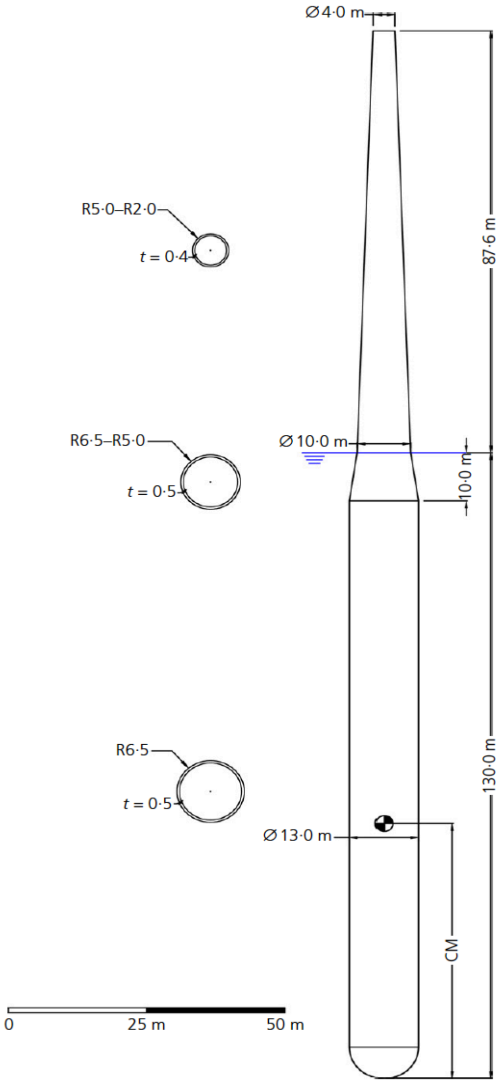


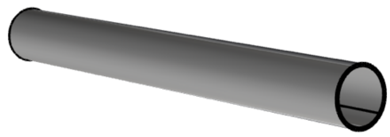
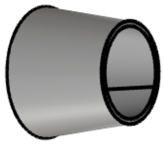
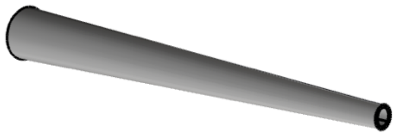
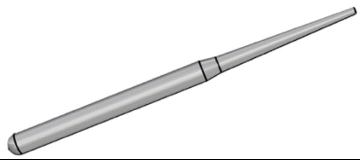
Figure 46. Main dimensions of Windcrete.
Source: Spar concrete monolithic design (Molins, et al., 2016)

The dimensions of the tower have been chosen so as to restrict pitch/roll and heave motions within acceptable limits. The typical range of wave periods varies from 3 seconds to about 25 seconds (Deo, 2013). For the design of Windcrete the wave period is set below 30s and the size and weight of the structure has been chosen to have a larger Eigenperiod to avoid resonance.

The Windcrete prototype to construct has been designed to operate at water depths greater than 150 m. The total draft of the system, including the ballast is set to 130 m and the gap between MSL and the lowest position of the blades is around 25 m.

The following table presents the geometry, volume and dead weight of each of the above-mentioned elements.

Table 12. Specifications of the main elements of Windcrete

ELEMENT	DIMENSION	CROSS-SECTIONAL AREA [M^2]	VOLUME** [M^3]	***DEAD WEIGHT [T]	SHAPE
floater L=120 m	*ϕext= 13 m, t=50cm*	*19.63*	*2356.2*	*5890.5*	
Transition L=10 m	*Lower ϕext= 13 m, t=50cm*	*19.63*	*172.8*	*432.0*	
	Upper ϕext= 10 m, t=50cm	*14.92*			
Tower L=87.6 m	*Lower ϕext= 10 m, t=40cm*	*12*	*726.6*	*1816.5*	
	Upper ϕext= 4 m, t=40cm	*4.52*			
Base* L=6.5 m	*ϕext= 13 m*	*132.73*	*575.2*	*1438.0*	
		Total	*3830.8 m3*	*9577 tonnes*	

*A massive semi-spherical base is considered

**$V_{trunc.cone} = \frac{\pi}{3} L \left[\left(R_{ext}{}^2 + r_{ext}{}^2 + R_{ext} \cdot r_{ext} \right) - \left(R_{int}{}^2 + r_{int}{}^2 + R_{int} \cdot r_{int} \right) \right]$

*** $V \cdot \gamma_{reinf.concrete}$ with $\gamma_{reinf.concrete} = 25\ {}^{kN}/_{m^3}$

3.4 Areas of cost reductions

Windcrete is a FOWT spar-buoy concept that is made out of concrete whilst presenting no joints. Together, these features give Windcrete the upper hand to become a competitive solution to the present-day challenges of offshore wind.

3.4.1 COST-EFFECTIVE INSTALLATION

As a FOWT, Windcrete can, by its very nature be floated directly in a fully or partially commissioned condition from the fabrication and out-fitting yard to the offshore site. Once construction has been completed, the structure can be directly launched to sea by flooding of a dry-dock or through the use of sliding/skidding system.

The structure is towed by simple tugboats to its final location where it is gradually flooded in a controlled way to vertical position. 90% of the structure is submerged so that top of the tower is below 20m above msl. The turbine is installed using a catamaran ship or equivalent.

Once the structure is safely secured by mooring lines and the turbine is successfully installed the emersion phase begins. During this stage, the upended structure is emerged from turbine-installation height to its final design height.

Water inside the floater is pumped out and replaced by heavyweight aggregates until the top of the tower reaches 87·6 m above MSL.

This simplified installation procedure is expected to efficiently reduce capex by drastically decreasing installation costs. This will be achieved by avoiding the use of heavy floating cranes. The installation process should aim at eliminating expensive vessels for both turbine installation and all the other phases of the implementation cycle.

3.4.2 LOWER MAINTENANCE COSTS

The other pragmatic attribute that makes Windcrete truly special is that it is made entirely out of prestressed concrete efficiently reducing maintenance costs to a radical minimum.

If properly mixed, concrete has excellent durability in the marine environment and requires no costly maintenance. This fact is supported by many studies, for instance 19 pre-stressed concrete barges constructed in the Philippines during 1964-1966. The average annual maintenance costs of the concrete barges were found to be about 1/3 compared to steel barges (Yee, 1977). It is noteworthy that even though concrete structures respond well in the marine environment and require little maintenance, ideally, if a concrete structure is joint-less, it would become potentially maintenance-free. Maintenance is one of the main cost drivers areas that offshore wind concepts made out of steel, both conventional concepts and other FOWT currently under investigation, fail to address properly.

The following table summarizes the main advantages of Windcrete over other FOWT concepts with regard to the choice of material:

Table 13. Main advantages of Windcrete with respect to other FOWT concepts made of steel or of steel and concrete

Steel / Hybrid FOWT	Windcrete
segmental designs→20 years design life-time	monolithic concrete structure→60 years life-time
Steel→Higher CAPEX	Concrete →Lower CAPEX (concrete is cheaper)
Joints→ corrosion, HIGH OPEX	No joints +Low permeability of concrete→ LOWER OPEX

3.4.3 OTHER ADVANTAGES OF CONCRETE IN OFFSHORE STRUCTURES

Concrete presents other great possibilities in the marine environment when compared to steel. Some of these advantages are of big importance as they translate to a direct impact on costs. They are now mentioned

LONGER LIFE OF THE STRUCTURE

For concrete structures, extension of design life from for instance 30 years to 50 or 70 years can be achieved without significant additional cost.

LOWER FABRICATION COSTS

The cost-effective installation process is not the only aspect that contributes to lowering capital costs. As concrete structures are cheaper than steel ones, a material cost reduction can also be expected. The material cost reduction has been estimated by previous works. Alexis Campos estimated as much as a 60% material cost reduction if concrete was used instead of steel. This comparison was performed considering the respective dimensions of a steel structure and concrete structure to withstand the same loads.

BETTER MOTION BEHAVIOUR

In ship design, the motion characteristics of a concrete hull were found to be better than for a steel floater designed for the same purpose. The generally larger mass and draught, result in improved motion characteristics. This conclusion can be drawn based on reports from ship captains during World War II (The Seasteading Insititute, 2010)

As stated, concrete is a good alternative to steel when building offshore structures. The ongoing interest demonstrated by the offshore industry serves as solid proof of this and will provide valuable experience.

Therefore, through the use of concrete Windcrete can efficiently reduce both CAPEX and OPEX due to the material cost reduction, its endurance in harsh marine environments and longer service life. Finally, if a monolithic structure is achieved, a truly significant OPEX reduction can be expected making Windcrete one of the most competitive concepts currently under consideration.

For further information on design of criteria, hydrodynamic analysis and other relevant details of Windcrete project refer to the paper Spar concrete monolithic design for offshore wind turbines (Molins, et al., 2016)

4. CONSIDERATIONS PRIOR TO CONSTRUCTION

4.1 PARTICULARITIES

As implied previously, Windcrete is not suitable for vertical slipforming if one considers a holistic view of the implementation process, particularly the transition from the end of the construction to the transport and installation stage.

The project involves a massive concrete placement (over 3800 m^3) that must satisfy high quality standards to resist harsh offshore conditions. There is currently no off-the-shelf solution to construct Windcrete. As of today, Windcrete has never been constructed which leaves a comfortable space with a wide range of possibilities to explore with regard to the construction procedure to be followed. In fact, the unresolved construction method of Windcrete should be seen as an advantage as it allows ample room to re-think the design procedure as a whole.

Besides stringent quality requirements common to all offshore structures like watertighness, resistance to chlorides and requirements with regard to reliability, Windcrete comes with its own specific requirements. Windcrete, or rather the construction process of Windcrete, must satisfy a particular set of requirements, 2 of which are set by the design and a third that is imposed by the author.

[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial production

[1] The first requirement is closely linked to the second and is in fact of practical nature. Given that the structure is intended to be transported horizontally, construction should also be done horizontally due to the size of the structure that constraints handling.

[2] Monolithic here means that Windcrete will be built as a single continuous piece, and as a result will result in a structure with no joints. Thus, the second requirement is imposed by the design. It seeks to minimize maintenance operations to a whole new level by the complete absence of joints. Note that if a single continuous structure results, handling is all that more difficult and **[1]** is enforced further. Note: This requirement is paramount to attain the claimed reduction in maintenance costs,

[3] The third requirements is imposed by the author who wishes to intervene in the design of a construction process at an advanced stage of major deployment of Windcrete. This preference is due to the fact that at commercial deployment level the widest possible range of construction methods should be considered, independently of their cost.

From this point on these requirements will rule the soon-to-be construction proposals.

The dilemma when it comes to planning construction is just how literally one understands monolithic structure. Windcrete presents itself as a close-to ideal solution to a complex problem. A structure capable of withstanding the harsh offshore environment with minimum maintenance throughout it's intended lifetime. What Windcrete hopes to achieve is a practically maintenance-free solution by combining the use of concrete and the absence of joints.

Civil Engineering has accomplished a remarkable knowledge on concrete technology, and has cast in a single pour structures far larger than Windcrete.

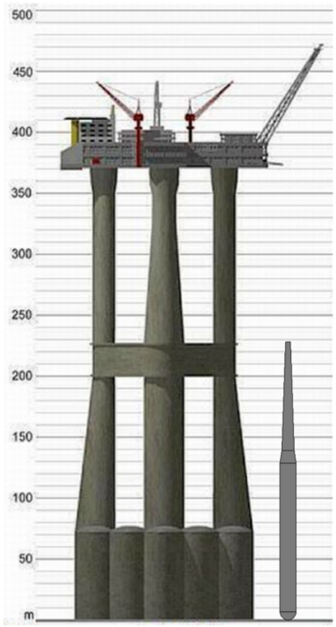


Figure 47. Troll-A & Windcrete dimensions.

Deep water concrete gravity-based structures -referred to as Condeep- used for oil extraction purposes are a readily available example of how large monolithic concrete structures can be achieved.

A breath-taking feat is Troll-A. Built by Norwegian Contractors for Norske Shell in 1995, the Troll A oil drilling platform has an overall height of 472 metres that was continuously slip-formed, more than double the height of Windcrete.

Troll-A, and another thirteen Condeep structures, show that with impeccable planning and good knowledge on concrete technology, large concrete placements can meet the desired high-quality requirements of the offshore industry. They are also solid proof that concrete is suitable for the marine environment and enhances durability when compared to steel.

Windcrete aims at providing pre-fabricated support structures entirely produced and completed on land, ready to be transported horizontally to the final location with minimum effort. This requirement conceals a striking difference between Windcrete and these inspiring Condeep projects other than the obvious differences of the economics of the oil industry ($650 million USD for Troll-A).

As opposed to troll-A, Windcrete should be constructed horizontally instead of vertically, to smoothly connect construction and transport phases.

Even if significantly smaller, Windcrete remains a colossal structure and moving it –if at all possible- is difficult, slow and expensive, and should be avoided at all costs. By only optimizing each individual phase as if they were independent one from another, unnecessary handling operations may be required. This, in turn, would shatter any hopes of producing Windcrete in a cost-effective process. What the author hopes to transmit in this introduction is that a reliable way of controlling costs is minimizing handling operations, fully justifying horizontal construction.

This brings us to some remarks on the optimization of the implementation process as whole. If one hopes to achieve a major cost-reduction, construction, transport and installation stages must be optimized. However, optimizing every single phase of construction, installation etc. individually is not practical due to the fact that the size of a finished Windcrete tower is huge. Instead what the entire process should be optimized in a holistic view in such a way that minimal handling between phases is required. Only by ensuring a swift and uncomplicated transition between phases can we truly present a cost-effective construction process. Keeping implementation costs within acceptable limits is the only way Windcrete can become a competitive alternative.

Another aspect worth considering is the sensitivity of joints on the overall quality of the structure and the impact on durability. Assessing the consequences of a well-sealed joint in concrete exposed to offshore conditions would provide some valuable insight and is without doubt a promising area for research. Much could be learned on whether the presence of joints is acceptable or yields unacceptable consequences on the soundness and durability of the structure. As interesting as it may be, for now data for such a structure is not available to conduct a sensitivity analysis on the impact of joints. Nonetheless, it is safe to assume that the deterioration rate of the structure, and of its mechanical properties, will be much lower in a structure with no joints at all. For such a jointless structure, maintenance costs are expected to fall dramatically, efficiently tackling the high O&M costs of offshore wind turbines.

Results of research on the adverse effects of joints could also help establish the grounds for the construction process. With more knowledge on this aspect, a trade-off between the acceptable number of joints and the cost of fabrication could be reached, as building a structure with no joints is potentially more expensive. Allowing several joints during construction may benefit the construction procedure, both in terms of costs and technical complexity.

Initially, to get this project running a cheaper construction process may be the best way forward, even if this means modifying the design. Tolerating a few joints must be considered if it drastically reduces the cost of producing towers.

That being said, this work has chosen to remain conservative with regard to the specified requirements. The construction procedures that have been elaborated are in accordance with the specified dimensions of the tower and comply with the given construction criteria, namely the monolithic feature.

The design specifications provided by Molins and his team in Spar concrete monolithic design for offshore wind turbines (Molins. *et al.*, 2016) are considered as fixed boundary conditions. No alterations of the design are scheduled in this academic work, however future adjustments should not be ruled out.

As a starting point, only construction procedures resulting from a monolithic pour are considered. This conservative pass-no-pass criterion has culminated in several construction proposals, all of which will be duly described. In broad terms, these proposals fall under 2 types of construction schools:

- Towers are poured horizontally in a seemingly monolithic way with highly specific mobile technology and in singular casting facilities

- Towers are poured in ring-segments that are cast separately and connected "in fresh" before concrete setting time is reached.

Both of these approaches will require an around-the-clock production. Exhaustive and meticulous planning and phasing will be required no matter the proposal.

Any given proposal is associated to a unique casting facility with singular requirements with regard to space and necessary technology. All casting facilities will have at least the following 2 aspects in common:

- Near-by to the sea
- Suitably equipped for large concrete placements
- Continuous supply of materials

Any attempt to construct Windcrete, regardless of the preferred construction procedure, will need a detailed investigation on formwork design. For this reason, an upcoming chapter focusses exclusively on formwork for Windcrete. The basic principles of formwork can be found in **APPENDIX. 1. FORMWORK BASICS.** Now the desirable features of formwork for Windcrete are

4.2 FORMWORK WINDCRETE

As Windcrete is a large concrete structure, formwork is bound to make up a significant part of the overall costs so constructability must remain a priority (see example from *RELATION BETWEEN DESIGN PROCESS AND CONSTRUCTION PROCESS* - **APPENDIX. 1**).

It can be said that Windcrete has adopted rather well the three concepts for economic formwork: design repetition, dimensional standards, and dimensional consistency (see **APPENDIX. 1. FORMWORK BASICS** for justification). By considering the constructability from the very start of the design phase we have a good chance at working towards a cost-efficient construction process.

Given that the design of Windcrete already includes the possibility to optimize formwork costs, one can begin to establish the desired qualities of the formwork to be used for the construction of Windcrete. Generally speaking, formwork will need to focus on quality while remaining suitable for serial production of towers.

The overall quality of the completed project is highly dependent on the formwork. Windcrete will be exposed to harsh offshore conditions and is therefore a structure with high technical requirements. The tower must be a watertight structure with a minimum number of joints (ideally no joints at all) and a minimum thickness ranging from 40cm to 50cm.

It is strongly recommended to consider formwork from the perspective of a mold instead of a temporary structure. Form design for Windcrete should be such that it can be erected and disassembled efficiently in order to maximize productivity. Serial production calls for a strategy focussed in minimizing cost from form handling and the use of economy of scale to produce the necessary forms.

Preoccupation for serial production from the very start may favour costs considerably in the long term. The chosen solution for Windcrete Formwork is of modular type and it should be designed to allow convenient erection and swift removal. A form cleaning and maintenance pattern should also be defined and may be worth mechanizing to a certain extent to avoid manually treating the surface of the forms.

4.2.1 MATERIAL CHOICE

The forms to build Windcrete will be made out of steel. Steel forms can be fabricated in large number in any desired modular shape or size. They are often used in large projects and are particularly suitable for circular or curved structures like those required by Windcrete. However, the main cost-benefit for using steel forms is the large number of reuses desired in a serial production.

Other reasons to prefer steel forms over timber formwork:

a) Steel forms are stronger, durable and have longer life than timber formwork and their reuses are more in number.
b) Steel forms can be installed and dismantled with greater ease and speed.
c) The quality of exposed concrete surface by using steel forms is good and such surfaces need no further treatment.
d) Steel formwork does not absorb moisture from concrete.
e) Steel formwork does not shrink or warp.

4.2.2 STANDARD FORM PANELS FOR WINDCRETE

Description of form-panels for Windcrete.
The cross-section of the floater is a large ring with external and internal radii of 6.5 m and 6 m.

The size of this ring clearly requires form panels to be subdivided into smaller curved forms. Generally, these forms will be in the shape of an arch and fall under the category of modular system formwork. Forms composing the modular system for Windcrete will be carried by cranes to allow for larger forms. By mounting the panels onto each other these arched forms will result in the desired ring shape.
The overall shape of a Windcrete tower will help identify how many different form designs should be contemplated.

The three elements that constitute Windcrete, floater, transition piece and tower determine the three different types of standard form panels. These forms are classified as follows:

- Arch form panels for the floater

- Conical forms for both the transition piece and the tower

- A semi-spherical form for the bottom of the structure

The number of forms will logically be a function of the size of these forms. Smaller forms will require an overall larger number of forms and of handling operations. The advantage of smaller forms is however a decrease in required crane capacity.

A few combinations for the modular system that could be used to construct Windcrete are now presented:

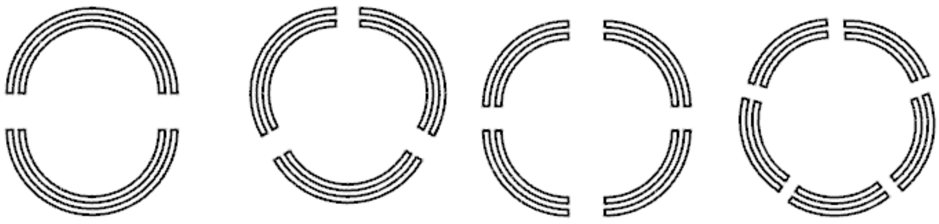


Figure 48. From left to right, modular forms subdivided in 2, 3 ,4 and 5 arch forms.

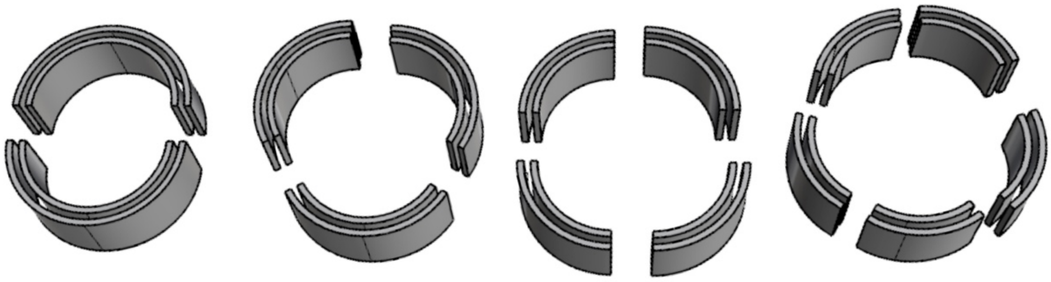


Figure 49. Simplified 3D view of different modular configurations.

Note that the above figure shows a simplified view of the forms in which form accessories like form-ties, form spacers, struts, braces and form interlocking mechanisms are not shown.

Another alternative is to use a combination of the former subdivided forms to produce the desired cross-section.

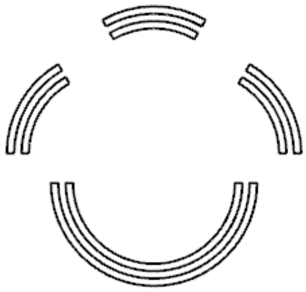


Figure 3

1 arch form for the lower half and 3 arch forms for the upper half

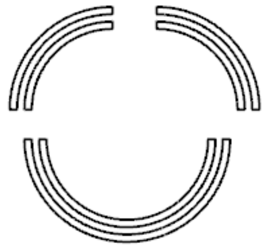


Figure 4

1 arch form for the lower half and 2 arch forms for the upper half

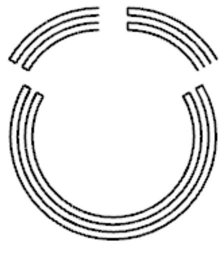


Figure 5

1 arch form of 270° and to upper arch forms each covering 45°

Simplified 3D-view of the former configurations. Once again form accessories and necessary form support system are not shown.

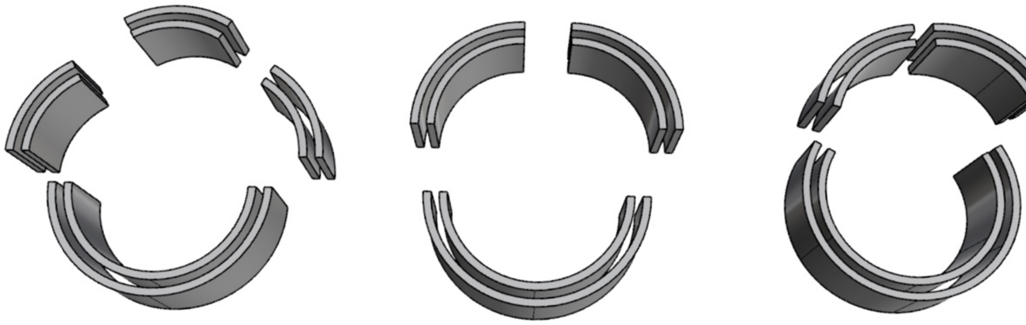


Figure 6. Simplified 3D view of different configurations.

Endless possibilities emerge and the preferred configuration will be the balance between the number and cost of handling operations and the lifting capacity and throughput of the cranes at the worksite.

It is interesting to note that with a small number of forms per cross-section (using larger forms), the formwork gradually becomes more of a 'mold' than a modular arrangement. For instance, in fig. 3 the lower part of the formwork covers an angle of 270 º which, if made of steel and in accordance with Windcrete dimensions, would be difficult to handle. This opens the door to semi-fixed approaches, that consider a certain section as a permanent mold embedded in a concrete slab for example.

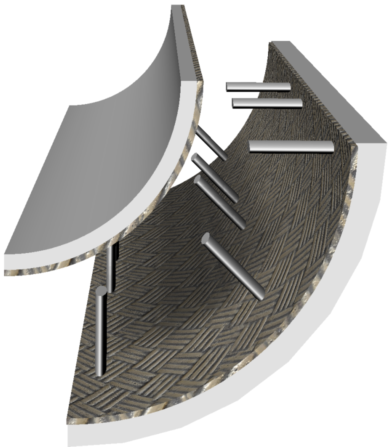


Figure 7. Standard Widcrete arch-formand sheathing with form ties (simpified).

Note that wales and interlocking mechanisms between forms have not been shown.

4.2.3 DESIRED FEATURES OF WINDCRETE FORMS

INTERLOCKING FEATURE

As a modular system will be used, these forms will have the ability to interlock with each other thanks to connection parts such as pins, shafts and levered locks. These locks should allow swift mounting and dismounting.

The interlocking feature will not only be relevant for formwork forming a ring section, it will also be extended to enable different consecutive sections to be connected.

Therefore, modular forms will have the ability to interlock with other forms rom the same section and the ability to interlock sections together.

EASE OF HANDLING FEATURE

Another desired feature of these form panels is a practical securing mechanism to attach them to the lifting equipment for handling. It would be preferable if this fastening mechanism was directly included and fixed to the panels to reduce handling time.

REFRIGERATING FEATURE

Hydration of cement is an exothermic reaction and in large-volume pours where heat dissipation is low, the temperature within the pour can rise significantly.
With regard to concrete mix design, there are several factors which will influence both the rate of hydration of the cement and the ultimate heat generated:

- Total content of cementious material
- Type and source of Portland cement
- The type and proportions of composite cements

Due to the extremely large amounts of concrete to be placed, hydration heat will be large. Given that concrete is negatively affected by high early age temperatures, formwork must include a cooling system. Refrigerating pipes running along forms either from the inside, the outside or a combination of both should be designed together with the forms.

For each of these systems once the thickness of the forms has been fixed, the weight per running meter can be computed. The length of the forms will be determined by the lifting capacity of the crane. Cranes at the worksite should be chosen specifically to handle these forms. Prior to choosing the length of the forms, a study on the most economical crane models should be done. Local crane suppliers should be able to provide information on available models, lifting capacity and prices.

Ultimately, the designer is responsible for producing a forming system that is safe, economical, and easily constructible at the jobsite.

4.2.4 GENERAL RECOMMENDATIONS ON FORMWORK

— Design the forms to provide required strength with the smallest amount of material and the most number of reuses.
— Use the largest practical prefabricated panels that can be handled by the equipment on the job.
— Do not specify or require a high-quality finish on concrete surfaces that will not be exposed to view by the public.
— Use the largest practical prefabricated panels that can be handled by the equipment on the job.
— Plan, draw, detail and prefabricate form members (not limited to panels) where possible.
— Bar Setting Form design can permit the rebar to be pre-assembled before installation.

— When planning forms, consider the sequence and methods of stripping them
— Bar Setting Form design can permit the rebar to be pre-assembled before installation.
— Use prefabricated panels where it is possible to do so.
— Consider using patented form panels and other patented members if possible.
— Develop standardized methods of making, erecting, and stripping forms to the maximum possible extent. Once operators learn these methods, they can work faster
— Strip forms as soon as it is safe and possible to do so if they are to be reused on the structure, in order to provide the maximum number of reuses.
— Always inspect the formwork prior to pouring
— Mark or number prefabricated re-usable panels and other members clearly for identification purposes.
— Use double-headed nails for temporary connections to facilitate their removal.
— Clean, oil, and renail form panels, if necessary, between reuses. Store them carefully to prevent distortion and damage.
— All formworks should be eased gradually and carefully in order to prevent the load being suddenly transferred to concrete.
— Conduct jobsite analyses and studies to evaluate the fabrication, erection, and removal of formwork. Such studies may reveal methods of increasing productivity rates and reducing costs.

4.2.5 SOME ADDITIONAL RECOMMENDATIONS ON FORMWORK FOR WINDCRETE

The cost of forms includes three items: materials, labour, and the use of equipment required to fabricate and handle the forms. Any practice that will reduce the combined cost of all these items will save money. Saving money is important for any project but is particularly crucial to FOWT, as they hope to become an economic alternative to conventional offshore turbines.

With the cost of concrete fairly well fixed through the purchase of ready-mixed concrete, little, if any, saving can be affected here. It is in the formwork that real economy can be achieved. For the economy of this project it is crucial the designer has good understanding of formwork logic at an early design phase. These are some specific recommendations for formwork used Windcrete construction:

- Planning for maximum reuse − A form designed for max reuse is stronger and more expensive, but it can save on the total form cost.
- Prepare the structural and formwork designs simultaneously to maximize constructability.
- Economical form construction – use shop-built-forms as it provides greatest efficiency in working conditions −it is recommended create shop area on the site− as form sections for Windcrete are large and transportation costs too.
- Design formwork for serial production
- Minimize the amount of "mobile" forms to reduce time and costs on form handling.
- Forms should be left in place to reduce evaporation, avoid curing and obtain high quality concrete, contrary to common practice, opposed to general recommendation #12 (see above).
- The previous recommendation suggests enough forms be available to cover the entire tower.
- Setting and stripping - repeat the same functions to increase the crew efficiency as the job progresses.
- Mechanize form handling and other tasks as much as possible.
- Do not specify high-quality finish of the inner face of the tower.
- Use non-recoverable ties to avoid holes in the structure.
- Cranes and Hoists - Size of form sections should be limited to the capacity of the largest crane planned for the job.
- Seek an optimal balance between the number and size of cranes at the jobsite, and the form size and weight.
- Review catalogues of commercial pre-fabricated forms to see. Tunnel lining formwork catalogues may be a good place to start.

Note that some of the proposals will require relatively fast concrete placement rates which increases the lateral pressure exerted on forms. Thus, the design strength of forms will need to be selected according to the placement rate of a given proposal.

4.3 ELABORATION OF CONSTRUCTION PROPOSALS

Common practice in Civil Engineering works is to refer to existing projects with similar characteristics successfully carried out in the past. Previous projects almost always will provide some valuable insight on adequate solutions to a given problem. It seems reasonable to look at the construction of current FOWT concepts.

However, if this philosophy is applied to assess Windcrete construction, one quickly finds that other FOWT concepts provide little inspiration. To date, steel elements have predominated the design of FOWT. This is not due to a misconception on the durability of concrete at sea but rather to the variety of floater concepts that lead to radically different design paradigms.

However, in general terms, one can see the current design trends see FOWT as made out of discrete elements, assembled in an outfitting yard and floated out to the offshore location.

Additionally, the fact that few spar-buoy concepts have reached full-scale deployment leaves us with few examples to seek inspiration. As of today, the Hywind project, the most relevant example of spar-buoy FOWT, is made entirely out of steel.

Even if the intended purpose of the structure is the same, the difference of material clearly rules out similarities regarding the construction process.

Broadening the scope to bottom-fixed structures is not very helpful either as the segment approach and the use of steel clearly dominates most of the current designs.

That being said, in terms of construction, the offshore wind industry will not provide as much inspiration as other civil engineering sectors.

As implied earlier, existing technology must play an important role on defining construction proposals for Windcrete towers. All of the proposals to build Windcrete that will be presented will feed from existing technologies. Most of these proposals will certainly contain heavily adapted versions of the original inspiring technology. It is expected that new methods will come from adapting current practices of civil engineers of a variety of fields. It could be argued that those proposals requiring the least specialized technology will be also be less expensive.

It is almost impossible to imagine constructing Windcrete towers with no prior design and construction of highly specialized equipment that fits the needs of the project. For this reason, formwork technology will be central to construction and highly mechanized systems will be preferred. This may mean high upfront costs at the beginning but serial production of towers will become more economical on the long-run.

As no off-the shelf technology exists, an extensive and open minded overview of civil engineering techniques has been carried out. Technologies from a wide range of fields of civil engineering will serve as inspiration if deemed useful to the progression of the project. Their relation to Windcrete will be justified as simply as possible and main relevant adaptations of each technology will be described.

Tunnelling practices involving specialized travelling formwork will be the most common source of inspiration. Other technologies like microtunnelling practices, the erector arm used by TBMs or post-tensioned box girders used in bridge construction will also be included in some of the construction proposals. Up-scaling certain technologies may also be a solution, like adapting the process of centrifugal reinforced concrete pipes to the suit the dimensions of Windcrete.

Another range of proposals will be based on breaking down the construction of the structure into smaller units that will be joined promptly in an assembly-line. The concept of assembly-line will require several identical "casting stations" that operate in staggered cycles. Maintaining a strict schedule will be the main challenge for these proposals.

Finally, some proposals will seek solutions through pure innovation resulting in truly singular technology tailored to the needs of Windcrete. For these proposals, creativity will play a fundamental role. The main downside of proposals based on innovation is of course the unproven nature of the technology involved. Innovative proposals will always encourage additional research prior to developing such new technologies. The more innovative proposals will promote the use of concepts such as the Ring Traveller or the Concrete Crown.

At first conservative pass-no-pass criterion was applied that only approved proposals consisting of a single pour monolithic. Later, the scope was broadened to include additional proposals that did not fulfil this requirement but led to interesting solutions that will be worth considering.

This preliminary "brainstorm" has culminated in 15 construction proposals, all of which will be duly described in **Chapter 8.**

4.4 ASSESSMENT METHODOLOGY OF CONSTRUCTION PROPOSALS

The assessment of the proposals will be as rigorous as possible, keeping in mind that aspects like costs, execution risk and technological complexity can only be roughly estimated. More creative proposals will be even harder to assess due to the lack of information.

CRITERIONS

All of the proposals will follow a similar assessment scheme. The proposals will be awarded a numerical score ranging from 1-10. Proposals with the highest score are estimated to be more constructible, technically and economically feasible, and present an acceptable execution risk.

Proposals with a low score will be estimated to be unfeasible for one or more reasons. Some proposals will be deemed unfeasible due to current the lack of specific research. These may become feasible in the future if further research in this direction is set in motion.

Previously Requirements [1], [2], [3] were introduced:

Requirement [1] Horizontal construction
Requirement [2] Monolithic structure
Requirement [3] Suitable for serial production

First, all of the proposals will be checked according to each of these three requirements. Together these correspond to the first criterion.

The rating will be as follows:

Table 14. Assessment of construction constraints

	0	2	4
Requirement [1]	Vertical construction		Horizontal construction
Requirement [2]	Proposals that include *construction joints*	Proposals based on the assembly line concept (*) Proposals than include *cold joints*	Proposals with low or no risk of joints
Requirement [3]	Little mechanization or Slow production process	Slight mechanization or Moderate speed production process	High mechanization or Fast production process

(*) The assembly-line concept will be extensively described further into this chapter.

Only those proposals that unequivocally produce monolithic structures will be awarded the highest rating (4)

Those proposals that involve the assembly-line process will automatically be awarded an intermediate rating (2)

due to the uncertain outcome of such an assembly-line concept. They will not receive the lowest score (0) as it is believed that the assembly-line concept has the (unproven) potential to produce monolithic structures whilst breaking down construction into separate units.

The remaining criterions will be presented in the final comparaison of proposals, in **Chapter 9,** when the main cost drivers for each method have been properly identified. To justify the construction proposals that will result from this work, first a few aspects that have been considered concerning cost-reduction are presented in the following chapter.

5. AREAS OF COST REDUCTION IN WINDCRETE CONSTRUCTION

FOWT, by their very nature, translate in a completely new way of understanding the installation phase as they can simply be floated to their final location. As mentioned earlier, this feature has a good chance at drastically reducing installation costs. However, the installation process is not the only stage where cost reductions should be sought. The construction process must ensure the high quality of the completed structure whilst minimizing construction costs.

Windcrete must take advantage of the main aspects of FOWT by offering the possibility to be fully constructed and assembled on-shore and transported to its final destination. This should remain a priority. The building philosophy should aim at pre-fabricating in factory conditions a ready-to-go support structure. The terms tower or Windcrete tower will commonly refer to the support structure, both floater and tower, constructed as a single continuous piece.

Listed below are a few points that will be discussed prior to defining the construction proposals if one hopes to achieve a cost-effective solution to the construction process:

I. Horizontal construction vs. Vertical Construction of the towers
II. Serial production vs Single production & Concept of production factory
III. Types of joints in concrete.
IV. Assembly-line production

5.1 HORIZONTAL CONSTRUCTION VS. VERTICAL CONSTRUCTION OF THE TOWERS

As far as this academic paper goes, the dimensions of the Windcrete Support structure (tower + floater) are fixed. While the shape of the structure is fairly simple, its dimensions are quite significant.

Now let's consider the hypothetic case in which the tower has been completely constructed in upright position by making use of a slipform method or similar. The structure would presumably have to be transported vertically to its final location or turned from standing to horizontal position. Together, floater, transition part and the tower span 217.6 m and weigh around 9 000 tonnes.

A brief overview on present day crane technology will allow us to better grasp the extent of these dimensions.

First let's take a look of at a large crane load chart library (http://www.bigge.com/crane-charts/). This database contains a comprehensive list of commercial crane specifications for the main crane categories.

- Vehicle Mounted Crane: [75-300] t
- Tower Crane: [4-64] t

- Rough Terrain Crane: [15-160] t
- Crawler Crane. [50-3200] t
- All Terrain Crane [30-1320] t
- Boom truck crane [3.5-55] t

Liebherr recently engineered the LR 13000, the most powerful conventional crawler crane in the world able to hoist extreme component weights with a max. hoist height of 245m and with max. load capacity 3000 t.

Only considering heavy duty cranes, one can easily see that even the most powerful crawler cranes fall short of being able to lift Windcrete's 9,000 tonnes. It's important to note that the maximum capacity is always measured by the shortest lift, lifts at any distance or height drops the maximum capacity dramatically. Present day conventional cranes' capabilities are no match for the size and weight of the Wincrete towers.

Although cranes with much higher lifting capacities exist, deploying them at the construction site may not be practical and will almost certainly lead to a peak increase in costs. However, even for these unconventional cranes, the significant height of the completed tower would remain an issue.

Vertical construction of the tower will result in an unpractical way to transport the tower, and at the same time will take no advantage of the inherent cost-reduction that comes with floating concepts with regard to transport. On the other hand, the dead-weight of the finished tower, as well as its dimensions, makes cranes unsuitable for the task of turning the tower and is simply not feasible.

We have ruled out the option of transporting the tower in vertical position, and the option of turning the completed tower to horizontal position which clearly falls in line with the horizontal construction anticipated by the designers.

5.2 SERIAL PRODUCTION VS SINGLE PRODUCTION

Formwork and other temporary structures like falsework can be the most expensive part of some construction projects. As mentioned earlier a major challenge for all FOWT concepts is to cut down costs from all areas of the supply chain. The economy of FOWT would benefit from a dramatic cost reduction in the production of the concrete towers. Designing cost-effective solutions to temporary structures means keeping in mind constructability when designing. Designer is expected to have a good understanding of formwork logic.

For some structures, more time and cost are required to make, erect, and remove formwork than the time and cost to place the concrete or reinforcing steel. Notice that if constructing a single tower, this is not a major issue, however in a serial production, time of formwork erection and removal does become a significant part of the delivery time of a completed structure. As this difference could potentially lead to different form design and has direct impact on the construction proposals it is elaborated further.

Serial production and production of a single tower have different constraints that may lead to a completely different formwork system. This difference alone will have a large impact on working patterns, production facilities and overall formwork design criteria. Given the importance of this difference, this paper should promptly define which of the two production principles it should adopt and design the formwork accordingly. As the title of the paper clearly indicates, this paper has chosen to focus on the serial production as the commercial deployment of Windcrete is the ultimate goal of this academic work.

A production of a single tower would be aimed at constructing a first to-scale demonstration structure to prove Windcrete as a concept capable of becoming a reliable technology ready for commercial deployment. A serial production comes into play in a later stage of the implementation of Windcrete, when the concept has been proved and can start to consolidate in a welcoming wind energy market. Designing a construction procedure for the fabrication of a single tower as opposed to a serial production has direct consequences on the construction possibilities and the required formwork. The main difference between the 2 scopes of fabrication is the scale of tower production (one tower vs. plenty of towers). Cost-reduction opportunities become significant when considering production at larger scale as serial-production can lower the overall costs of producing a Windcrete tower.

Depending on the desired scale of production, delivery time also becomes a major difference. If a single tower is to be constructed, a considerable amount of time can be devoted to placing erecting and stripping of the forms, whereas delivery time would need to be optimized if producing several towers was the objective. In a serial production facility, erecting and removing forms would have to be a mechanized process that can be repeated swiftly. Different equipment may be required and the forms may be equipped with a sliding system to speed up the placing and stripping of the forms. When considering a serial production, the time of uncasting and removal of the structure from the formwork should be considered, as well as the time required to apply a release agent on the forms and all other relevant maintenance activities between re-uses. The duration of all these stages will contribute to the overall delivery time and must be properly quantified and standardized. Presumably, forms will be heavy and lifting equipment will be required, safety must remain a priority at all times.

5.3 TYPES OF JOINTS IN CONCRETE

JOINTS IN CONCRETE, CONSTRUCTION JOINTS AND "COLD" JOINTS

Joints are always a critical aspect of concrete structures. The behaviour of joints requires careful consideration to ensure that they are capable of transmitting the required loads through the structure while remaining watertight. There are several ways to classify joints, a common distinction is to consider joints as either construction joints, expansion joints, contraction joints and isolation joints. However, for the project at hand this classification is not very relevant. Here a different classification will be used, namely 2 types of joints, construction joints and cold joints

Before going any further in assessing the construction options of Windcrete, it is deemed useful to define what a is meant by "cold joint" in concrete structures, as opposed to construction joint. These terms are often used for concrete slabs, for road construction for example but the notions can be extended to other concrete structures.

CONSTRUCTION JOINTS

Construction joints are made where the concrete placement operations are voluntarily interrupted, for instance at the end of a working day, in between shifts or where one structural element is cast against a previously cast concrete element. Construction joints are normally conceived in advance and are used to break down construction tasks into daily activities. As they have been foreseen by the structural designer or by the contractor, they are only used when they represent no risk to the soundness of the overall structure. Construction joints can be sealed after concrete has hardened.

To seal construction joints, two options are available: fillers and sealers. They both have different purposes.

A filler is a rigid material that supports the edge of the joint and is only effective with saw-cut joints.

A sealer is soft and able to accommodate the concrete expansion and contraction. They are used to prevent water, ice, and dirt from getting into the joint.

Both sealers and fillers should be installed only after the concrete has had a chance to shrink as much as possible. Fillers are only effective if installed after the concrete has completely shrunk, which can take quite some time, whereas sealers can be more easily repaired or replaced.

Furthermore, construction joints can be divided in wet joints and dry joints.

Wet joints are constructed using epoxy glue or using cast-in-place concrete poured between the precast elements. The use of epoxy joints provides lubrication to help in the fit-up and alignment of the mating segments and minimizes the effect of hard point contact between segments (Chu, 2010).

Dry joints are constructed by simply bolting or welding together steel plates or other steel inserts cast for this purpose into the ends of the precast elements.

COLD JOINTS

Cold Joints are formed primarily between two batches of concrete where the delivery and placement of the second batch has been delayed and the initial placed and compacted concrete has started to set. A Cold Joint is the intersection between the end of an earlier concrete pour and the beginning of a new pour, placed later on.

The Cold Joint is a weak area that could allow the entry of water or in some extreme cases, undermine the structural soundness of the structure. If referring to concrete slabs for road construction, cold joints can be more or less efficiently dealt with, without affecting the structural resistance of the overall slab by using appropriate sealing methods. However, for other more complexly loaded structures, cold joints could turn out to be mechanical weak planes that should be avoided. For Windcrete, cold joints could even undermine the overall structure by compromising the water tightness of the completed tower.

These joints allow some load to be transferred from one structural element to another through the use of keys or (for some slabs and pavement) dowels. Note that the construction joint extends entirely through the concrete element.

JOINTS AND WINDCRETE

When it comes to Windcrete, construction joints contradict one of the desired key features of the construction procedure: building a monolithic structure. For now, construction joints will not even be considered.

Nonetheless, the same cannot be said about "cold" joints. Whereas cold joints should be avoided at all costs, as they represent a weak plane in the structure. Specific research on casting discrete segments and joining them in fresh -if possible- would be valuable feedback to Windcrete. If this could be achieved before cold joints have time to form it would be a game-changer.

By answering accurately the following question: *What is the allowable time limit for successive concrete placements during a monolithic pour*? Or more simply put: *How long before a cold joint forms?* One could presumably construct a monolithic structure by constructing individual segments and quickly assemble them when still in fresh conditions. This is very relevant to Windcrete and offers a major turning-point in the construction procedure of the towers. It can make room to more familiar casting techniques and more economical approaches that make use of smaller formwork units, easier to construct and handle which might yield in cost savings. While tackling the construction process with a segment approach, the main requirement of building a monolithic structure could still be fulfilled.

It is not common for national standards, building codes or structural concrete specifications to provide any reference to a set time limit. That's probably because of the several factors to consider in determining initial set. In cold weather, you can wait longer to place the next batch than you can during hot and dry weather. If the previously placed concrete is still plastic (an internal vibrator should be able to penetrate it), you can safely place the next layer of concrete without producing a cold joint. The American Concrete Institute in *ACI's Guide for Consolidation of Concrete*, ACI 309R-96, gives the following advice:

> *"To avoid cold joints, placing should be resumed before the surface hardens. For unusually long delays during concreting, the concrete should be kept live by periodically re-vibrating it. Concrete should be vibrated at approximately 15-minute intervals or less depending upon job conditions. However, concrete should not be over vibrated to the point of causing segregation. Furthermore, should the concrete approach time of initial setting, vibration should be*

discontinued and the concrete should be allowed to harden. A cold joint will result and suitable surface preparation measures should be applied."

The recommendation is that before breaking down construction into a smaller segment approach, exhaustive research would have to be carried out on concrete mixtures, concrete setting times, factors affecting setting time and available means to accurately control the setting time of concrete. Tests would have to be done on site at regular intervals on site to assess the setting time of every batch. The construction of Windcrete would benefit substantially from in depth investigation and technology linked to the monitoring and control of concrete setting time so as to avoid any types of joints.

As several of the construction proposals that are presented in this academic work integrate this "sticking system" concept it will be further developed.

5.4 ASSEMBLY LINE CONCEPT

First of all, assembly line construction is based on the assumption that exhaustive research has been undertaken on concrete setting time which has led to optimistic results on how to control setting time of concrete in such a way that elements produced separately can be joined in fresh before a cold joint has time to form.

The proposals that consider an assembly line will feed on relevant investigation and will require an in-depth analysis on the exact time required to produce an element. The concept of assembly-line is presented within Windcrete's cost reduction possibilities because it is estimated that subdividing the construction into practical and smaller "casting units", will result in more familiar construction practices which in turn will yield cost savings.

To subdivide the construction into smaller units, the connection between these separate units would need to be impeccably well-coordinated. If one is to avoid cold joints, the different rings would have to be swiftly put together while the concrete is still fresh. This working principle requires several elements to be produced at a constant (known) rate simultaneously, and the subsequent transport of the concrete together with the mold to a near-by assembly line. All these elements would be joined subsequently, as they enter the assembly line.

CASTING STATION CONCEPT

A carefully planned schedule is the only effective way to achieve a monolithic structure through a segment approach. Concrete formwork will be in the shape of a ring or a series of modular arches that once assembled results in a ring. The so-called casting station is where the reinforcement is placed and the formwork is filled with concrete. Several casting stations would need to produce rings simultaneously. By including a slight time lag between the respective starts of two consecutive casting stations a finite number of production stations can be computed.

PARAMETERS OF THE ASSEMBLY-LINE CONCEPT

To show this idea an operative cycle for this assembly line production will be described but first a few definitions are in order:

$t_{production}$ is the time required to produce an arbitrary ring. This time accounts for the following terms.

$$t_{production} = t_{\substack{reinforcement \\ placement}} + t_{filling} + t_{\substack{transport \\ to\ assemby-line}} + t_{\substack{locking \\ in\ assembly-line}}$$

t_{lag}, is the time between the start of 2 consecutive casting stations.

t_{reset} is the required preparation time of a casting station. It is the time between the end of a completed ring and the start of the next ring by the same station.

Note that t_{reset} is implicitly included in $t_{production}$ as during the transport of the ring to the assembly lines, preparations for the next cycle can begin.

Let´s take a closer look at how to estimate $t_{production}$:

- $\boldsymbol{t_{\substack{reinforcement \\ placement}}}$ → this time should comprise all the steps of preparing, welding and placing of the reinforcement inside the mold.

- $\boldsymbol{t_{filling}}$→ time required to fill the mold with concrete will be a function of the size of the mold, on the placement method and the pouring rate of concrete.

- $\boldsymbol{t_{\substack{transport \\ to\ assemby-line}}}$ → time that it takes to move the mold filled with concrete from the casting station to its final position in the assembly line.

- $\boldsymbol{t_{locking}}$ → time that it takes to lock the mold to the previous molds already placed in the assembly line. Once two consecutive molds have been locked together, additional concrete can be pumped at the interphase to ensure proper bonding and no voids.

OPERATIVE CYCLE

A typical sequence could be:

Station 1 starts at $t = 0$ and finishes at $t = t_{production}$ and restarts all over again after a time equal t_{reset}.

Station 2 starts at $t = t_{lag}$ min and finishes at $t = t_{lag} + t_{production}$ and restarts all over again after a time equal t_{reset}.

Station 3 starts at $t = 2 \cdot t_{lag}$ min and finishes at $t = 2 \cdot t_{lag} + t_{production}$ and restarts all over again after a time equal t_{reset}.

Station n starts at t = (n -1) $\cdot t_{lag}$n and finishes at $t = (n-1) \cdot t_{lag} + t_{production}$ and restarts all over again.

The main assumption will be that $t_{production}$ is known and equal for all n stations.

he idea of the assembly line concept is that when the last station n has produced its first ring, the first station should be close to finishing its second ring for a smooth connection between Station n and Station 1.

The required number of production stations n can be computed from the following relation, which is equivalent to the condition mentioned above.

$$(n-1) \cdot t_{lag} + t_{production} = 2 \cdot t_{production}$$

The required number of production stations is

$$n = \frac{t_{production}}{t_{lag}} + 1$$

The second condition that the operative cycle must comply with is that the production, subsequent transport to the assembly line and connection with previous rings should be done before concrete sets. Thus, a maximum time to connect two consecutive rings should be determined based on concrete properties.

When a ring in Station ($n-2$) is completed and transported to the assembly line, this ring is connected to a previous ring and will 'wait' in place during a time $t_{waiting}$ before the next ring is ready and launched onto the assembly line. Logically $t_{finish,n-2} - t_{finish,n-1} = t_{waiting} = t_{lag}$.

$t_{waiting}$ between two consecutive rings must be smaller than the setting time of concrete. The second condition then translates to:

$$t_{finish,n-1} - t_{finish,n-2} = t_{waiting} < t_{setting\ concrete}$$

EXAMPLE OF ASSEMBLY-LINE CONCEPT

Now that the working principle of the assembly line concept has been introduced, let's put it into practice.

Consider an unknown number of stations n that produce sections of the floater.

These stations will produce ring segments with an outer diameter of 13 m and a uniform thickness of 0,5 m. The cross-sectional area is $A = 19{,}65\ m^2$.

The length of these segments is fixed and chosen as 6 m long as the total weight (actual weight of the forms + weight of fresh concrete + weight of reinforcement) still enables handling. The total volume of concrete for one ring segment is $19{,}65 \cdot 6 = 118\ m^3$.

Pumps will be chosen to fill the ring forms. Pump output can vary between $35\ {m^3}/{h}$ and $110\ {m^3}/{h}$, and even more according to Concrete Pumping and Spraying: A Practical Guide (T. H. Cooke, 1990).

Here three pumps have been chosen each with an output of $60\ {m^3}/{h}$. If all three pumps work together they should fill the 6-metre-long ring mold in well under an hour ($\frac{118\ m^3}{3 \cdot 60\ {m^3}/{h}} \cdot 60\ min \approx 40\ min$).

Filling time is just one of the terms of $t_{production}$, $t_{\substack{reinforcement\\placement}}$ should also be computed approximately as well as the time to move the filled mold from the casting station to its position in the assembly line, where it will be locked to previously launched rings.

For simplicity, all the activities together are assumed to amount to an hour.

A time lag $t_{lag} = 15\ min$ between two consecutive stations has been chosen. For illustration purposes $t_{reset} = t_{lag}$ has been chosen, which means it takes 15 min for a casting station to re-start a cycle.

Now let's compute the number of stations required. The number of stations n should satisfy:

$$(n-1) \cdot t_{lag} + t_{production} = 2 \cdot t_{production}$$

$t_{production} = 60\ min$

$t_{lag} = 15\ min$

$$(n-1) \cdot 15 + 60\ min = 2 \cdot 60 min$$

The resulting number of stations is $n = 5$ stations.

The following table shows the work schedule for the different stations. For illustration purposes, station 1 is said to start at $t = 0$ and sets the timeline for the remainder of the stations

Table 15. Staggered schedule of 5 identical casting stations

Station #	First ring		Second ring		Third ring	
	t_{start}	t_{finish}	t_{start}	t_{finish}	t_{start}	t_{finish}
1	0	1h	1h	2h	2h	3h
2	15 min	1h15min	1h15min	2h15min	2h15min	3h15min
3	30 min	1h30min	1h30min	2h30min	2h30min	3h30min
4	45 min	1h45min	1h45min	2h45min	2h45min	3h45min
5	1h min	2h	2h	3h	3h	4h

Cells in green show the coordination between the time the second ring is completed at Station No. 1 and the time the last station (Station No. 5) completes its first ring. From that point on stations can connect rings for as long as required.

Cells in blue show the coordination between the second ring produced by Station nNo. 5 and the third ring produced at Station No. 1.

One can see from the schedule table above that before two consecutive rings are joined "in fresh" there is a time difference of 15 minutes. This time difference is dangerous as it may be enough to produce a cold joint in the concrete and should be considered with care. A way to deal with problem that will minimise the risk of a cold joint is to continue to add some concrete during these 15 minutes through a cart moving along the assembly line while the recently completed ring awaits to be connected to the next. Combining ring-producing stations with in-situ casting of the interphases the rings could potentially truly be joined in fresh.

This schedule is obviously simplified, for instance one can argue that it is unrealistic to consider that a station can start to produce rings all over again immediately after it has completed the previous ring. Some additional time (t_{reset}) will be required to erect the forms before pouring can begin. This has been addressed by accounting for this additional time in $t_{production}$.

As one can see from the previous example, in approximately 4 hours, these five stations will have produced 15 rings 6 metre long.

Note that in such an assembly-line for rings 6 meters long, the entire 120 m of the floater could be achieved in just over 5 hours. The forms however would remain in place the sufficient amount of time for concrete to cure satisfyingly.

If smaller rings were used, say 4 m long rings, the time required to complete the floater would increase to eight hours. Logically, this is partially incorrect as $t_{production}$ would decrease for filling smaller volume molds.

However, one finds that the delivery time for a completed structure will typically be within the range of a day. Nonetheless, the forms would be left in place until adequate curing of concrete takes place.

It is important to note that the assembly-line concept requires knowledge on the exact duration of each activity and calls for standardisation of the procedures to maintain constant timing of all these activities. The setting time of concrete must also be known and similar for all the different concrete batches on site. As the setting time of the concrete will vary with the temperature on the worksite during pouring, temperature variations should be closely monitored.

A mechanism to postpone hardening is revibrating the mix at regular intervals. This technique should be carefully studied and must never cause segregation of the concrete mix.

To further control and modify the setting time of concrete the use of admixtures is recommended. These admixtures are as follows:

1. **ACCELERATORS**: To shorten the time of setting or increase the rate of hardening or strength development Ex: calcium chloride. Used commonly during cold weather or repair works.

2. **RETARDERS**: To delay the setting time of cement normally used in hot weather conditions. These admixtures can be soluble zinc salts gypsum, sugar, carbohydrate derivatives, lignosulphates.

Such an assembly-line production will most probably make use of the later, as retarders will be convenient to slow down the setting time of concrete to ensure proper bonding of two consecutive. rings. Also, any delays due to unforeseen events in the production rate of the casting stations could be mitigated with the proper use to retarders.

ADVANTAGES

One of the main advantages of this method is production time. Such an assembly process does not involve slipforming the structure, which generally is a reliable but somewhat slow process. Instead quicker concrete placement methods can be used to fill the molds, like tremies directly from mixing trucks or conveyors discharging in the open mold thus optimizing productivity. With an optimum amount of casting stations working around-the-clock delivery time of a completed structure could be in the range of a day.

Once in the assembly line, extra concrete can be easily provided at the interphase between rings to guarantee proper bonding and a monolithic result. This technique would be similar to constructing a wet joint except the two elements to join would not be pre-fabricated but freshly cast segments.

It is noteworthy to realize that this process allows for a high degree of automation which should be seen as advantage, especially if a serial production is sought.

DISADVANTAGES

A major disadvantage, which could potentially rule out such an assembly line approach is that it remains unclear how to place the longitudinal reinforcement and connect it with that of the remaining rings.

Another downside of this method is that it would involve a fairly large amount of heavy “pushing” operations to move the freshly filled molds from the production stations to their position in the assembly line. A rail-track based system should definitively be considered and the production stations, located at either side of the assembly line, should be as close as possible. Molds should be equipped with wheels or rails to allow convenient transport from the production station to the assembly line. It may be interesting to mount the molds on bogies similar to those used by trains to move them swiftly.

Another disadvantage is that this ‘high-speed’ method will require a large number of forms as sections are produced simultaneously making it difficult to re-use forms for the same structure.

CONCLUSIONS ON ASSEMBLY-LINE CONCEPT

Firstly, one must state that the possibility of avoiding joints in such an assembly-line has yet to be demonstrated and should not be taken for granted before adequate research is done. At the time of writing, all those proposals involving an assembly-line production will assume that the risk of a cold joint exists. Thus, from a conservative view, these proposals will be said to only partially satisfy the monolithic requirement.

Organizing effectively the assembly line production means that the produced elements can be joined together with minimum delay. Without describing, for now, the manner in which the concrete rings would be casted, ring-production facilities would have to be fairly quick to support an agile “sticking” process of two consecutive freshly-casted ring segments with no cold joints. Choosing an appropriate rate of placement is critical to avoid cold joints. A quick placement rate results in higher lateral pressure exerted on the forms by the fresh concrete which will also have to be accounted for in formwork design.

The minimum number of casting stations depends on the required amount of time for a station to produce a single ring. As explained, by carefully interconnecting several concrete segments “in the fresh” casted separately, one will need to calculate the required casting time for a particular mold and choose the number of number of stations accordingly. These stations will produce rings (almost) simultaneously.

The working cycle described above is extremely time sensible and strongly relies on an efficient and constant workflow and accurate knowledge on the time required for each procedure, on the setting time of concrete available on site and a continuous supply of material so construction never stops.

The coordinated action of the so-called production stations and the working schedule they must follow will require an outstanding planning phase. To successfully cast rings and join them in a near-by assembly line with minimum time delay, mitigation measures should be included in the planning phase in case activities fall behind on schedule. Back-up equipment should also be available near-by at all times for a quick response in the event of failure of the equipment and to keep up with the planned schedule.

The actual casting method of these production stations has been deliberately left unspecified. This is to show that this working cycle can be practiced almost independently on the method chosen to produce these rings. While the philosophy will remain the same –quasi-simultaneous ring production in different stations- the actual cycle time and the overall system schedule will be adjusted to the chosen method to produce these rings. By allowing a wider range of alternatives to adopt and complement this working cycle, this procedure hopes to present itself as a flexible solution, highly adjustable to the preferred method.

A requisite for production is to cast and transport the rings to the assembly line before they have time to dry. Note that this requirement does not apply to the entire ring segment but rather the volume of concrete near the edges of the mold corresponding to the region of connexion between rings.

6. WINDCRETE AND CONSTRUCTION TECHNOLOGY

Technology will play a central role in defining cost-effective ways to construct Windcrete towers. To properly present some of the most relevant technologies first a brief overview on basic types of formwork will be done. Technologies will be taken from a wide range of civil engineering disciplines. When speaking of construction technology, inevitably we will mainly refer to engineered formwork systems, but other interesting technologies will also be described if deemed useful. For some construction practices, the entire process will be looked at for inspiration and a series of adaptations will follow. In other cases, a particular single aspect feature of the relevant technology will be extracted rather than the entire procedure.

6.1. TYPES OF FORMWORK

Formwork systems can be generally classified as Vertical Systems (wall and column) and Horizontal Systems (slab and beam). Formworks can also be named based on the type of structural member they produce such as slab and beam formwork (horizontal systems) and wall formwork or column formwork (vertical systems). However, this classification is deemed insufficient to properly address the construction options for Windcrete. A more detailed list on types of formwork has been elaborated that already begins to consider the specific requirements of the structure to build. Throughout this chapter, the term formwork be used in its broadest sense which includes the total support system of fresh concrete, that accounts for both formwork and falsework. For definitions of formwork elements, accessories and further information on formwork refer to **APPENDIX 1: FORMWORK BASICS.**

6.1.1. TRADITIONAL FORMWORK

Figure 50. TRIO Wall formwork with standard panels up to 3.30 m x 2.40 m

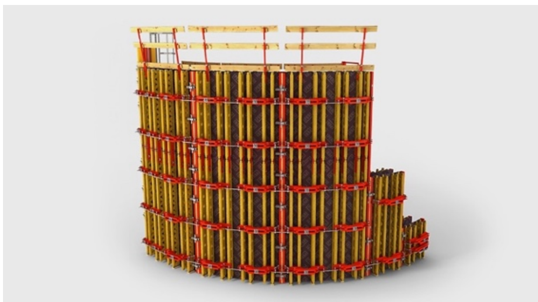


Figure 51. RUNDFLEX wall formwork with adjustable radius (product by Peri).

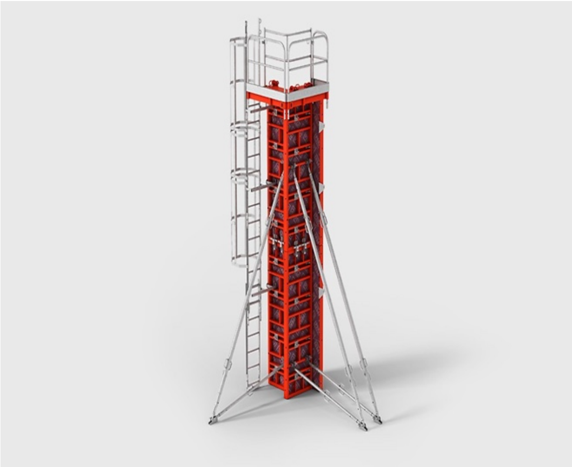


Figure 52. TRIO Colum Formwork (product by Peri)

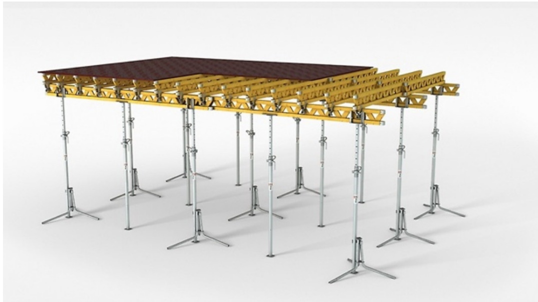


Figure 53. MULTIFLEX Girder Slab (product by Peri)

Traditional type of formwork system often regarded as timber formwork, is labour intensive, time consuming, and with low output. It is not very suitable for a project like Windcrete which involves a massive concrete placement. However, the circular wall formwork system provides some insight on the variety of shapes that can be achieved by forms. The availability of curved systems will definitively be useful to build the cylindrical Windcrete towers.

6.1.2. ENGINEERED FORMWORK SYSTEMS

This category includes a wide range of formwork systems that are generally customized and manufactured for a highly specific project using 3D building models. Usual applications of formwork systems include but are not limited to:

- Building technology formwork systems
- Slab, bridge deck and cast in-situ box girders formwork systems
- Cast in-situ tunnel lining formwork systems
- Slipforming formwork systems

Engineered formwork systems use prefabricated moulds made from a metal frame, usually either steel or aluminium. They can be designed for a singular project or a set of projects with similar characteristics. Engineered formwork can be made from a variety of materials, such as plastic, metal or steel giving it the material advantage. Engineered formwork is very durable and if proper maintenance is performed it can be reused for up to 2,000 cycles.

Engineered formwork is a big investment up front, but can save significant time and money on the long term as it involves less man hours in labour. Engineered Formwork is designed for efficiency and highly optimized for repetitive processes.

The previous conventional formwork systems may be cheaper initially, but for large projects Engineered Formwork is more economical. Additionally, engineered formwork has health and safety features built into it.

For our project the most interesting family of Engineered formwork will be those with the ability to move, either thanks to a jacking system or because they are mounted on a special carriage. This type of engineered formwork is called travelling or sliding formwork.

TRAVELLING FORMWORK

A form traveller or a travelling formwork -also known as movable shuttering system- is a movable formwork carried by a mobile structure, which can be re-used after striking without having to be disassembled.

Travelling formwork has flourished in the tunnel industry which will be developed further in the upcoming chapters. This type of formwork acts both as falsework and formwork since the bearing system (the falsework) is a part of the equipment. The most important characteristic of this type of formwork is the movement capacity. Of course, there is a very close relationship between the design of this type of formwork and of the main structure. If travelling formwork was considered to construct Windcrete, it would surely have to be design to satisfy the particular dimensions of Windcrete.

During the launching process, structural scheme changes and its load distribution. The worst situation in all the phases of movement must be checked as the launching and movement stage concentrates a high level of risks. In addition to structural requirements, standards related to electrical, mechanical and hydraulic equipment must be considered

One must not expect national standards to cover the design of this type of formwork. A design document must be developed by professionals with the specific expertise in this type of equipment. It may require close collaboration between electrical, mechanical and structural engineers.

Sliding or slip forming formwork is perhaps the most well-known type of travelling formwork, which will be used as inspiration for some of the construction proposals.

6.1.3. SLIDING OR SLIPFORMING

Slipforming is a specific type of travelling formwork but due to the interest for the project at hand it will be treated in separetly. Slipforming formwork can be classified as follows:

- Horizontal sliding systems
- Vertical sliding systems

Slipforming, also known as sliding form, offers the advantages of speed, the ability to produce a monolithic structure and economy of operation. Slipform drastically reduces the amount of required forms. One can distinguish horizontal and vertical slipforming. The latter is used in more eye-catching applications like pouring high-rise concrete structures in a single non-stop operation. The former has a rather limited number of applications but has the particularity of pouring concrete interruptedly while advancing horizontally.

Horizontal slipforming.

Horizontal slipforming is usually done against a reliable ground or rock that supports the form while it moves. The slipform machine normally moves on rails and may or may not be self-propelled.

Horizontal slipforming techniques were developed to pave highways in a reliable and highly automated process. In fact, slipform pavers used for this purpose are the single most common application of horizontal slipforming.

The machine pours and distributes concrete, then passes over the concrete moulding it to approximately the desired shape, vibrates it and compacts it. Trailing equipment attached to the machine smoothens the surface and the edges of the concrete.

Other typical applications include the construction of medium barriers, tunnel inverts and canal linings. All these machines share the same working principle with minor adaptations regarding the shape or the orientation of the placed concrete, to produce a concrete slope for canal linings machines, or by adopting a curved shape for tunnel inverts.

Vertical slipforming

Typically, civil engineers have been able to construct high-rise structures by continuously casting concrete in the vertical direction. This technique, called slipforming, allows concrete to be erected as a monolithic or joint-less structure while reducing overall project duration.

Concrete is poured into a continuously moving form which supports itself on the recently placed concrete.

A rigid mould, which also serves as a working deck, is slowly jacked upwards at a controlled rate of about 20-30 cm an hour. The hydraulic jacks are anchored in the concrete structure itself and raise the mould shutter a few centimetres so that the pouring can start all over again. The placing of concrete is continuous and fresh concrete is compacted through its own weight. A reliable high quality, watertight structure results, in minimum construction time. This technique is also said to allow safer working conditions for workers due to the sharp decrease of heavy form lifting operations.

The previously mentioned troll-A oil platform was erected using this method. Slipforming is arguably the most productive technique for construction of high-rise structures.

This technique offers superior performance characteristics over construction methods using discrete form elements and is by far the preferred approach when building tower-like structures. Due to its very nature, if no leaks or gaps are desired, slipforming must be done on an around-the-clock basis and even a brief pause during construction must be avoided.
There is a lot of available experience in slipforming, structures like silos, nuclear facilities have used this technique as it is the quickest. The fact that offshore drilling platforms have also

successfully applied slipforming is also encouraging. This experience would be without doubt valuable for the construction of Windcrete.

SELF-PROPELLED FORMWORK FOR TUNNELLINING CAST-IN SITU

This is a highly automated particular type of travelling formwork that, due to its believed relevance to Windcrete construction, will be treated with sufficient detail in an independent section.

Tunnel construction using cast-in-place concrete lining has achieved a high degree of mechanization and has allowed for the development of arguably some of the most sophisticated tunnel formwork systems. These formwork systems are traveling systems and have the ability to support concreting equipment at their core. There are two main types of formwork that will be of interest:

Travelling Non-telescoping formwork

The whole formwork is preassembled and mounted on a travelling frame fixed with wheels running on a track. The sections are hinged to permit collapsing once the concrete has hardened thanks to a system of hydraulic struts. The traveller can the move to the next section to pour. Jacks are required for bracing and aligning the forms.

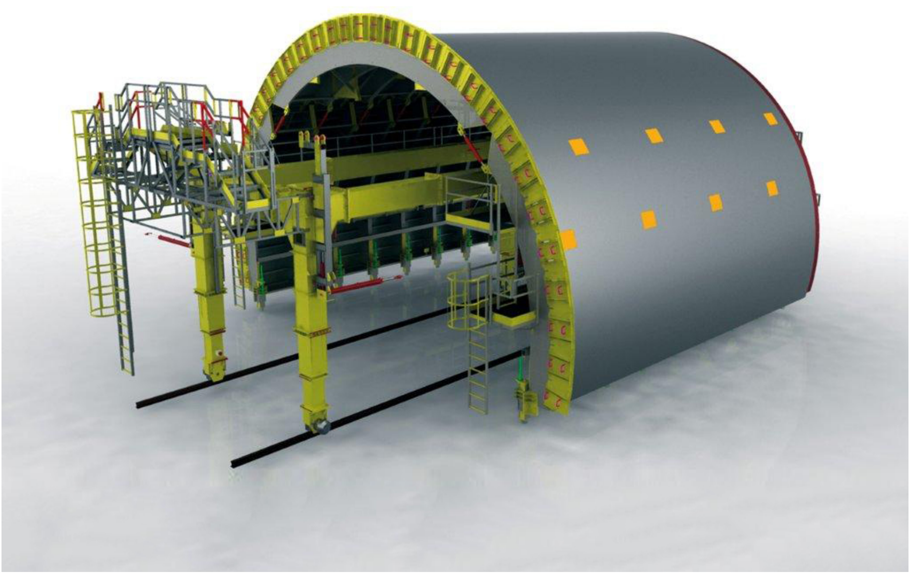


Figure 54. Non-telescopic travelling formwork. Technology by Rubrica www.rubricaingenieria.es
Source: http://www.alsina.com/en/solution/mine-tunnel-formwork/

Travelling Telescoping formwork

This formwork is similar to the previous but sees an increase of productivity. These systems are designed so that the back unit can be collapse and moved forward through the front unit without disturbing it. Side plates are hinged to the top arch plate so that it is possible to collapse them. The traveller is equipped with jacks and other accessories for this purpose.

It cannot be stressed enough how fitting and appealing these formwork systems are for the needs of Windcrete. Both in terms of productivity and of the shape produced, these self-propelled telescoping carriages are definitively worth looking into. For this reason, it will be described further as well as all the main manoeuvres linked to the operational phases of the self-propelled steel form.

The equipment is composed of articulated steel forms of self-reacting type, which do not require any external anchorage during the concreting as all the support is provided by the carriage which serves as both formwork and falsework.

The advancement of the formwork is possible by using a specifically designed carrier integrated in the form frame. The carrier is equipped with double-acting hydraulic jacks for the different movements of the steel form during the setting-up and dismantling. This system includes hydraulic struts for the support and stabilization during the concreting phase. Once the concreting phase is complete, which depends on pouring rate and on the length of the traveller, the concrete can start to harden while the traveller remains in place. Generally, after a few hours from the end of the casting, the concrete is hard and can start to cure during a pre-established period. Where concrete is already hard, the steel forms can be collapsed by the retraction of hydraulic struts and they can move through the frame of the carriage to the front of the construction.

The motorized sliding wheels of the carriage allow it to move to the next section to be casted. The forms, or shuttering, are placed in position and pouring can re-start all over again.

Other formwork systems for tunnelling will be mentioned again in the upcoming part on tunnel technology. Tunnel industry provides a rich source for ideas that may ease Windcrete construction.

6.2. CURRENT CONSTRUCTION TECHNOLOGY AND WINDCRETE

As implied, Windcrete construction will need to feed on existing technologies used in different areas of Civil Engineering to successfully define potential construction schemes. Thus, current construction technology is believed to have a large impact on solving the construction.

This part will take a look at readily available construction technology commonly employed in several branches of civil engineering that could serve the purposes of Windcrete. These technologies will be described in their usual context and then related to the needs particular needs of our project.

Here the tunnel and the microtunnelling industry will be relevant. Centrifugation, a special method of concrete compaction used in the production of reinforced concrete pipes will also be discussed. Finally, a particularly interesting example of caisson technology –Acciona's Kugira– will be presented. The description of these technologies will be coupled with considerations on adaptations to suit the needs of Windcrete. Some of these technologies will come closer than others in satisfying the requirements of the project, however all will need an adaptation process. Transforming readily available technologies and applying them to our construction process is the best way forward.

6.3. TUNNEL TECHNOLOGY

The tunnel industry provides a set of inspiring ideas that could be helpful to construct the Windcrete towers. Some obvious resemblances are the horizontal travelling of the formwork and the similar hollow cylindrical shape of the sections.

It would be wise to learn from the accumulated experience of the tunnel industry and assess the suitability of engineered formwork systems currently used by contractors for tunnelling projects. Another reason why this technology is appealing to Windcrete is itss similar order of magnitude in cross-sectional dimensions, it is not uncommon to find tunnels with 13-metre diameter, even if these do correspond to fairly large tunnels.

Specific types of engineered formwork systems have already been presented. The tunnelling industry englobes a very wide range of interesting techniques that are however of little interest to progress in defining a suitable construction method for Windcrete. Only a brief overview of those tunnelling practices than comprise helpful features or technologies will be described.

The development of tunnel construction has allowed a parallel evolution of formwork technologies which have improved considerably with standardized systems with an increasing degree of automation. Cast in-situ tunnel lining formwork is perhaps one of the best examples. The features of this specific type of tunnelling formwork will with no doubt be useful to our project.

Broadly speaking, tunnelling methods may or may not require placement of lining depending on the geology. In a competent of ground with stable rock, the excavation may be able to support itself whereas in soft soils some sort of support will be required if the tunnel is to retain adequate stability. This support is achieved via the placement of lining. In reality even tunnels cut through reliable rock will use some sort of minor support system. Tunnel lining is nothing more than the wall of the tunnel. Fabrication of tunnel lining falls in three types:

- Precast concrete segments that form rings.
- Cast in-situ concrete lining using specialized formwork.
- Shotcrete lining.

Tunnel lining is closely linked to the reason why tunnel technology is seen as a promising source of inspiration. Therefore, we can narrow the scope to those methods requiring the use of lining. Intuitively, the most relevant of the above-mentioned types of linings are those cast in-situ as Windcrete too will be cast on site.

But precast concrete segments, or rather the handling of these segments, will also be lead to an interesting piece of equipment that may get us one step closer to the constructing Windcrete towers.

6.3.1. CAST-IN SITU TUNNEL CONSTRUCTION

Tunnels cut through hard rock with drill-and-blast method, or similar, may be lined with concrete cast in situ after waste rocks and soils are transported out.

Generally, a long length (or the entire length) of the tunnel is excavated before lining, with some temporary roof support provided by rock bolting. For tunnels in soft ground, precast linings will usually be installed as excavation progresses, though sprayed concrete may be used to give a temporary support before an in-situ lining is cast (The Concrete Society, 2014). In-situ lining is usually possible through the use of a specific formwork system that slides on a service track like the self-propelled form system described earlier. The two types of self-propelled formwork systems- travelling telescopic and non-telescopic formwork- mentioned earlier are extensively used and both will be relevant in several of the upcoming construction proposals for Windcrete.

6.3.2. TBM TUNNEL CONSTRUCTION

For excavating long tunnels Tunnel Boring Machine (TBM) are often used. TBM represent the state-of-the-art in mechanized tunnelling. The type of TMB must be selected according to the rock mass and the geological conditions. The TBM may be suitable for excavating tunnels which contain competent rocks that can provide adequate geological stability for boring a long section tunnel without structural support. However, extremely hard rock can cause significant wear of the and may slow down the progress of the tunnelling works to the point where TBM becomes inefficient and uneconomical and may take longer time than the drill-and-blast tunnelling method.

A set of hydraulic thrust cylinders allow the forward movement of the TBM shield by pushing on previously placed segment linings. What will be relevant to our project about TBM technology is precisely the way segment linings are placed.
The segment linings are placed into position by an erector located within the TBM. The erector arm is essentially a rotating remote-controlled crane arm, which picks up segment linings mechanically or by suction and places them in position.

It is believed that the erector arm used in a TBM may be useful in the elaboration of some of the construction proposals.

6.3.3. TUNNEL TECHNOLOGY AND WINDCRETE

Two major differences with the desired result can be noticed.

The first is that typically, the use of tunnelling formwork does not allow for a continuous pouring but requires the striking of the concrete before the movable formwork can be launched again to pour the next segment, creating joints. The formwork is only retracted when the concrete has gained sufficient strength. Only then does the form move to the next ring. Thus, if a fully continuous operative cycle resulting in a cylinder with no joints is desired, this technology would have to be slightly adapted.

The other noticeable difference is related to the final shape of the cross section which is not always entirely circular for most tunnels involving travelling formwork

Despite these differences, the use travelling formwork is definitively a solution to constructing the towers. Or at the very least, movement should be integrated in the design however the formwork should be able to move as soon as the concrete is in place to pour the next ring before the previous has hardened. Mechanization of formwork for Windcrete is the best way to achieve the rates of productivity necessary to a serial production but some adaptations of tunnel travelling systems will be in order.

These differences, and how to address them properly are discussed in greater detail in **APPENDIX 2- CONSIDERATIONS ON ADAPTING TUNNEL FORMWORK**

6.4. MICROTUNNELLING

Microtunneling is a trenchless construction method for installing sewer pipes beneath densely packed areas. It is defined as a remotely-controlled, guided, pipe-jacking operation.

Microtunneling can be performed by directly jacking a pipe into the soil that serves as initial construction lining, or by jacking the pipe behind a microtunnel boring machine (MTBM). Both variations require a hydraulic jacking system located in a jacking shaft.

The MTBM is pushed into the earth by hydraulic jacks mounted and aligned in the jacking shaft. The jacks are then retracted and a prefabricated ring casing is lowered into the shaft and inserted between the jacking frame and the MTBM or previously jacked pipe. The jacking operation can start all over again and the pipe and MTBM are advanced another stroke. This jacking process is repeated until the MTBM reaches the reception shaft where it is retrieved.

At first, it is true that no immediate relation seams to exist between microtunnelling and Windcrete. Microtunnelling is typically done for small sections. Furthermore, this technique involves pushing separate prefabricated segments into the soil in discrete steps, resulting in a structure with many joints. Also, the use of prefabricated elements clearly opposes an essential characteristic of Windcrete, that requires the concrete to be cast in place and without segments. The way in which this technology can aid the construction process of Windcrete is not obvious at all.

However, there is a single interesting feature of microtunnelling that draws attention: the hydraulic jacking system arranged in a circular fashion. The way this hydraulic system pushes the structure through a fixed hole, so to speak, is believed useful for Windcrete, or at least worth considering.

The idea that would like to be extracted from microtunnelling practices is the process of extruding a section by means of a jacking system. In reality, microtunnelling does not exactly extrude a cross-section, as instead it is constantly fed with new ring elements.

However, an adapted process could be imagined in which the jacking system does actually extrude a section a number of times to construct a structure. In this adaptation, hydraulic jacks don't push pre-cast elements through a hole but rather push steel ring-forms, previously filled with concrete through a concreting eye. Behind this concreting-eye, adequate space is provided to receive the extruded moulds filled with fresh concrete. Additional concrete be pumped through internal and/or external valves. The adaptation of this technology would focus on swapping pre-cast concrete rings for pre-assembled circular moulds. The jacking-system would push directly onto the moulds leaving an empty space in the concreting eye. The jacks are then retracted and a new mould is introduced ready for concrete filling.

6.5. CENTRIFUGAL REINFORCED CONCRETE PIPES

Centrifugation is a special method of concrete compaction. This technique uses the spinning process as a compaction method. It is widely used since the beginning of the 20th century in the metallurgy industry and also for production of concrete and reinforced concrete members which are circular in cross-section such as concrete pipes or concrete lamp posts. In centrifugal casting, a permanent mould is rotated about its axis at high speeds (300 to 3000 rpm).

In this method, the concrete is fed into the mold while it is being spun at a slow speed. The spinning speed is increased to a very high value after the pre-calculated amounts of concrete has been fed into the mold. High speed spinning forces out the water from the mix and the concrete finished by slowly reducing the spinning action and sprinkling dry cement on the surface in order to eliminate the risks of increased water cement ratio due to free water. Since the compaction is effected by centrifugal forces, it results in water tight products like pipes for water supply, storm water drains and sewage disposal pipes.

Hollow centrifuged concrete members show an increase in physical properties such as density, Young modulus and mechanical properties such as the load-bearing capacity.

The advantage of centrifuging is that during the spinning formwork the plastic wet concrete mix is uniformly distributed by the centrifugation pressure, distances between the aggregates and other solid particles diminish and weakly bonded excess water is pressed out from the compacted concrete mix. The increase of concrete density helps retain a circular shape. Physical centrifuging results in a decrease of concrete porosity, an increase in strength and a more homogeneous structure of the concrete.

Figure 55. Centrifuge concrete casting machine: turning device and mold engineered by oceana Pre-cast machinery Source: http://concretepipemachine.sell.everychina.com/

The centrifugation process can be said to consist of 4 phases (Figure 54):

1st phase – uniformly distribution of wet concrete mix along formwork or steel tube length at low rotational velocity of centrifuge machine;

2nd phase – formation of concrete core layer, as the rotational velocity is increased and centrifugal forces start to act, so compression of wet concrete mix to formwork surface begins;

3rd phase – compaction of concrete core, with rotational velocity increased to the calculated one, when concrete core achieves a more uniform thickness, squeezing water out of the mix starts;

4th phase – with rotational velocity doubled further compaction of the concrete continues and the core reaches its designed uniform thickness and excess water is pressured out of concrete core. (Kuranovas & Kazimieras Kvedaras, 2010)

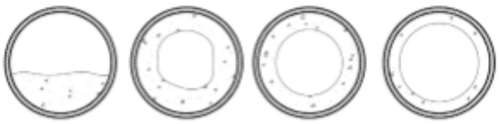


Figure 56. Spinning phase 1, 2, 3 & 4. Source: (Kuranovas & Kazimieras Kvedaras, 2010)

Note that the required spinning velocity depends on the concrete mix. For a lower quantity of excess water the stiffness of the concrete mix is higher, and a more intensive mechanical action on it must be applied. Compaction of stiff mixes requires some action which influences rupture of mix structure and transfers it to a more viscous substance.

For further general specifications on the main parameters required for the design of centrifuging machines refer to **APPENDIX 3: CENTRIFUGATION BASICS.**

6.6. CAISSON TECHNOLOGY AND DRY-DOCKS

Definitions

DRY-DOCK. A dry dock is a unique construction that is used for repairs and maintenance of merchant vessels. It is typically a rectangular solid concrete area with walls and gates constructed on a land near to coastal water. If the gate is opened, sea-water fills up in that area, also known as lock, and the vessel can be manoeuvred inside the dock and rested on blocks. After the ship is in required position, the gate is closed and water is removed. (Wankhede, 2016)

Dry docks can be of three types:

- **Graving dock**: fixed dry-dock usually located in or close to a port like the one described above.

- **Floating dock**: mobile "U" structure used to carry ships from mid sea unable to sail further because of an accident. Several "U" type floating docks can be joined to carry a large vessel.

- **Construction dock**: a temporary construction near to the sea or a waterway that is surrounded by dykes built specifically for the purpose of keeping the area dry. Once construction has been completed, the dykes are breached and the flooding of the dock allows elements to be floated out.

CAISSON. A caisson is a prefabricated hollow structure, usually in the shape of a box that serves as a watertight chamber. It is extensively used as a deep foundation for bridge piers in under water construction works, breakwaters, port terminals and underwater storage. Another interesting example were caissons were used was the foundations of the Eiffel Tower (Paris) for which watertight metal *caissons* were used. The water coming from the near-by Seine River was excluded from the caisson chamber by means of compressed air. This type of caisson is called pneumatic caisson. Other types of caisson include box caisson, open caisson and single wall open caisson, which will not be described further. Caisson technology is a vast and interesting field but treating it in depth is not the aim of this academic work. Instead this part will focus on the floating feature of caissons. What makes caissons so popular is they can be constructed on land, floated to the job site and sunk into place by adding ballast.

Caisson technology will be relevant for the demolding/un-casting and transport phases as it provides a fine example on how large concrete structures can be moved without the need of cranes.

A readily available example is the Construction of a liquefied natural gas terminal at the Harbour Perimeter of Campamento (Algeciras) by Acciona. After construction of the terminal was completed, the structure was tugged during 21 days. It sailed along the North-African coast and went around Palermo and Italy's "boot" and was finally installed in the north of the Adriatic Sea, 17 km off the coast of Venice. (Acciona, 2014)

This project proves the advantages of undertaking construction in a dry-dock.

Another interesting project also developed by Acciona is the Kugira floating dock. This technology is able to cast large concrete elements directly at sea. It is introduced now but will serve as inspiration for a particular construction proposal. The Kugira floating dock is 74 m long, 49 m wide and 56 m high and casts 66 m x 24 m x 21 m concrete caissons. It employs **200** people working around the clock every day to build the biggest reinforced concrete caissons on the planet in just ten days. (Acciona, 2014)

The feature of this high-tech floating formwork that would like to be extracted and adapted further in upcoming chapters is the idea of casting concrete directly at sea in a highly efficient manner. This will be developed further on.

As stated, Windcrete will be built in a dry-dock, either specifically constructed for the Windcrete project or using a readily available dry-dock in a port with good access to waters of main European players.

Note that flooding of a dry-dock is an inexpensive and effortless procedure commonly used to float out a hollow structure.

However, the subsequent pumping out of the flooded dry-dock can be a slow process that can last for weeks during which the workers are left idle. All the equipment used during construction would have to be removed from the dry-dock before the flooding operation can begin.

If a large dry-dock is used, it will be more convenient to construct the maximum number of towers that can be accommodated, and only then should the flooding operation begin. Several towers could be floated out in a single filling of the dry-dock, thus considerably reducing the amount of time required to put a structure in the sea. Transport of the completed structures could begin while the dry dock is being emptied and prepare for a new production cycle.

A fine example of this procedure is the construction process of the Eastern Scheldt storm surge barrier in the Netherlands. For this project, the construction of 65 colossal piers was necessary as they were the backbone of the barrier Each pier is a hollow concrete form, thirty to forty meters high and weighing 18,000 tons. The exact height of each pier depended on its place in the channel.

All 65 piers were built at three enormous construction docks. A special unit was set up to produce the concrete and it took nearly a year and a half to produce each pier. Production was staggered, with work on a new pier starting every two weeks. When all the piers in a construction dock were finished, the entire dock was flooded and the surrounding dyke was opened so that they could be transported. (Rijkswaterstaat, 2016)

Figure 57. Pier in construction dock.
Source: Rijkswaterstraat- Ministry of Infrastructure and the Environment

Alternatively, if the structures are to be floated out one by one as they are completed, the smallest possible dry-dock should be built to minimise the amount of water to pump out. These smaller dry-docks could be constructed within a large dry-dock and have the ability to be flooded independently. The dimensions would be such that the dry-dock closely encloses the outline of a tower and the surrounding volume just sufficient to enable flotation of the structure once flooded. A particular construction procedure will elaborate further on this concept of smaller dry-dock.

7. CONSTRUCTION OF WINDCRETE

7.1. PLANNING FOR LARGE-VOLUME POURS

7.1.1. MAIN CONSIDERATIONS

In large-volume construction, planning and phasing of the construction activities requires strict scheduling and rigorous monitoring. Any unforeseen event should trigger a quick response and promptly corrected if planning was done carefully. Main considerations are (Bamforth, 2003):

- Maintaining a high rate of placement.
- Impeccable coordination of all the necessary activities.
- Distribution of concrete over a large area.
- Monitoring and quick access to large construction site.
- Labour, shifts and work teams.
- Material supply and access.
- Timing
- Quality assurance and monitoring.

Maintaining continuity of placement is no easy task and calls for meticulous planning, A high level of coordination between contractor and concrete supplier is needed.

The placing rate will determine the minimum number of concrete plants. However, even if the casting rate is within the capacity of a single plant it is still advisable to utilize more than one to ensure continuity of concrete supply even under unexpected events. All the concrete plants should be within a reasonable distance of the working site.

Access for the concrete supplier should be carefully studied, roads with heavy traffic may cause delays and should be avoided. The planning stage should consider the access time during the workdays and weekends, night and day. Access within the site should also be convenient and with no obstacles from the access point to the delivery/pour location.

The quality of the concrete supplied must be excellent. An appropriate quality assurance system must be designed and the standards of conformance non-conformance must be set and provided to the supplier. A quality system should include on-site inspection and testing of materials.

Working around-the-clock means night working will be required, standard lighting must be provided to all areas where activities will be carried out to ensure safe working conditions for the workers.

It is essential that sufficient labour is allocated to each stage of the casting process to ensure that construction proceeds without interruption.

Schedules, lengths of shifts and changeover times, back-up teams must be available to accommodate work breaks and agreements should be reached with workers.

In view of the importance of maintaining continuity of placement, back-up for all essential items of the work site must be available.

7.1.2. CONCRETE PLACEMENT- GENERAL METHODS

Before concreting can begin the entire placing, programme must be planned and formwork must be inspected and found suitable for placement. Mixing, transporting, and handling of concrete must always be carefully coordinated with placing operations. Concrete should be placed in successive uniform horizontal layers as rapidly as practicable for proper bonding and to prevent the formation of cold joints or planes of weakness between layers. A variety of methods are used to place concrete (Office of Materials and Road Research, 2003). Some of the most common techniques are:

- hand-shoveling and wheelbarrows;
- buckets hoisted by a crane;
- conveyor belts;
- short chutes;
- gravity-fed tremies;
- pump-line placement.

The placement should be a continuous operation All methods should ensure the free-fall of concrete is minimized to less than 1.5m and must never exceed 2m. Chutes provide a rapid method of distribution of rather high-workable mixes while conveyors are more suitable for use with low-workability mixes. Above all the chosen method must be suitable for the size and characteristics of the project. However, most of the above-mentioned techniques have low throughputs and/or are not continuous.

7.1.3. CONCRETE PUMPS

In Germany in 1988, a record 17 000 m3 pour was cast continuously using four pumps over a period of 78 hours. The average placing rate per pump was about 55 m3/h, and 90 ready-mix trucks were used, operating from six batching plants. A placing rate of 100 m3/h per pump were achieved in the USA in 1990, where a 5700 m3 pour was cast in only 11 ½ hours.

Table 16. Some examples of large volume pours. Source: (Newman & Choo, 2003)

Ref no.	Location/ date	Pour details		Time taken (hr)	Average rate of placing (m^3/h)	Plant used	Average rate per pump (m^3/h)	Concrete mix details
		Vol. (m^3)	Thickness (m)					
15	Frankfurt, Germany, 1988	17 000	8.5	78	218	4 pumps	55	Not given
10	California, USA, 1990	5700	1.7–3.8	11½	496	5 pumps	99	Grade 20 pfa
11	Seattle, USA, 1989	8230	4.7	13½	610	9 pumps	68	Grade 40, 30% pfa
12	Jamshedpur, India, 1990	3600	4.3	44	82	6 pumps	15	Grade 25, BFS Cement, w/c = 0.42
13	Thames Barrier, 1982	6600	5.0	72	92	Tremie	–	Grade 30 50% pfa
14	Sheffield, 1976	3000	2.0	22	136	2 pumps	68	Not given

The number of pumps needed will depend not only on the placing rate to be achieved but also on the plan area of the pour. Mobile pumps have folding distribution booms which vary in length from 15m to over 50 m. Boom pumps are particularly suitable for large scale-area large-volume pours.

Windcrete is a large concrete placement that requires a rapid non-stop continuous placement method.

Most large-volume pours rely on pumps to achieve high rates of concrete placement. Typically, pumps can achieve placing rates in the range of 30 to 120 m^3/h compared with average rates of the order of 8-12 m^3/h with crane and skip. A nominal output of 30 m^3/hh is considered sufficient for routine concreting operations but it is estimated that most Windcrete construction proposals will require a greater output.

Using a pump to place the concrete allows for a steady flow from the delivery truck to the placement locations and increased productivity. A concrete pump consists of a hopper, a piston system and piping. The pump works by truck mixers pouring the concrete into a hopper that funnels the concrete to hydraulic pistons that push the concrete through the piping. To maintain a continuous flow of concrete deliveries of concrete truck will have to be coordinated such that as one truck is empty a full truck can being discharge to the hopper.

Squeeze pumps or peristaltic pumps are the ones that use vacuum pumping. These pumps can cover a distance of 90 m horizontally and 30 m vertically, and are capable of pumping 20 m3 of concrete per hour using 8 cm pipes (The Concrete Portal, 2012)

SELECTING A SUITABLE CONCRETE PUMP

Concrete pumps are selected based on two primary parameters, the maximum desired volumetric output of concrete per hour, Q, and the peak pumping pressure, p. The required power of the drive unit depends on these two parameters (The Concrete Portal, 2012). The delivery output and the pumping pressure are related by the expression of the hydraulic output H:

$$H = Q \times p$$

SOME REQUIREMENTS FOR PUMPED CONCRETE

Water is the only pumpable component in the concrete, and transmits the pressure on to the other components. With low water in the mix, coarse particles exert pressure on the pipe walls leading to damage and quick weathering.

1 High cement content in concrete is generally beneficial for pumping.
2 A slump between 50 and 150 mm is recommended (note that pumping induces partial compaction, so the slump at delivery point may be decreased).
3 If the water content in the mixture is low, the friction is minimized at the correct water contents.
4 The presence of a lubricating film of mortar at the walls of the pipe also greatly reduces the friction.

7.1.4. ADVANCED METHODS FOR CONCRETE PLACEMENT

The tunnel industry which also deals with large-volume pours provides a series of more sophisticated concrete placement procedures all of which rely on pumps but may combine pumping with other methods. It would be wise to integrate these concreting procedures in the construction of Windcrete.

As mentioned earlier, the forms for Windcrete will be in the shape of an arch. The technique of concrete placement used in tunnelling is introducing concrete at the top of the arch until the forms are filled and a new fragment of forms can be added and filled until the entire ring is achieved. For larger tunnels, it is common practice to place concrete in horizontal layers from internal and external chutes and elephant trunks which are fed by one or more pipelines (Hurd, 2005).

The entire concrete handling and placement system is positioned on a travelling bridge which backs away as the arch forms are filled. The concrete can me mixed outside the formwork system (*Figure 56.*) and deposited in the forms by conveyors or by buckets and chutes.

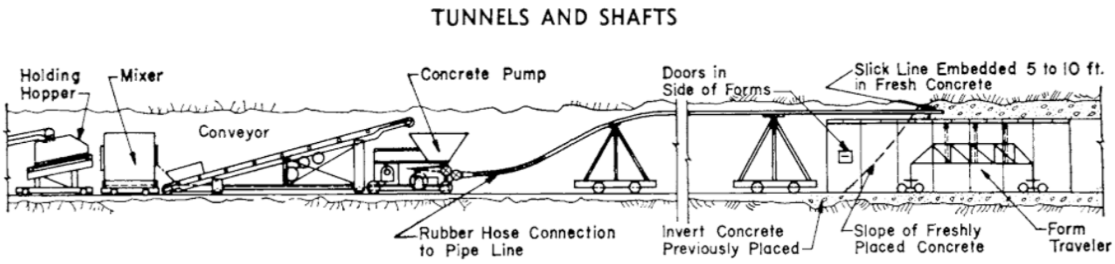


Figure 58. Arrangement of equipment for arch concreting within the tunnel.
Source: (Hurd, 2005)

7.2. CONCRETING OF WINDCRETE TOWERS

Broadly speaking the concreting of Windcrete will fall under one of the following categories:

- The concreting front advances as construction progresses, typically mounted on travelling formwork or similar

- The concrete is introduced at a fixed location and it is the structure that is subsequently 'launched' as construction progresses

The concreting equipment and method that should be adopted for construction of the Windcrete towers will depend on the construction proposal itself. Practically all the proposals that will be presented will make use of a pump line, large hoses and a distributor machine that pours concrete inside the form using valves in the form panels. Almost for sure some sort of travelling formwork will be used in the construction. As will be seen further into this chapter, for those proposals requiring a travelling formwork system, that may be or may not be self-propelled, the traveller may be supporting the structure cast in-situ from the inside, similar to form travellers used in the tunnel industry, or it may support it from the outside by an engineered formwork specifically designed for the task.

For those proposals inspired in the tunnelling practices, the construction will employ a concrete pump connected with articulated pipes to a self-propelled concrete distributor trolley installed on the travelling formwork system. The concrete is introduced laterally with flexible hoses through doors in the forms. These doors, before being reached by the level of concrete are closed and hoses can be connected and pour through a higher layer of doors. The pouring is then carried out in subsequent horizontal layers and should comply with the formwork calculation hypothesis. The concreting doors can be equipped with guillotine-safety valves which allow the perfect filling of the formwork and minimises risk. Concrete overpressure should be looked out for.

Depending on the form traveller that will be chosen, the concrete distributor will be located inside the structure or will envelop it from the outside, or a combination of the two to maximize filling rate when required. To place concrete into the space between forms this distributor should have the ability to move and connect to valves distributed along the length of the forms, at different heights to make sure no voids remain in the forms during filling. An interesting arrangement for these valves could be a radial configuration to ensure no uneven placement occurs.

Note that concrete must be fed into the forms uninterruptedly, however forms themselves can be placed at discrete intervals as long as sufficient space is provided inside the forms to keep pouring concrete until the next set of forms are placed (see *Figure 57*). This in turn means that the concrete train and the actual formwork may be expected to work independently.

Thus, for some proposals it may be interesting to detach the concreting unit from the travelling formwork.

A manned concreting train moving on rails and connected to a concrete pump with a distribution hose system could efficiently fill forms through valves at a constant speed. Another option could be a self-propelled remotely-controlled concreting train equipped with a concrete distributor as described above. These independent concreting trains could move on wheels or separate, smaller rails than those used by the formwork to avoid obstruction between equipment.

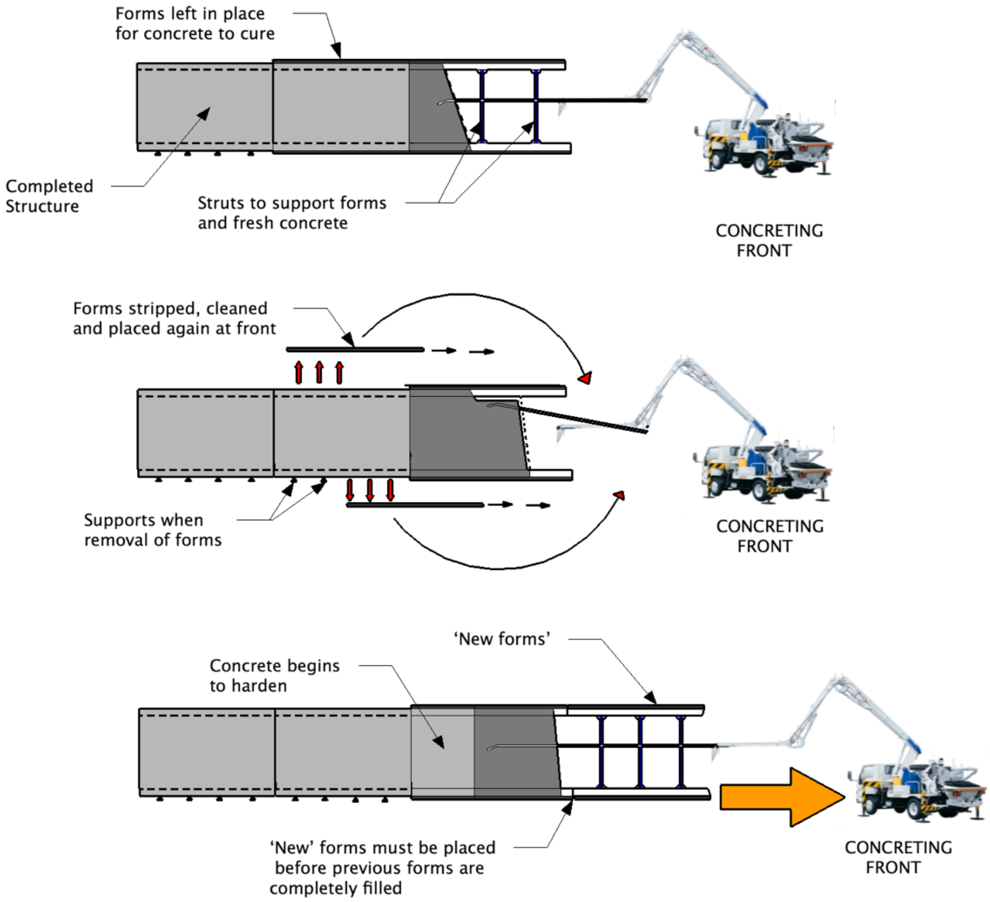


Figure 59. Advancement of concreting front.

The orange arrow shows the direction of movement of the concreting front.

Placement of reinforcement has not been shown to keep the sketch as simple as possible.

Struts are placed to support empty forms and forms filled with fresh concrete. Once concrete is hard enough to support itself and forms are ready to be stripped, struts can be removed and re-used further away.

In *Figure 3* one can see that forms are placed discontinuously but concrete is placed continuously.

A Kyokuto squeeze concrete pump truck model was used solely for illustration purposes. In reality several of these pump trucks will be required to pour simultaneously into the forms. Alternatively, other methods with higher throughputs can be used. Japanese company Kyokuto, specialized in special purpose vehicles, provides information on maximum output volume for their different models that range from $35m^3/h$ to $65m^3/h$.

It is important to place the new section of forms before the previous section is completely filled so that the pouring can proceed without interruptions once a form is full. Interference between form placing and concrete pouring must be carefully studied and avoided at all costs.

7.2.1. FILLING OF THE FORMS

Pouring of concrete will be done by a wide range of ways. Boom pumps with hight output will be the single most common equipment used to place concrete during Windcrete construction. These pumps can fill forms in a variety of directions. Indpendantly on the preferred approach, pumping will have to be an around-the-clock operation.

Forms will be in the shape of arcs for the floater part of the structure and cone-like for the remainder of the tower.

Placement from a vertical position into accessible forms is extremely more efficient than placement whilst advancing horizontally. This is demonstrated by the proved efficiency of slipforming techniques and by the few methods that cast-in situ concrete axially whilst advancing horizontally.

What is understood here by horizontal placement is concreting perpendicular to the cross-section of a structure is lying on the ground. This has immediate effects on the pouring philosophy.

To depict the several possibilities a simplified arbitrary arch-form has been represented with different concreting schemes. Note that concrete should always be placed in layers as horizontal as possible.

PLACEMENT FROM ABOVE

Vertical placement of concrete. When the lower section of forms has been filled, the next set of modular forms can be placed and casting can continue. Note that this method would require introducing concrete laterally through valves during the installation of the next set of form panels to avoid interrupting the casting operation.

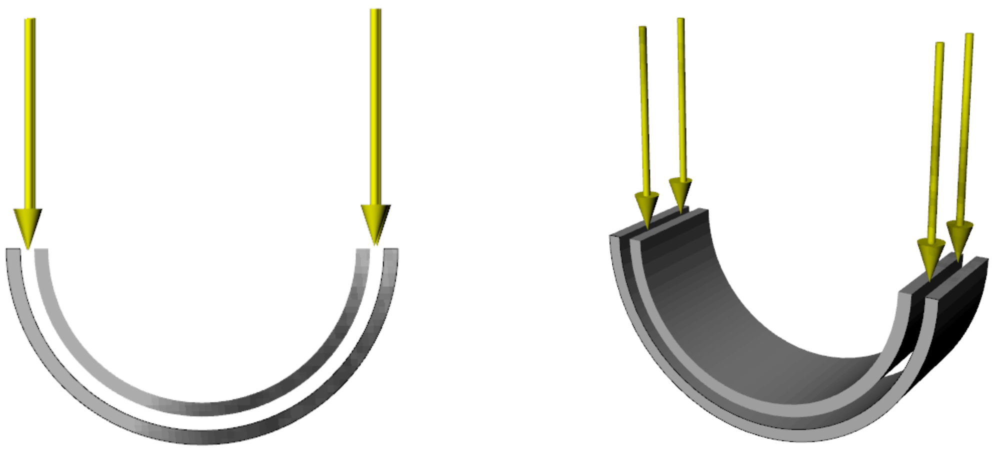


Figure 60. Overhead placement of concrete into openmold using modular forms.

This placement scheme will be relevant for those construction proposals involving the use of overhead concreting platforms. For instance, a particular construction proposal considers a semi-fixed mold and concrete equipment mounted on a large overhead gantry-crane-like structure. Note that for the filling of the lower part of the section, it may be more economical and fast to discharge concrete directly through conveyor belts or mixing trucks if adequate access is provided. Once the upper forms are in place concreting will continue through pumping or other convenient methods for pouring at a certain height.

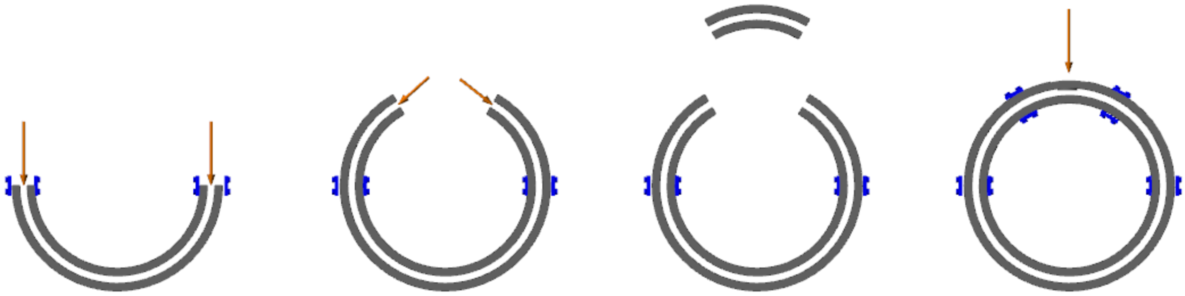


Figure 61. Filling sequence for modular formwork

Note the elements in blue represent the locking devices. Concrete level has not been shown for simplicity.

RADIAL PLACEMENT

This pouring scheme will be used by those proposals making use of inner travelling formwork system and concreting trains, similar to those used in the tunnel industry. The arrow colours represent the sequence of valves through which concrete is poured. First the concrete will be poured from the lowest line of valves (shown in yellow), before concrete reaches this height, valves in the panels will be closed and pouring can proceed via the next set of valves (here shown in orange). The last set of valves that will be used, when the forms are almost full, will logically be located at the highest point of the panels to ensure adequate filling.

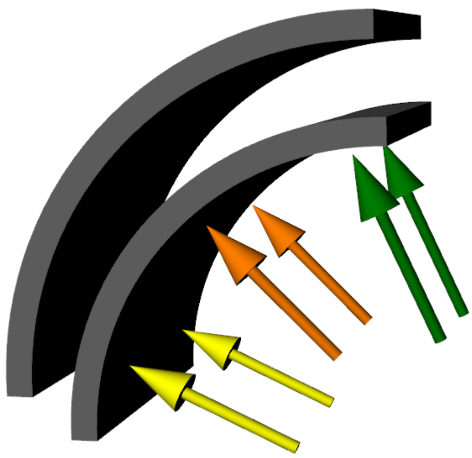


Figure 62. Placement of concrete from inside using a radial configuration of pouring valves.

Note that valves have not been represented in this figure.

A similar concreting scheme can be applied from the outside of the forms.

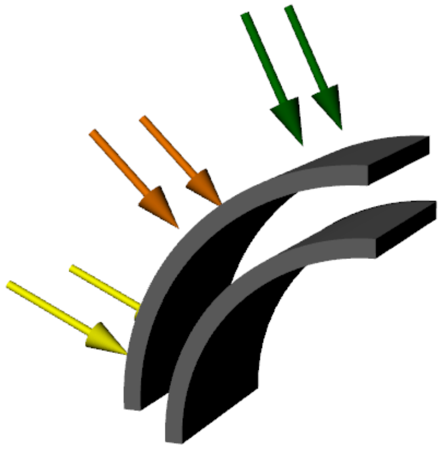


Figure 63. Placement of concrete from the outside in a radial configuration of pouring valves.

This pouring scheme will be used mainly by those proposals requiring a travelling formwork system that supports the structure from the exterior. Here too concrete will be placed through valves in ascending order.

A combination of the two previous methods sees simultaneous concrete placing from the inside and outside through a radial configuration of pouring valves.

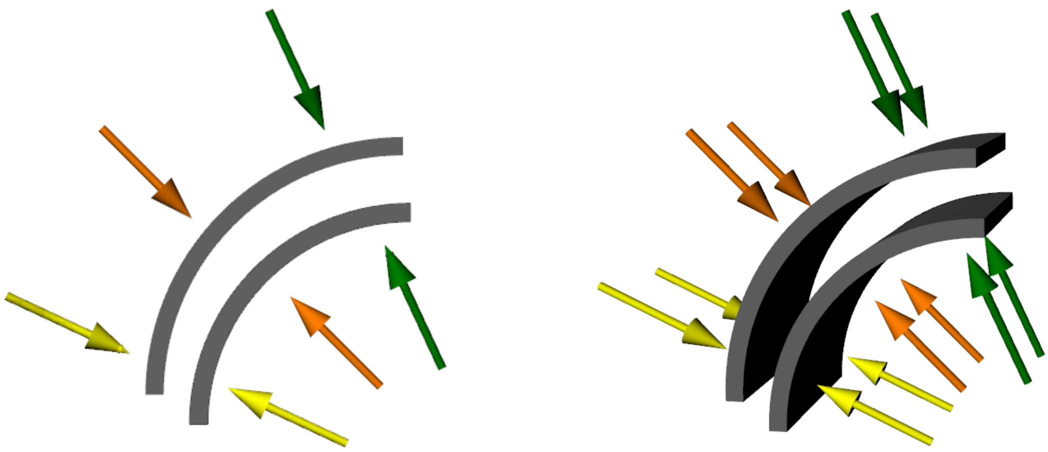


Figure 64. Internal and external radial configuration for concrete placement

Note that for all the combinations of radial pouring of concrete, the mold is gradually filled in horizontal homogenous layers resulting in good conditions for quality placement.

AXIAL CONCRETE PLACEMENT

The placement of concrete perpendicular to the cross-section is a less than ideal way of filling forms. The fact that the structure lies on its side means that the pouring direction will run parallel to the ground causing concrete to collapse and segregate as it is placed.

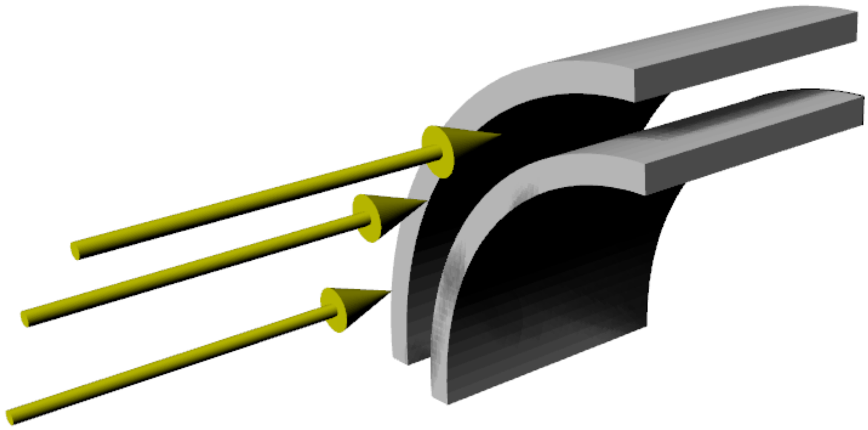


Figure 65. Axial concrete placement scheme.

These are unfavourable and troublesome conditions for concrete casting due to the weight of the concrete unable to support itself.

This method will be used however when combined with others and will be particularly relevant for proposals involving travelling formwork that gradually backs away while pouring concrete in between the form.

The only way concrete pouring in this direction can be adopted on its own, without the need of combing it with other previously mentioned methods is by designing a concreting 'crown'. This means designing highly-specialized equipment that should theoretically be able to distribute concrete axially throughout the entire cross-section by means of a circular arrangement pumps with high to very-high rate of placement. This concreting scheme will be particularly relevant to those proposals involving a travelling formwork. In fact, the benefits of developing such a concreting 'crown' are believed to have a lasting and favourable effect on casting towers horizontally. The concept of concrete crown will be the centrepiece of a particular construction proposal where it will be discussed further.

SUPPORTING AXIALLY PLACED CONCRETE

Axial placement of concrete will require creating a heap of concrete with a mild slope within the forms so as to provide an adequate base for concrete to fall on. The free fall of concrete should always be minimised and limited to a couple of meters at the most.

As an alternative to this heap, or in combination with it, it may be necessary to provide a vertical support system to prevent newly placed concrete from collapsing. This system can come in the form of a metal grid, net, mesh or other. This grid would have to suit the shape of the cross-section of the tower, whilst providing holes for reinforcement and pump nozzles. It is important to state that such a grid should not obstruct in anyway the continuity of the reinforcement.

The grid would be introduced and fixed inside the forms to hold a section of concrete in place. It is likely that retrieving this grid may become difficult as concrete adheres to it, therefore this support system may have to be of losable type and remain embedded in the permanent structure. If a losable grid is used, it will preferably be made out of stainless steel to avoid corrosion. Other materials may be used like polymers or reinforced plastics as long as they are inert and do not react with the concrete.

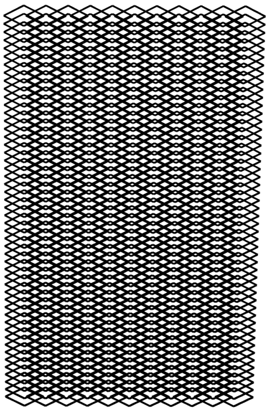


Figure 66. Concept of losable mesh for supporting concrete.

Note that the mesh represented above should have to be cut in order to match the circular cross-section of Windcrete. This mesh clearly ressembles the so called "métal deployé", extensively used in arquitecture and readily available in multiple sizes and shapes from suppliers.

Some additional considerations on the direction of concrete placement:

- Concrete can also be injected from the bottom by pumping it.

- Each of the above mentioned concrete pouring schemes will be suitable for a particular construction process. A given process may use one or a combination of these schemes throughout the several stages of a full operative cycle.

- Travelling formwork will often be combined with introducing concrete radially and axially.

- Some proposals involving travelling formwork will clearly benefit from axial concrete placement fully justifying further research on the concept of concreting crown

- Discharging concrete from a certain height in horizontal layers should always be the preferred approach.

- The assembly-line concept that considers joining ring segments in "fresh" would benefit from some additional radial placement of concrete, specially in the interphase of two consecutive rings to increase safety and make sure proper bonding is achieved and the connexion is sufficiently strong. This radial placement of concrete would be carried out at the assembly line where consecutive molds have already been interlocked.

In reality the recommendation is to use a combination of all the above-mentioned schemes for filling of forms during the different stages of the operative cycle of building the structure.

7.3. SLIP-FORMING WINDCRETE TOWERS

7.3.1. FIRST CONSIDERATIONS ON 'DIRECT' VERTICAL-HORIZONTAL SLIPFORMING

The advantages of vertical slipforming are precisely what makes this technique so desirable to Windcrete. It is by far the preferred approach when building tall circular tower-like structures. It optimizes the amount of formwork, maximizes productivity, enables repetition and maintains a smooth workflow (Carter, 1982). This technique also allows continuous pouring of concrete and only stops when the structure has been completed, making it ideal when a monolithic structure is required, fulfilling one of the most challenging desired features of Windcrete.

Other benefits of slip-forming, besides a construction with no joints, also respond very well to the specific requirements of the Windcrete Towers. To name a few

- It is particularly suitable for watertight structures.
- It is particularly suitable for large concrete structures with a constant cross-section. Also, tapered slipforming exists and can easily account for the gradual variation of the cross-section.
- It is a fast, cost-effective and reliable process, meeting all the desired aspects of serial production.

As the name implies, vertical slip-forming is essentially vertical and relies on gravity to compact the freshly placed concrete, which in turn allows the mold to jack upwards.

Yet the feasibility of the Windcrete project requires horizontal construction of the structure.

This difference is fundamental and clearly poses an obstacle. This method cannot be directly applied to construct Windcrete.

Using vertical slip-forming in the horizontal direction, at least as we know it, is impossible. That being said, as a technique that allows continuous pouring of concrete and only stops when the structure has been completed, it should come as no surprise that slip-forming is far too attractive to be ruled out. Adapting this technology could potentially solve the construction process and hold the key to producing towers under the specified conditions. For his reason, efforts towards adjusting this technology to the horizontal direction are fully justified.

7.3.2. ADAPTATION OF VERTICAL SLIPFORMING

We now need to assess If classic vertical slip-forming is compatible with the horizontal direction and just how easy these adjustments can be made. If on the contrary such a direct adaptation is impossible, the idea of slip-forming should not be abandoned but combined with other configurations. Although additional apparatus may be required, this should not be seen as a drawback.

The idea is to reconfigure slipforming techniques so that typical sections produced through vertical slipforming can be obtained horizontally.

The ability to move or 'travel' of formwork is provided by a jacking-system for vertical slipforming and by rails for horizontal systems. It is safe to declare than this horizontal system will have to be mounted on rails, or adopt both rails and hydraulic jacks to be able to move.

The first obstacle that comes to mind is that, if placed horizontally, the moving slipform is unable to sustain the previously placed concrete, which is still fresh and unable to sustain itself. Due to its own weight, concrete would simply collapse, fall off almost immediately.

This problem could be addressed by temporarily supporting the concrete with a longer slipform. A horizontal slipforming machine would therefore need to support all the wet concrete at the same time that it pours new concrete and moves. To keep the desired shape, both the external and the internal face of the concrete structure would have to be supported.

Apart from the pouring platform, this slipform would have a trailing jacket that holds the concrete until it has reached sufficient strength. The jacket should be long enough to cover the entire area of the structure that is still too wet to hold in place. The length of the jacket would have to cover the entire length of concrete that cannot support itself, while taking into account the actual speed of the slipmold. Understood differently, if the shortest jacket was used, the speed of the slipmold would have to be exactly the speed at which concrete becomes just strong enough so that it doesn't collapse.

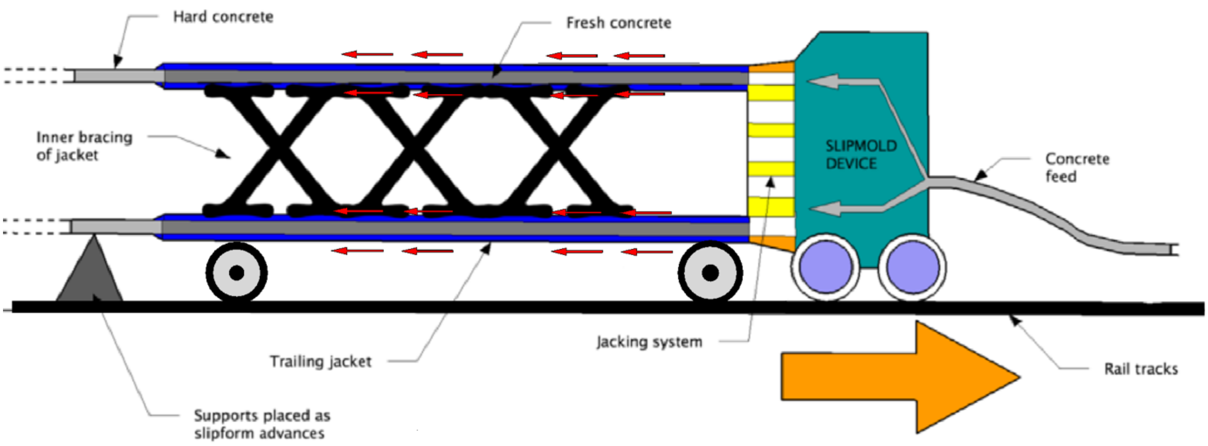


Figure 67. Simplified slip-form mechanism.

The **orange arrow** shows the direction of movement of both jacket and slipmold device.
Red arrows represent the friction force opposing the movement of the slipform. It is expected to develop at both internal and external steel-concrete interface.

The jacket, represented in blue, must support both the inner and outer surface of the fresh concrete.

A simplified representation of a bracing system to hold the inner core of the jacket is shown.

No detailed representation of the actual slipmold is given as the feasibility of such a device is still under discussion. Also, not shown in the figure but certainly necessary are some additional sliding supports or wheels for the jacket to slide.

As the structure hardens, the jacket moves and must be replaced by temporary supports to hold the concrete. This operation would demand good timing.

Supporting the concrete is no longer a problem but now sliding the jacket becomes the issue. If attached to the slipform, this jacket would be expected to 'slide' behind the advancing slipmold and would be subject to high friction forces opposing the direction of movement. Usually, steel does not slide well on concrete.

An experimental investigation found the average effective coefficient of static friction varied between 0.57 and 0.70.
It is recommended that the coefficient of static friction for concrete cast on steel plate and grout cast below steel plate should be taken as 0.65 for a wet interface. For dry interface, this coefficient should be taken as 0.57. (Rabbat, et al., 1985).

The volume of concrete for one running meter (in the floater) is $\pi \cdot (6.5^2 - 6^2) \cdot 1\, m = 19.63\ \mathrm{m}^3$

The weight W of this volume is $\mathrm{W} = 19.63 \cdot 25 \frac{kN}{\mathrm{m}^3} = 490\ kN$

$\gamma_{reinf-concrete} = 25\ \mathrm{kN/m^3}$ accounts for the weight of both concrete and reinforcement bars.

The friction force per running meter results in $F_{friction} = \mu \cdot W = 0.60 \cdot 490 \approx 300\ kN$

An intermediate vaue μ =0.6 has been chosen as the interface will neither be wet (or else concrete will colapse) nor will it be completely dry. Note that different sections will all present different degrees of water in their interface with the steel jacket.

In this case, the contact area of steel and concrete per running meter is quite considerable and equal to $2\pi \cdot 6.5 + 2\pi \cdot 6 = 78{,}54\ \mathrm{m^2/m}$.

This large contact area is likely to lead to high frictional forces opposing the movement of the slipformer. Forces resisting the movement will be even higher due to the fact that steel must support the weight of the concrete while sliding.

Besides the large friction force to overcome that must carried out by the jacks, the sticking of concrete to the jacket is bound to happen. As the jacket slides it may remove some concrete from the structure undermining the quality of the tower. This also happens in conventional vertical slipforming which is why a continuous upward movement is preferred.

In this case, it would become difficult to keep a constant pace of movement for the slipmold while making sure concrete doesn´t stick to the jacket. If any unacceptable amount of sticking were to occur, the slipmold may be forced to stop and the entire process would be compromised.

At the time of writing, no references have been found on such a way of slipforming horizontally.

7.3.3. CONCLUSIONS ON 'DIRECT' ADAPTATION OF VERTICAL SLIPFORMING

What can be drawn from this first attempt to directly adapt vertical slipforming practice to a horizontal configuration is that high frictional forces will develop and hinder the constant speed of the slipform. To avoid large spans within the jacket of the slipformer, the travelling speed would have to be slow enough to allow concrete to harden in between the shortest possible jacket. Finally, this adaptation is estimated to be too slow due to the slow placement speed required to allow concrete at the rear to harden whils fresh concrete is placed at the front.

Additionally, the invert section (the bottom arch of the circular cross-section) may interfere at a given moment with the rail track used by the slipmold.

Even if another lighter material was used for the jacket, which may be studied further, the concept of sliding jacket turns quite quickly into an unpractical solution to temporarily support the concrete. This approach will not be pursued further.

Although the principle of slipforming the towers should not be abandoned, additional adaptations will be necessary. More convenient slipforming techniques will be discussed throughout the different construction proposals, all optimized to fit the specific needs of Windcrete. Several variations to slipform the towers will be presented, all with their own particularities. However, broadly speaking, these techniques will have the following three aspects in common:

- A carriage mounted on rails will be used and may additionally be combined with a special arrangement of hydraulic jacks.

- Support of the concrete will be achieved by leaving forms in place the required amount of time for concrete to harden. After stripping of forms, they can be fed to the concreting front and filled again. Thus, sliding mechanism and forms will work separately.

- The slipmold will not advance continuously but in discrete steps. However, the concrete will be placed continuously at constant rate through foldable pumps.

Note that the last point directly contradicts the very nature of slipforming. By definition, slipforming involves a continuous movement of the mold. Whereas vertical pouring of concrete never stops advancing and can reach speeds of up to 60 cm/hour, horizontal placement is more difficult and time consuming. Given that the direction of casting underpins the speed the slipmold moves, it is deemed more convenient to detach the forms from the travelling device so they can stay in place while concrete hardens. While the forms remain in place, the travelling device can jack-away and make room for new forms to be placed. The travelling device should be equipped with pump lines sufficiently long to continuously pour concrete into the furthermost part of forms. These pump lines will fold and become shorter as they gradually fill the mold and get closer to the travelling device. Alternatively, concrete could be poured through valves from the inside or outside of the forms at the required distance.

For the reasons mentioned above, some of the approaches that will be considered are not slipforming techniques, strictly speaking. Nonetheless, they will be designed to guarantee non-stop pouring of concrete.

8. CONSTRUCTION PROPOSALS

Construction proposals should be seen as a preliminary brainstorm if you will, rather than detailed solutions to construction of Windcrete towers. This brainstorm will emerge from a broad-minded overview of civil engineering practices and readily existing technology. It hopes to set the base for future research so as to narrow the range of possibilities that will need.

Some of these proposals will be accompanied by renderings done on rhino to further illustrate their working principle or to attempt a preliminary design of facilities.
These drawings fall mainly in two types:
- 2D-drawings representatioms to illustrate the full operative cycle of a given proposal, or to represent a particular technological aspect involved.
- 3D-renderings from diferent perspectives of a given proposal.

For clarity, in these 3D-renderings**,** the falsework surrounding the structure has **not** been shown in the representations of the construction proposals.

In reality**, all** of the proposals will require some sort of support structure around the structure. Falsework will be a system of tubular steel frames that surround the cross-section whilst capable of holding formwork in place. The falsework will include load bearing towers designed for large shoring-heights and high loads. Falsweork will have built-in anchoring points for form ties (see *Figure 68*). Through the use of heavy-duty form ties, the external falsework will support forms corresponding to both the inner and outer face of the structure. Forms will be equipped with 'doors', or valves, to radially place concrete (see *Figure 68*). The idea is to mainly support the formwork from the outside to minimise the amount of inner falsework. Falsework will aso include working decks at different heights to place concrete radially during the different pouring stages (*Figure 67*)

Figure 68. Exterior tunnel falsework with working decks used in road construction of RN 88, France. Technology by Peri.
Source: http://www.worldhighways.com/categories/road-highway-structures/features/winning-formula-for-formwork/

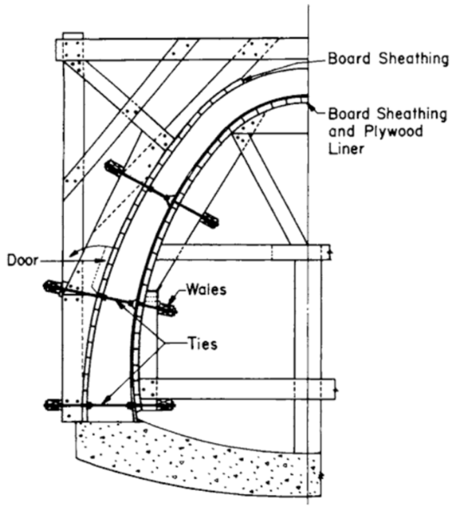


Figure 69. Arch forms supported by form-ties.
Source: (Hurd, 2005).

SUMMARY OF CONSTRUCTION PROPOSALS

Proposal	TECH. REQUIREMENTS	STATUS	RISK OF EXECUTION	INSPIRING TECHNOLOGY	ADAPTATION DEGREE	PRELIMINARY COMMENTS	MAIN DOWNSIDE
1. *VERTICAL CASTING OF THE STRUCTURE (ON LAND)* **pages 134-136**	Vertical Slipformer (on shore)	**PROVED**	**LOW**	Condeep O&G drilling platforms	**NONE**	Un feasible in most locations	Unpractical transport of finished structure
2. *VERTICAL CASTING OF THE STRUCTURE IN SEGMENTS* **pages 137-139**	- Several casting stations -Crane able to flip molds 90° -Assembly line	**UNPROVED**	**HIGH**		**NONE**	Relies on ASSEMBLY-LINE CONCEPT -yields HIGH production speed	-Difficult to place reinforcement -High risk of cold joints
3. *HORIZONTAL CASTING IN ASSEMBLY-LINE* **pages 140-149**	- Several casting stations - Wheeled forms -Assembly line	**UNPROVED** Seemingly reliable	**MODERATE**		**NONE**	Relies on ASSEMBLY-LINE CONCEPT -yields HIGH production speed	-Unresolved reinforcement placement -Moderate risk of cold joints - Heavy pushing of forms+fresh concrete
4. *OPEN-CUT TUNNELING METHOD* **pages 150-152**	Regular formwork	**PROVED**	**LOW**	**Tunnel Technology** (open-cut)	**MINOR**	Potential to use products of the tunnel industry	- Labour intensive - Formwork rails may lead to design modifications
5. *HORIZONTAL CASTING IN A SEMI-FIXED MOLD - THE BIGGEST MOULD IN HISTORY* **pages 153-160**	Massive permanent mold	**UNPROVED** Seemingly reliable	**LOW**	Turbine blade casting facility	**MINOR**	- Semi-fixed mold -Pouring entire length of the structure at once→Fast -Optimized uncasting procedure	-High upfront investment Requires high tower demand

Proposal	TECH. REQUIREMENTS	STATUS	RISK OF EXECUTION	INSPIRING TECHNOLOGY	ADAPTATION DEGREE	PRELIMINARY COMMENTS	MAIN DOWNSIDE
6. *FIXED JACKING SYSTEM* **pages 161-167**	- Jacking pressure ring - Wheeled forms - 'Concrete Eye' - Reception lane	**UNPROVED** Seemingly reliable	**LOW-MODERATE**	**Trenchless technology**	MAJOR	Launching of previously filled molds into a reception lane	High to very high jacking forces→ heavy duty hydraulic jacking system
7. *SELF ADVANCING TELESCOPIC TRAVELLING FORMWORK SYSTEM* **pages 168-169**	Telescopic travelling formwork Complex form	**PROVED**	**LOW**	**Tunnel Technology** (in-situ cast linings)	**MINOR**	Uses adapted tunnel lining formwork	- Formwork rails may lead to design modifications
8. *SELF-ADVANCING 'CANTILEVER CARRIAGE' SYSTEM* **pages 170-171**	Cantilever carriage	**UNPROVED** Seemingly reliable	**LOW**		**NEW TECHNO.**	No need for rails inside the structure	Investment in new technology
9. *CONCRETE CROWN* **pages 172-176**	Concrete crown	**UNPROVED**	MODERATE-HIGH		**NEW TECHNO.**	Unproved method	Investment in new technology
10. *TBM-ADAPTATION (ERECTOR-ARM)* **pages 177-179**	Erector arm to place forms mounted on wheels	**UNPROVED** Seemingly reliable	**LOW**	**Tunnel Technology** (TBM)	**MAJOR**	-Highly automated method - No travelling formwork required	High-tech adapted erector arm
11. *TBM-ADAPTATION (2.0)* **pages 180-181**	Erector arm to place forms mounted on wheels hydraulic thrust cylinders	**UNPROVED**	**LOW**	**Tunnel Technology** (TBM)	**MAJOR**	-Excessive damage, buckling & wearing of forms -Unnecessarily complex	Unpractical

Proposal	TECH. REQUIREMENTS	STATUS	RISK OF EXECUTION	INSPIRING TECHNOLOGY	ADAPTATION DEGREE	PRELIMINARY COMMENTS	MAIN DOWNSIDE
12. *EXTERIOR TRAVELLING FORMWORK – 'RING FRAME'* **pages 182-187**	-Exterior 'Ring frame' travelling formwork - 'Gripping ring'	**UNPROVED**	**MODERATE**		**NEW TECHNO.**	- Very large sophisticated (unproven) travelling formwork - Casting of large sections at once	Investment in new technology
13. *CENTRIFUGE ENTIRE TOWER* **pages 188-191**	- Centrifugation plant - Large spinning mechanisms (gears, cogwheels, truck wheels)	**UNPROVED** for large scale applications	**HIGH**	Centrifugal Reinforced - Concrete pipes	**MAJOR**	- Upscaling existing techno. - Ideal for circular cross-sections - Eliminates the need for cores -Enhanced mechanical durability	- Very high execution risk - High energy requirement - interdependency between elements →propagation of failure
14. *POST-TENSIONED PREFAB (CENTRIFUGE) RINGS-ALTERNATIVE 0* **pages 192-196**	Centrifugation stations	**UNPROVED** for large diameters	**LOW-MODERATE**	- Hybrid FOWT,Nagasaki - Bridge box girders	**MINOR**	- eliminates the need for cores - prefab centrifuge rings	segmental-precast rings→ construction joints
15. *VERTICAL CASTING IN AN OFFSHORE FACTORY (O&G PLATFORM)* **pages 197-199**	- Vertical slipformer (offshore) - O&G platform due to be decomissioned	**UNPROVED**	**HIGH**	-Kugira -Adaptation of O&G drilling platform	**MAJOR**	- Relies on cooperation of O&G industry to be feasible - Ability to extend lifetime of O&G platforms	Offshore concrete batching plant

Each of these construction proposals will be duly described in the upcoming part. They will be presented in the same order as in this table and will include additional considerations such as the presumed delivery time for each method, the main cost-drivers that can be expected and type of formwork system that will be required. At the beginning of each proposal a table summarizing the claimed benefits and advantages.

CONSTRUCTION PROPOSAL 1: VERTICAL CASTING OF THE STRUCTURE (ON LAND)

Req. 1 Req. 2. Req. 3	*execution risk*	*innovation degree*	*techn. complexity*	*main cost driver*	*production time*	*formwork type*	*design modifications*
NO	*low*	*None*	*Low*	*Transport finished structure*	*Fast (20-40 days/structure)*	*slipform*	*No*
YES							
YES							

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	(CLAIMED) DISADVANTAGES
- Proven and familiar technology - No risk of cold joints - Minimum formwork - Constant production speed 20-40 $^{cm}/_{h}$ - Uses the advantages of vertical casting - Ideal for casting of transition piece	- Incompatible connection with subsequent transport phase - No use of the floating feature of FOWT - Unreasonable handling, from an economic and technical perspective

METHOD STATEMENT

Construction of the structure using conventional slipforming technique. Standard practice with extensive experience available, a high-quality structure results while optimizing productivity. As demonstrated by Condeep O&G platforms, Windcrete height is not an issue when it comes to slip-forming.

COMMENTS

- There is good knowledge on slipforming procedures as they are extensively used. Information with regard to the speed of the slip-mold is readily available from previous projects, and typically ranges between 20-40 $^{cm}/_{h}$. This means that for this method, delivery time for completing a Windcrete tower can be quite accurately computed. Assuming an average speed of 50 $^{cm}/_{h}$ and a total slipformed height of 220 m, it would take 19 days to produce a single tower.

- This proposal is a good example on the importance of optimizing the implementation process from a holistic perspective rather than simply optimizing the construction process without considering the subsequent transport phase.

Just for illustration purposes, a simple sketch of what this transport phase would look like is presented bellow using a typical vessel used by the offshore wind industry has been used.

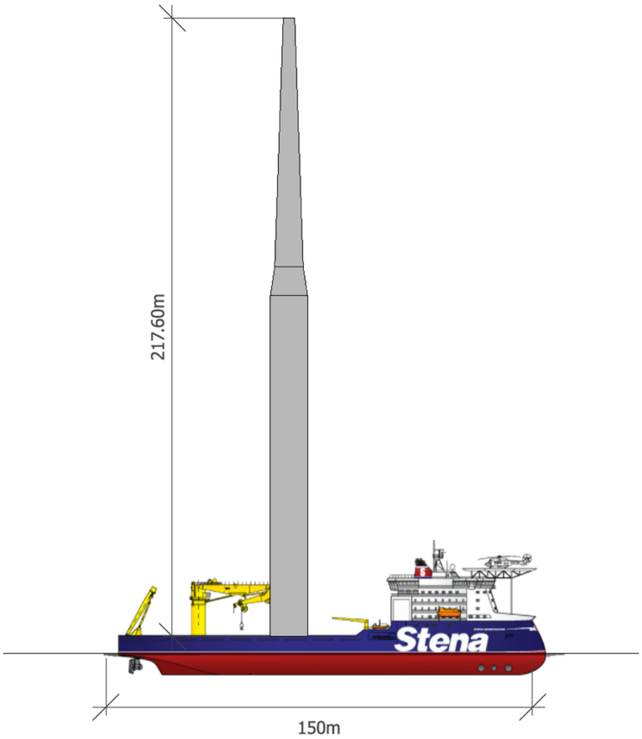


Figure 70. Vertical transport of the structure.

Once at the permanent location, the vessel would have to gradually lower the structure into the water, a highly risky manoeuvre. The vessel used to elaborate this sketch is a typical 'Construction Vessel' used in the offshore wind industry. It serves as a flexible construction platform for functions as dive support vessel and subsea heavy lift vessel.

Marine consultancy firm Knud E. Hansen provides technical data on vessel dimensions.

Table 17. Construction vessel for offshore wind.
Source:http://www.knudehansen.com/references/offshore-offshore-wind-vessels/construction-vessel

Length	149.70 m
Breadth	28.60 m
Depth	12.00 m
Draught, design	6.90 m
Draught, max	8.00 m
Deadweight	11000 t
Service speed	15 kn
Crane capacity	300 t
Capacity (crew)	75 pers.

Reasons to dismiss this proposal

Out of all the proposals that will be presented, this is the only one that will be ruled out categorically. Whereas the construction process itself would clearly benefit from the advantages of slip-forming, the transport of the finished structure will become the real challenge. Presumably, the structure would have to be loaded onto a vessel and transported vertically to its offshore location. If at all possible, this would require a highly-specialized vessel of terrific dimensions. The upright structure would be exposed to high wind loads during the journey causing instability. The floating feature of Windcrete is what makes it competitive, and is definitively worth taking advantage of for cost-effective transport. In this method, no use is made of the inherent ability of FOWT to float.

FOWT have a major challenge to overcome, which is high costs. Any construction proposal must take advantage of all the new promising features of FOWT than can reduce costs, namely an easy transport by floating the structure to site and a "simplified" installation process with regard to bottom-fixed offshore turbines.

Vertical construction would fail to integrate the floating aspect in the transport phase, and would miss out on the great potential of FOWT to reduce transport and installation costs. Additionally, this method would require mobilising expensive heavy-lifting vessels, similar to conventional offshore turbines, crushing any hopes to keep costs with acceptable limits.

Note, however, that the vertical casting yields in good quality and would be interesting to integrate somehow into the construction process.

CONSTRUCTION PROPOSAL 2: VERTICAL CASTING OF THE STRUCTURE IN SEGMENTS – *'BUILD N' STICK' METHOD*

Req. 1 *Req. 2.* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
NO *PARTIALLY* *YES*	*HIGH*	*None*	*Low*	*Turning rings*	*FAST*	*Conventiona circular wall formsl*	*No*

Requirements:

[1] Horizontal construction: NOT SATISFIED. Casting is vertical and assembly is horizontal
[2] Monolithic structure: PARTIALLY SATISFIED. Relies on assembly-line theory
[3] Suitable for serial construction: SATISFIED

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Speed of production - Uses the advantages of vertical casting - Ideal for casting of transition piece - Flexible w.r.t crane size and initial upfront investment - Conventional curved wall formwork - High-degree of automation possible - Delivery time of a complete tower could be adjusted to the size of the initial capital investment.	- Unresolved placing of reinforcement - High risk of cold joints - Unproven assembly-line concept - Research, developping and construction of highly specialized 'flip-mold' technology - High energy costs to flip the fresh concrete rings - Flip operation may cause segregation of the concrete

METHOD STATEMENT

This method builds on the assembly-line concept involving several identical casting stations that start work almost simultaneously operating in staggered cycles. Time lag between the start of the cycles of two consecutive casting-stations must be defined.

The idea is to pour the concrete vertically into conventional molds at high placement speed. Once the mold is completely filled and concrete is still fresh, it is subsequently turned an angle of 90° from upright position to horizontal position and lowered directly onto the assembly line. It is important to note that the concrete should not be allowed to harden in the vertical position, as it is sole for casting purposes.

Several casting stations must produce rings in a coordinated manner so as to join them while concrete is still fresh. Additionally, radial pumping of extra concrete could be used to fully bond 2 consecutive segments.

The casting station is composed of conventional vertical ring-shaped formwork and a turning mechanism to 'flip' these molds from vertical to horizontal position.

This sets the main requirement for this approach which is equipment capable of turning the mold together with the fresh concrete around its horizontal axis.

Crane capacity will mainly determine the feasibility of this method. Smaller cranes should be able to 'flip' smaller molds, thus a larger number of cranes would be required to produce segments at acceptable that can be joined while fresh. On the contrary, if large cranes are deployed, longer rings can be cast in one pouring operation. Regardless of crane capacity, cranes will need to work in staggered operative cycles.

Alternatively, the mold could be placed on a rotating platform, or fixed to a rotating mechanical arm. This 'flip-mold' may be a "necessary" innovation to pursue this approach. At the time of writing, the author was unable to find any confirmation that such mold actually exists which means it should be designed specifically for the Windcrete project.

This is likely to increase costs with regard to cranes. In fact, according to the assembly-line concept, several of these "flip-molds" would need to be fabricated in order to assemble various segments with minimum delay.

Downside of this method is that placing reinforcement and allowing reinforcement continuity throughout the structure is unclear and appears to be difficult. This aspect alone may imply ruling out this proposal.

COMMENTS

This method may appear far-fetched but it is worth considering for a number of reasons:

- By casting vertically, the building process could benefit from all the proven qualities of vertical casting: speed, quality control and well compacted concrete.

- This method would be particularly suitable to cast the transition piece in a single pouring.

- The upper part of the tower, smaller in diameter, could be cast in longer segments, and 'flipped' with the help of conventional cranes

- If a large number of these 'flip mechanism´ were made available and ring production is optimized and well-coordinated, construction time of the entire tower could be in the range of a day.

- Delivery time of a complete tower could be adjusted to the size of the initial capital investment. This delivery time could be reduced in a flexible way by speeding placement rate and adding ring-producing-fliping stations later on.

- Repetitive basis, maximum performance can be achieved.

ADDITIONAL COMMENTS

- Unclear if it will work due to difficult formwork placement

- Sophisticated flip-mold technology could be replaced by adequate cranes

- Pouring speed should be such that molds are completely filled, turned and transported before the first layer of placed concrete has time to harden

- Once turned, the molds in horizontal position (assembly position) should be placed on rails or similar and pushed with minimum effort to their final position in the assembly line.

- Freshly filled molds could be directly placed on boogies, similar to trains, to agilize transport.

- Height and weight of the ring forms will be limited by the flipping capabilities of the 'Flip mold'. The smaller the rings the less power will be required to turn them. However, the samaller the rings, the more ring-producing stations will be required to joig rings in fresh.

- Smaller molds increases number of forms to be stripped in the uncasting phase

- The ring producing molds should be organized at close distance around the final structure to minimize transport time to the assembly line, delays and avoid any cold joints.

- The segregation in the concrete could be addressed by pumping some additional concrete under pressure through inner and outer nozzles, specially at the interphase between consecutive rings.

- The optimal balance between the crane power required to flip the molds and the size and weight of these molds should be sought.

CONSTRUCTION PROPOSAL 3: HORIZONTAL CASTING IN ASSEMBLY-LINE

Req. 1 *Req. 2.* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *PARTIALLY* *YES*	*MODERATE*	*None*	*Low*	*Moving rings*	*FAST*	*Conventional circular wall forms*	*No*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Speed of production (within a day) - High-degree of automation possible -Smaller units allow more familiar techniques - Train bogies and optimized rail-tracks can ease pushing operations	- Unresolved placing of reinforcement - Moderate risk of cold joints - Unproven assembly-line concept - Unconventional 'wheeled' forms - High energy costs to push the molds filled with fresh concrete - Requires multiple 'Casting Stations' - Time sensitive method

METHOD STATEMENT

This proposal also relies on the concept of assembly-line and staggered production. The main difference is that this method does not require turning the molds as concrete is placed directly into horizontally assembled molds. Once a given mold is completely filled it is transferred via rails to an assembly line and interlocked with other molds.

Like the previous, this method assumes there is sufficient knowledge on setting time of concrete and that the properties of the mixture available on site are well known.

Cold joints will be avoided in a well-coordinated "assembly-line system" with staggered production. Staggered production mean several rings are produced almost simultaneously with a fixed time lag between the start of 2 consecutive casting stations. The aim is to assemble the different elements while concrete is still fresh but using a segment approach.

Segment approach is expected to allow the use of more conventional equipment and more familiar techniques saving costs. Extra time before concrete sets can be gained by periodically re-vibrating the interface of the concrete to keep it alive.

The system (forms + fresh concrete) can be placed onto a bogie or automated carriage for transport to the assembly line. Train technology could serve as a source of inspiration to design the most efficient transport scheme. Under all circumstances the casting stations should be located as close as possible to the assembly line to minimize the delay between the connection of two consecutive segments.

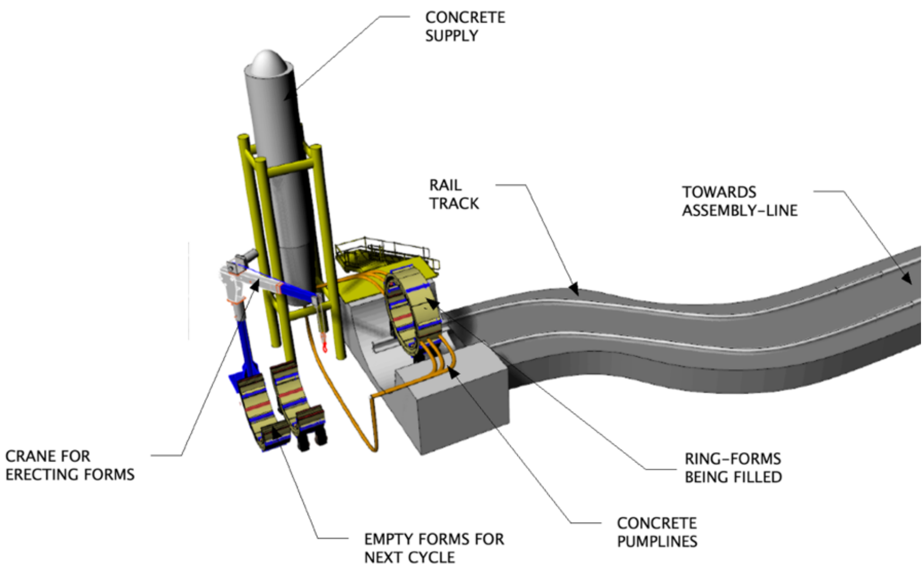


Figure 71. Elements of standards Casting Station.

OPERATIVE CYCLE

To define the operative cycle of this method, the example presented in the previous chapter will be further developed ("4. Assembly line concept- introduction to construction").

This operative cycle will focus on the construction of the floater as the tower and transition part can be produced in a similar fashion.

The cross-sectional area of the floater is $A = 19{,}65\ m^2$. The length of the floater is 120 m and the volume of the floater is therefore $2\ 358\ m^3$.

To illustrate a typical cycle of this method, molds 6-meter-long have been chosen, containing $2\ 358\ m^3/_{20} = 118\ m^3$ each.

The length of the molds is believed to be adequate for subsequent transport on train-like bogies or similar to the assembly line.

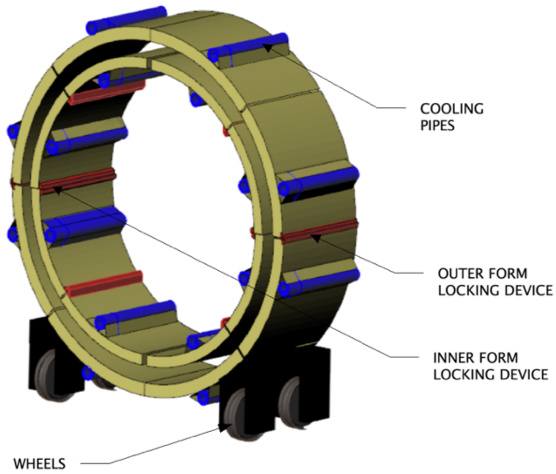


Figure 72. Standard wheeled Ring-mold composed of modular arch forms.

Note that the inner forms are supported from the outside by steel rods anchored to the outter face. These rods are not shown in the figure.

The basic parameters fort he assembly-line concept are:

- $t_{lag} = 15\ min$, is the time between the start of 2 consecutive casting stations.

- $t_{filling} = 40\ min$, using 3 pumps with $60\ {m^3}/{h}$ output.

- $t_{production} = 60\ min$, is the total time production of a 6-metre-long ring-segment including reinforcement placement and pouring $118\ m^3$ of concrete.

- $t_1 = 5\ min$, is the time taken to unfasten the filled mold from the casting station.

- $t_2 = 10\ min$,is the time it takes to prepare a casting station for a new production cycle which involves mounting the forms and preparation of the concreting equipment.

- $t_{waiting} = 15\ min$, is the time a freshly produced ring will 'wait' in the assembly line before the next ring is connected.

According to part 4. Assembly-line concept, the following 2 conditions must be satisfied.

(1)

$$(n-1) \cdot t_{lag} + t_{production} = 2 \cdot t_{production}$$

Where n is the number of casting stations. This is equivalent to imposing that the time the last station n has produced its first ring is equal to the time it takes for the first station to produce 2 rings. In this case $n = 5$.

5 stations will be used to illustrate the operative cycle.

(2)

$$t_{waiting} < t_{\text{setting concrete}}$$

$t_{\text{setting concrete}}$ depends on the following factors:

1. **Water/cement (w/c) ratio** - The setting time of cement increase with the increase of w/c ratio.

2. **Temperature and relative humidity** - The setting time of cement decreases with a rise in temperature and decrease of relative humidity.

3. **Fineness of cement** - The setting time of cement decreases with a rise in fineness of cement.

4. **Chemical composition** - Such as the presence of Gypsum a retarding agent commonly used in concrete mixes cement. Accelerators and other admixtures will also have an impact on the setting time

5. **Storage conditions** - inappropriate storage will expose cement to moisture and temperatures which will decrease the setting time.

The following table presents the expected set time for a normal concrete mix. Settting time of concrete can vary considerable and these figures should only be taken as a rough inidication on usual times that can be expected. In reality the setting time of the concrete available on site should be carefully studied and monitored.

Table 18. Approximate Set Time of concrete. Source: *(Gurley, 2010)*

TEMPERATURE (°C)	APPROXIMATE SET TIME FOR A SAMPLE MIX
37.8	*1h 40 min*
32.2	*2h 40 min*
26.7	*4h*
21.1	*6h*
15.6	*8h*
10	*10h 40 min*
4.4	*14h 40 min*

From the table above we can see that a 30 percent decrease in set time can be expected for each 5.5 °C increase in concrete temperature.

$$t_{\text{waiting}} = 15 \text{ min} \ll t_{\text{setting concrete}}$$

One can see that a short maximum allowable waiting time has been chosen to be on the safe side, well below usual concrete setting times.

To illustrate the "staggered" operative cycle a particular diagram will now be introduced.

The x-axis is the time expressed in minutes and the y-axis is the amount of m^3 of concrete poured into a given mold. Note that the slope or gradient of the curve is constant and equal to the rate of concrete placement rate, $V_{placement}$. The area underneath the curve is the volume (m^3 of concrete) corresponding to a full mold.

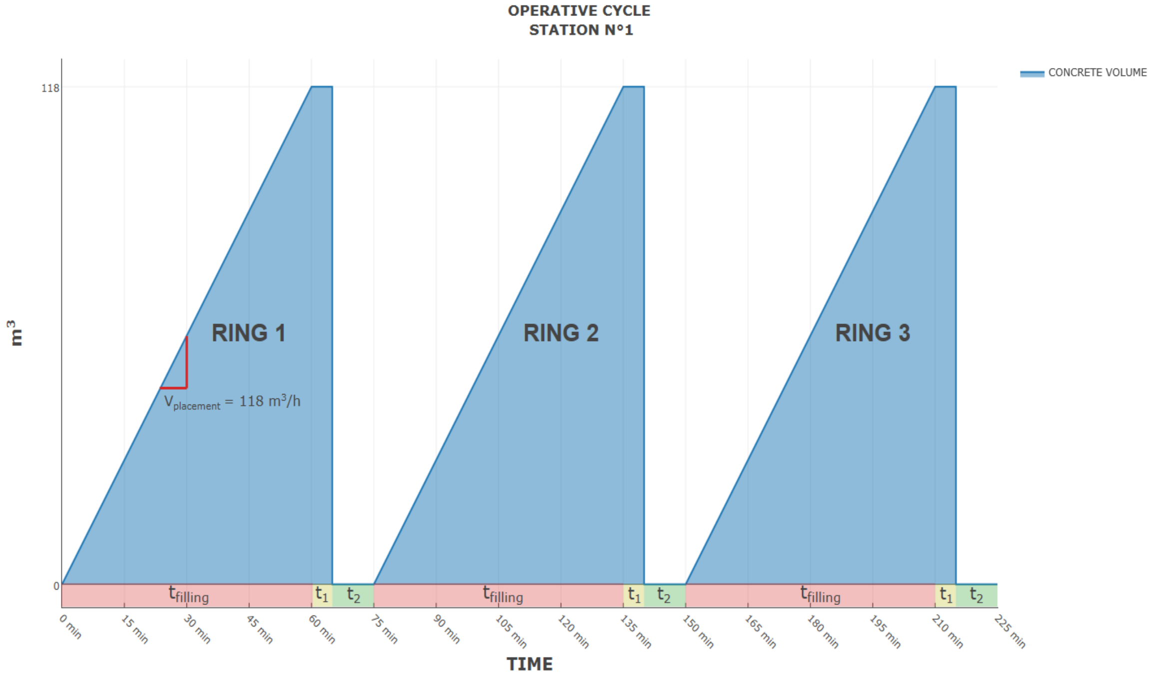


Figure 73. 3 operative cycles of Station No.1 of the assembly-line

This diagram shows 3 full operative cycles for Station No. 1 which will result in 3 completed rings in 210 min.

Here each mold has a fixed volume of 118 m^3.

$V_{placement}$ is chosen such as to completely fill a standard mold well within 60 min.

Times t_1 and t_2 are the amount of time required to 'release' the mold from the casting station and to prepare the station for a new cycle respectively. During t_1 , concrete is no longer placed inside the mold, thus the horizontal line. After $t = t_1$ the forms filled with concrete will be transported to the assembly line (not shown in the diagram) and concreting will begin again after a time $t = t_2$.

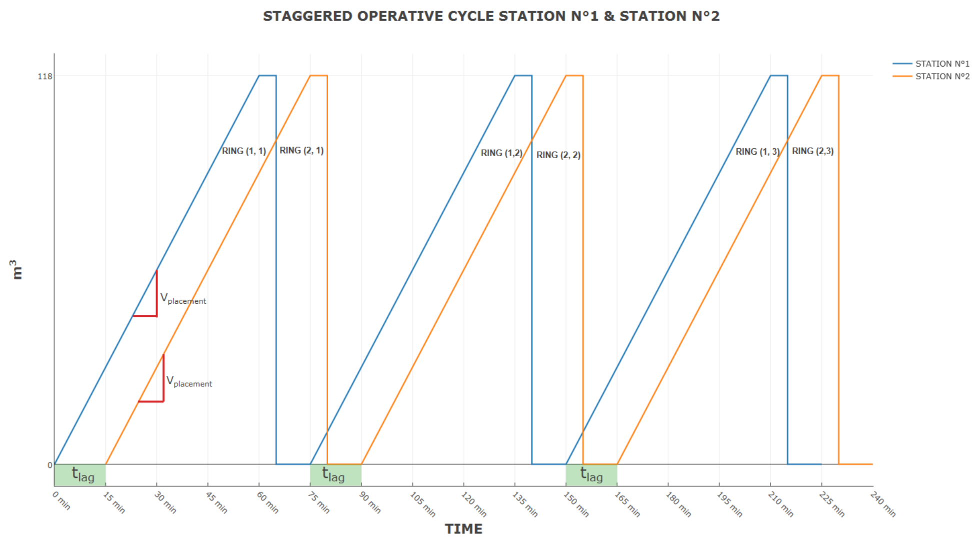


Figure 74. Staggered cycles for Station No.1 & Station No. 2.

This diagram shows 3 full cycles but this time for two stations, Station No. 1 and Station No. 2. The difference between the start of a cycle for Station No. 1 and the start of a cycle for Station n°2 is equal to $t_{lag} = 15 \text{ min}$. This time difference should be maintained throughout the entire staggered process so as to ensure a good coordination between stations.

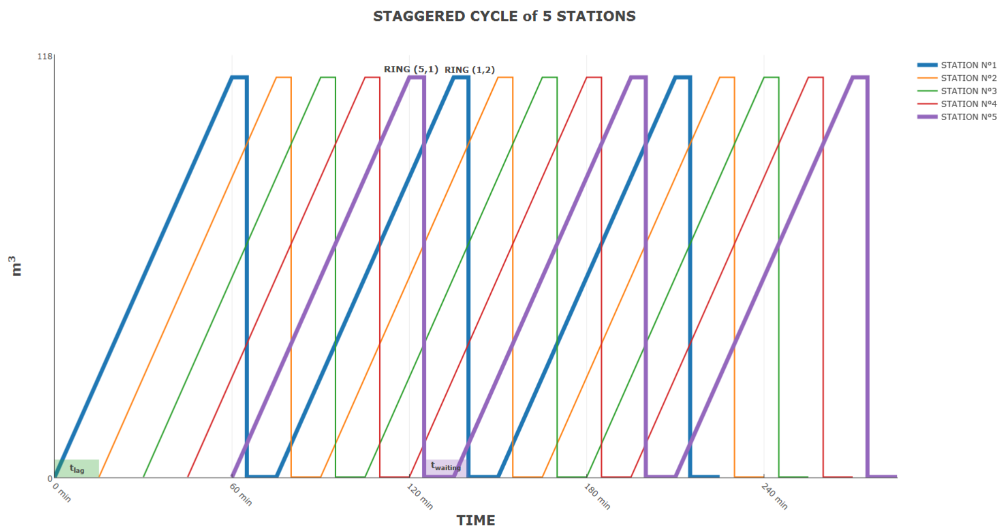


Figure 75. Staggered schedule for 5 casting stations.

Finally, this diagram hopes to show the staggered nature of the operative cycles of all 5 stations. Here only the first 3 cycles for all 5 stations are represented.

The notation Ring (# Station, # Ring) is used to indicate which ring is being produced at a given station.

The lines corresponding to the operative cycles of Station No. 1 and Station No. 5 have been shown with different thickness to point out the smooth connection between Ring (5,1) and Ring (1,2), the first ring and the second ring produced by the fifth and first station respectively.

Station No. 5 completes the filling of the ring at $t = 120 \text{ min}$ which is 'released' from the station 5 minutes later and taken to the assembly line to be connected to the previous ring produced by Station No.4.

Station No. 1 completes the filling of Ring (1,2) at $t = 135 \text{ min}$, which is then 'released' from the station and connected to Ring (5,1) in the assembly line. One can see that $t_{waiting} \approx 15 \text{ min}$, well in time before concrete in Ring (5,1) has time to harden.

Note that t_{lag} between stations is always the same for all 5 stations and should be maintained until the structure has been completed.

From the staggered schedule above one can see that in just over 120 minutes all five stations will have produced 5 complete rings.

Keeping in mind that the rings produced are 6-metre-long, to reach the entire length of the floater (120 m) 20 identical rings will need to be produced. By using the staggered operative cycle described above, this could be achieved within 8 hour.

REPRESENTATION OF ASSEMBLY-LINE

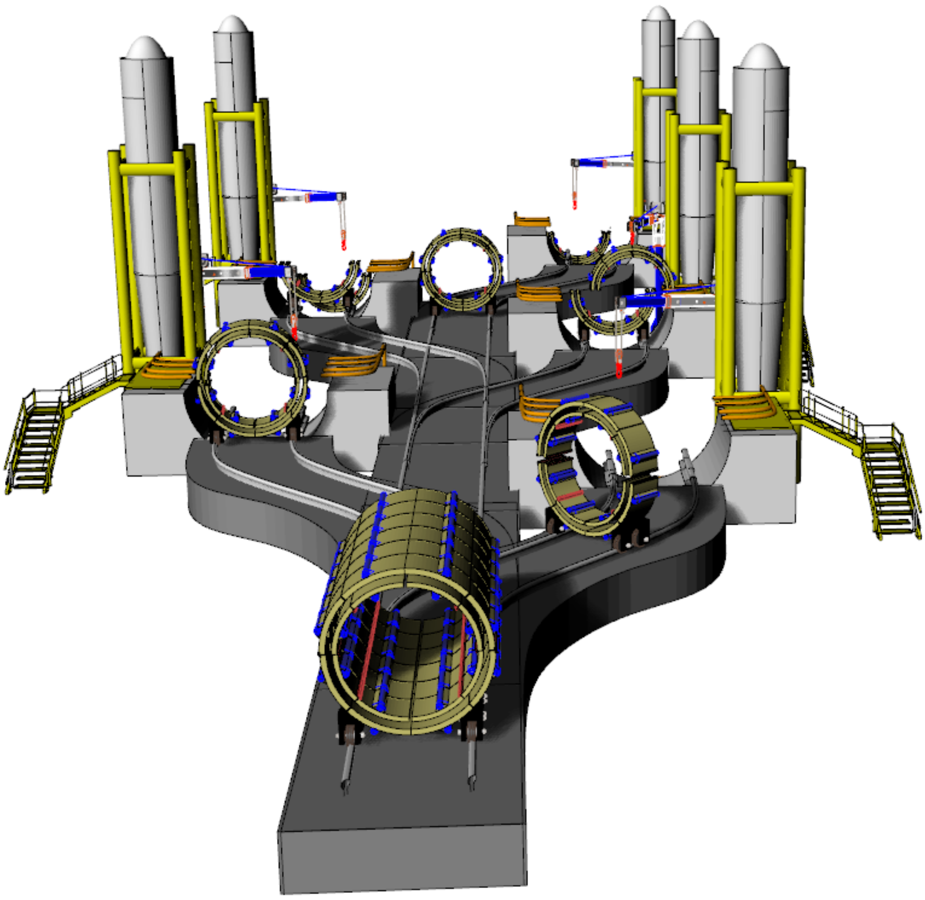


Figure 76. 3D Front view of Assembly-line with 5 Stations.

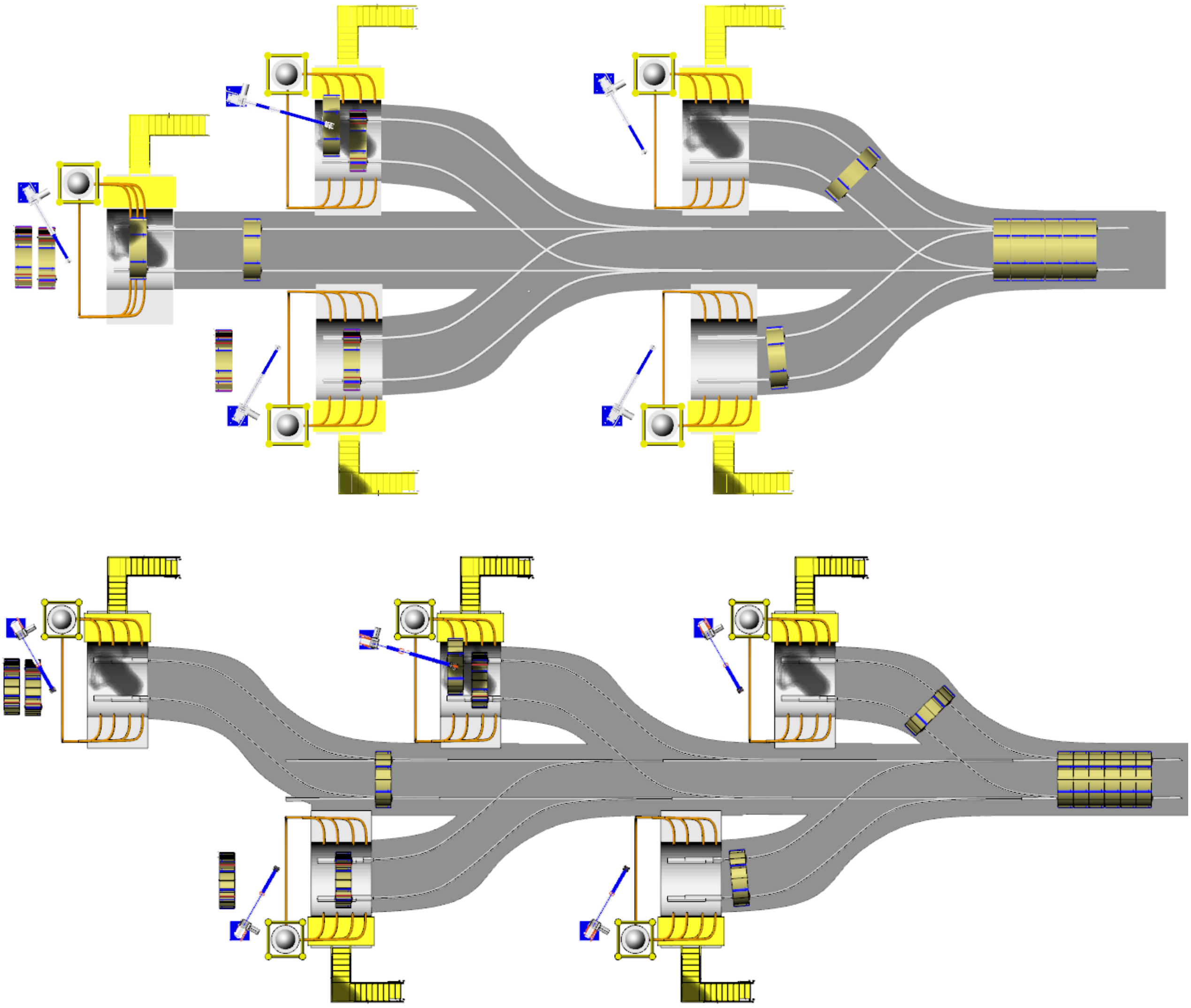


Figure 77. Top view of 2 different configurations for the assembly-line with 5 Stations.

Note that the entire length of the assembly-line has not been shown in these ilustrations. In reality, besides the rail-track connecting the casting stations to the assembly-line, sufficient space must be available to fully assemble the entire structure in horizontal position.

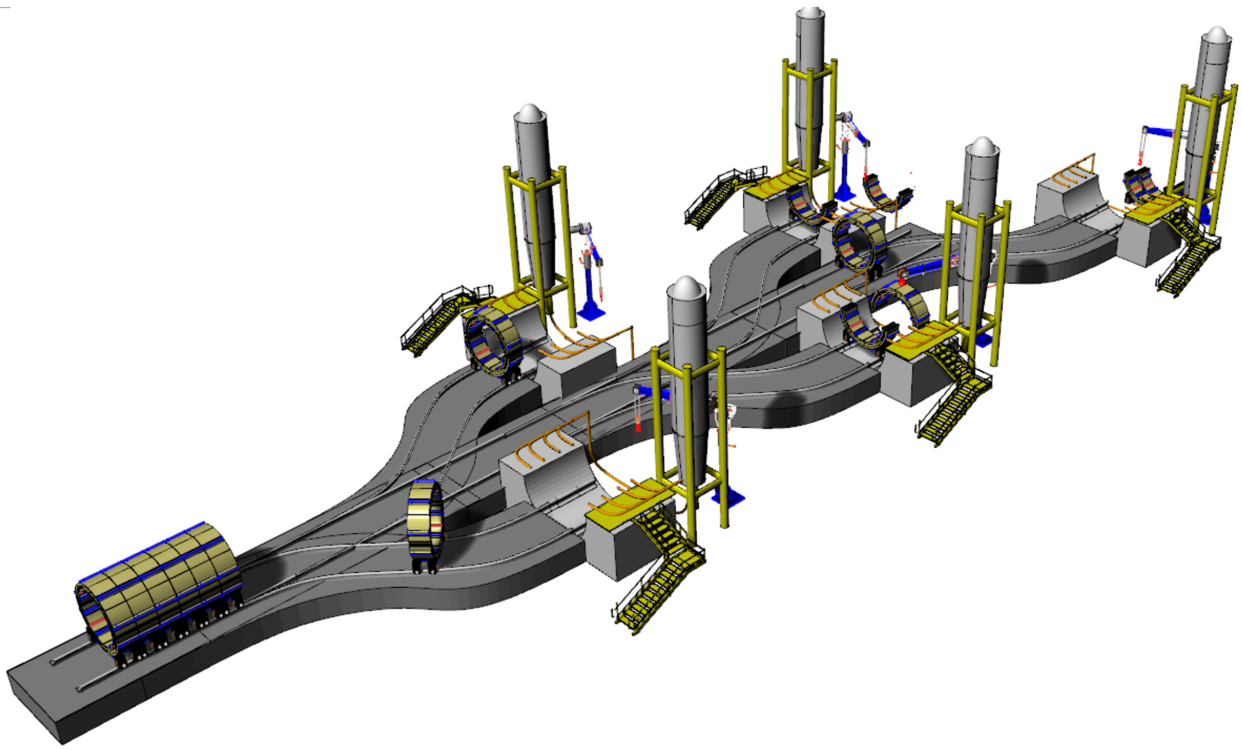


Figure 78. Bird view of Assembly-line with 5 Stations.

COMMENTS

- Whereas the risk of cold joints still remains, this method is expected to have a lower risk of cold joints than the previous assembly-line in vertical direction.

- The success of this construction proposal relies on a tight schedule which makes it extremely time sensible and requires impeccable timing and planning.

- Back-up equipment should be readily available at the work site to minimise delay on schedule if failure of a casting station occurs.

- A quick-response plan and mitigation measures should be in place to avoid propagation of delay and undermining the entire process.

- All the relevant variables $t_{lag}, t_{filling}, t_{production}, t_{waiting}, t_1$ and t_2 must be well-known in advance by accurately defining form size, placement method and distance from the castin station to the assembly line.

- The maximum allowable time before connecting two consecutive rings, $t_{waiting}$, should always be chosen according to the concrete available at the worksite and updated if necessary. A conservative estimation is recommended when deciding on $t_{waiting}$.

- Working around-the-clock calls for careful scheduling of shifts and back-up teams. Shift lengths should include the necessary breaks for workers.

- Train technology may be useful to establish a rapid transport mechanism of the molds to the assembly line.

- Given the speed of the process forms will only be used once per production cycle of a tower.

- An extra amount of concrete can be pumped at the interphases between two connecting rings to further ensure bonding.

- Re-vibrating the interface at regular intervals is also an option to minimise further the risk of cold joints.

- If constructing an assembly-line using rail-tracks is deemed uneconomical, an alternative transport method to move rings from the casting station to the assembly-line could involve the use of a boat travel lift like the one seen below with a capacity of 560 t. The shape of the boat lifter is certainly suitable to lift a ring whereas the size can easily be.

Figure 79. Cimolai Technology Spa MBH 560 - 55 boat lifter.
Source: http://www.cimolaitechnology.com/es/

CONSTRUCTION PROPOSAL 4: OPEN-CUT TUNNELING METHOD

Req. 1 *Req. 2* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *YES* *YES*	*NONE*	*None*	*Low*	*FORM HANDLING*	*SLOW*	*CAST IN-SITU TUNNEL LINNING FORMWORK*	*YES*

[1] Horizontal construction: SATISFIED.
[2] Monolithic structure: SATISFIED.
[3] Suitable for serial construction: SATISFIED.

Figure 80. Open-cut tunnelling method. Zehun Bridge, Czech Republic. Technology by Peri.
Source: https://www.peri.com/en/projects/civil-engineering/deer-crossing-bridge-zehun.html

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Proven and familiar technology - Low risk of cold joints - Little technological complexity - Constant production speed - Certain degree of automation possible - Minor adaptation of current tunnel technology required - Potencial to use commercial products from the tunnel industry	- Large amount of form handling - Time consuming - Slow process - Adding reinforcement to the design may be required to cast some bases for rail tracks aiding construction

METHOD STATEMENT

In many ways, it is the construction proposal closest to conventional practices and appears as a reliable method to achieve the desired result. It is inspired in open cut tunnel construction method, but is a simplified version as this proposal seeks to use only the simplest type of travelling formwork, a non-telescopic form traveller.

This approach considers building the structure in horizontal position by using a collapsing travelling formwork for the inner forms and modular forms for the external face erected with the help of cranes surrounding the structure. Both the inner face and the outer face forms will be connected by form ties that are adequately supported by falsework around the structure. Forms will be mainly supported from the outside but support from inside will also be necessary.

Erection of the exterior forms can either be done all at once for the entire structure before pouring of concrete begins or alternatively it can be done progressively as construction advances. The later would require a lower amount of forms as they can be re-erected more than once per production cycle, as concrete hardens and forms are stripped. This approach optimizes the amount of formwork and is the one that will be developed.

The inner forms are erected and supported by an adequate steel frame of travelling type. The traveller stays in place until concrete has hardened. Steel frames and forms will be removed when concrete is self-supporting and can be transported further ahead in the construction for re-use. This method calls for a good coordination of the activities so empty forms are always ready when reached by the concreting equipment.

This method includes almost no mechanization of formwork nor the use of a heavy traveller (see *Figure 80*). However, a smaller and lighter concreting train equipped with a high-throughput concrete distributor should be used to fill the forms. The distributor must be connected to pumplines feeding concrete uninterruptedly until the tower is complete. Additional concrete can be placed from the exterior through valves. It is estimated that the smaller rails used by this concreting train will not require any substantial modification of the structural design. In reality, construction loads should be assessed for all the stages of the operative cycle and reinforced sections added if necessary.

Figure 81. Open cut construction method: Tunnel Neumarkt project 2.2- Austria.
Source: http://www.mooser.net/startseite.html

Comments

- Too much handling results not only in longer delivery times but in an increase of costs.

- This approach may be suitable for the production of a single tower; however, frequent and excessive handling of heavy forms may make it barely ideal for a serial production.
- Abundant handling activities would govern the production cycle and lifting activities also come with persistent risk of failure.
- It does not involve any highly-specialized formwork or complex equipment which is more economical on the short term but yields poor productivity.
- If this method is to be considered for a serial production of Windcrete towers, stripping and erecting, cleaning and treating of the forms should be mechanized as much as possible.
- Optimal balance between the weight of the forms and the size and capacity of the mobilized cranes should be sought.
- Remotely controlled inner concreting trains may be considered

CONCLUSION

Downside of method is alot of erecting and stripping of formwork, inducing a lot of handling of forms. As stated earlier, when formwork basics were presented, for some structures, more time is required to erect, and remove formwork than the time to place the concrete and reinforcing steel. This should be kept in mind when designing a construction procedure for mass production.

Given the length of a Windcrete Tower, over 200 metres long, constantly installing and removing the forms could make up for a considerable amount of time of the overall production cycle. In order to speed up the placing of forms, move-on-wheels formwork should be considered. The placing and removal of forms could be somewhat optimized by mounting them on rails. The necessary falsework to support the forms should be fixed to the forms and mounted on rail tracks too in order to avoid removing the and re-erecting the falsework for each tower. This would speed up the process but the construction loads exerted by the forms may lead to a modification of structural design of the towers.

CONSTRUCTION PROPOSAL 5: HORIZONTAL CASTING IN A SEMI-FIXED MOLD - *THE BIGGEST MOULD IN HISTORY*

Req. 1 *Req. 2.* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *YES* *YES*	*NONE*	*None*	*Low*	*FIXEX-MOLD FACILITIES*	*FAST-VERY FAST*	*FIXED-MOLD + ARCH FORMS*	*NO*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(Claimed) ADVANTAGES	*(Claimed) DISADVANTAGES*
- Low execution risk - Optimal concrete placement - High quality structure results - Little technological complexity - Adjustable delivery time - Optimized un-casting process - Gantry cranes allow use of larger forms - Lower amount of forms and form handling operations - Certain degree of automation possible	- Large up-front to costs to manufacture permanent half-mold and build facilities prior to tower production - Massive (permanent) facilities - Necessarily involves production plant concept - High degree of permanency of facilities - Frequent maintenance of mold required - Requires a high demand of tower production to be feasible - No re-use of forms within the same production cycle - One-by-one production

METHOD STATEMENT

This approach could be seen as a variation of the previous, in response to the excessive handling of forms. This proposal regards formwork more as a mold than a temporary structure. It has the capacity to drastically cut down production time by simultaneous pouring concrete across the entire length of the structure, yielding highest possible throughput, surpassing productivity of slipforming methods.

The proposal is fairly straightforward and considers the construction of the tower in horizontal direction by using a hybrid formwork design, the bottom half of the cross section is a fixed-mold spanning the entire length of the structure. This bottom half fixed-mold could be embedded in a large concrete slab. The top half of the cross section are a series of removable forms that are placed and removed by gantry cranes. The top forms could be rather simple arch formwork. To reduce even more handling operations, gantry cranes could be used allowing for larger and heavier forms. The width of these arch-forms, hence the weight, will ultimately be determined by the lifting capacity of the handling equipment.

The top half arch forms could be mounted on wheels and at the surface of the concrete slab, embedded rails could guide the top forms with minimum need of gantry crane. Cranes could lift the arch forms onto the rails and a smaller pushing system could place the forms at their desired location thus minimising the number of required cranes.

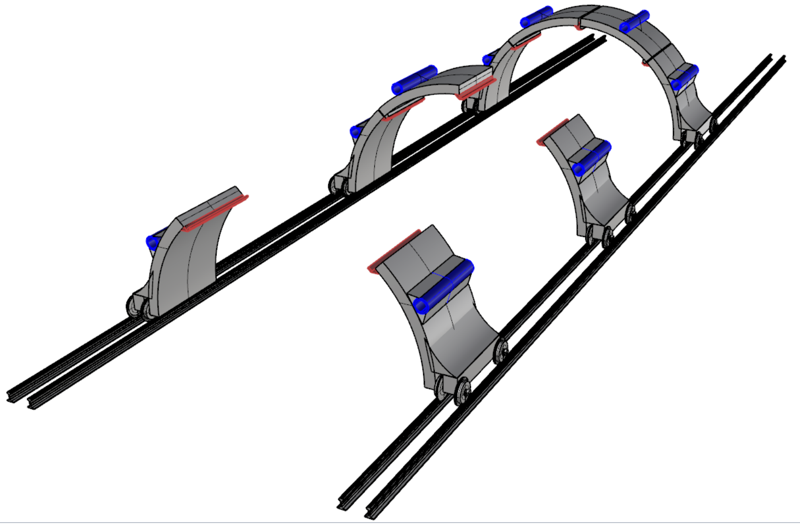


Figure 82. Modular feature of top half of the mold.

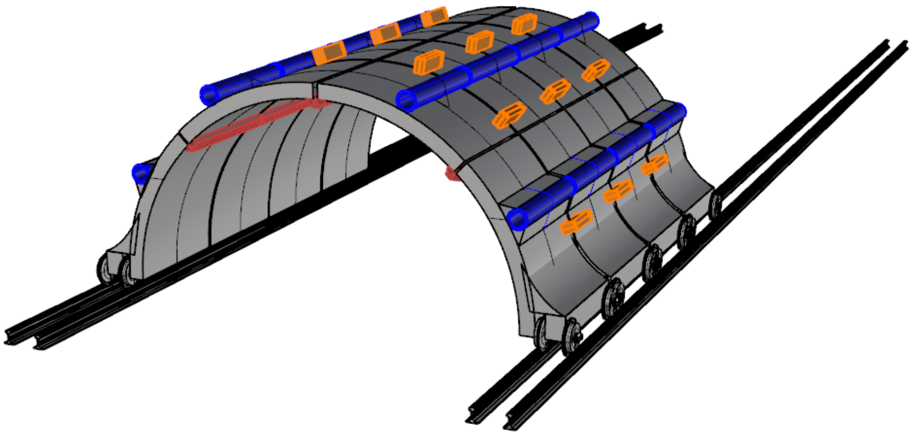


Figure 83. Top half of the mold: 4 consecutive arch forms fully connected.

The red elements are the interlocking mechanism to joint modular forms from the same arch. The orange elements represent the interlocking mechanism between two consecutive arch forms.

The blue pipes are for refrigerating purposes to keep the forms relatively cool during hydration reaction of concrete.

Operative cycle

This proposal is capable of fulfilling the main requisite of constructing a monolithical structure. Here is a brief overview of the different phases of a full operative cycle.

Inspection of the lower half of the mold and placement of release agent:

a) Placing of reinforcement.

b) Lowering of the core into the mold and placed on suitable supports.

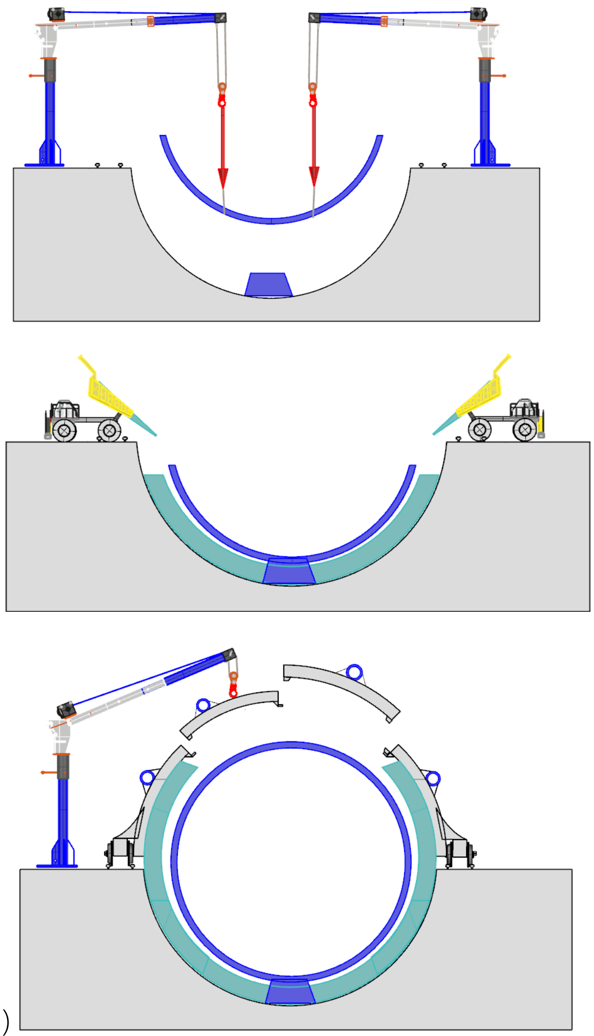
c) Casting can begin simultaneously at constant rate throughout the length of the structure. (Adjustable delivery time).

d) Gradual closing of the mold as concrete level rises. As concrete level increases, discharging trucks are replaced by pumplines

e) Forms remain in place until adequate curing of concrete.

f) Removal and cleaning of forms of the upper half of the mold.

g) Flooding of the mold to uncast the structure.'



(a), (b)

(c)

(d)

(d)
(e)

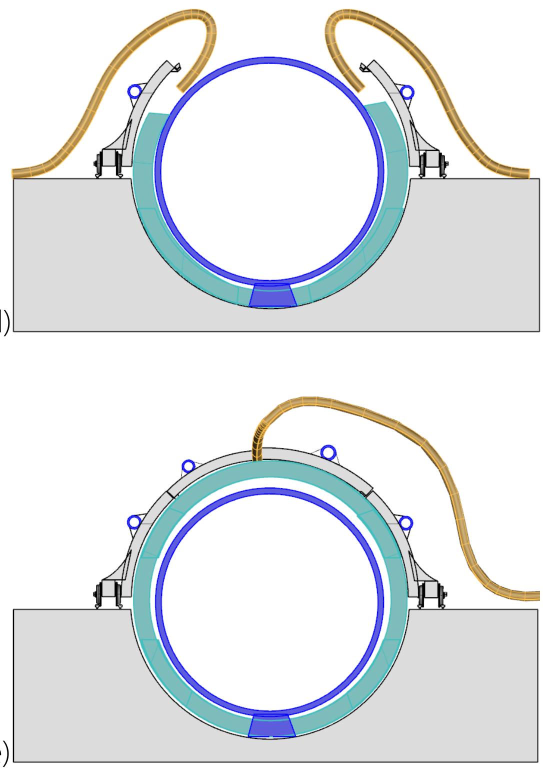


Figure 84. Operative cycle of semi-fixed mold method

REPRESENTATION OF FIXED-MOLD

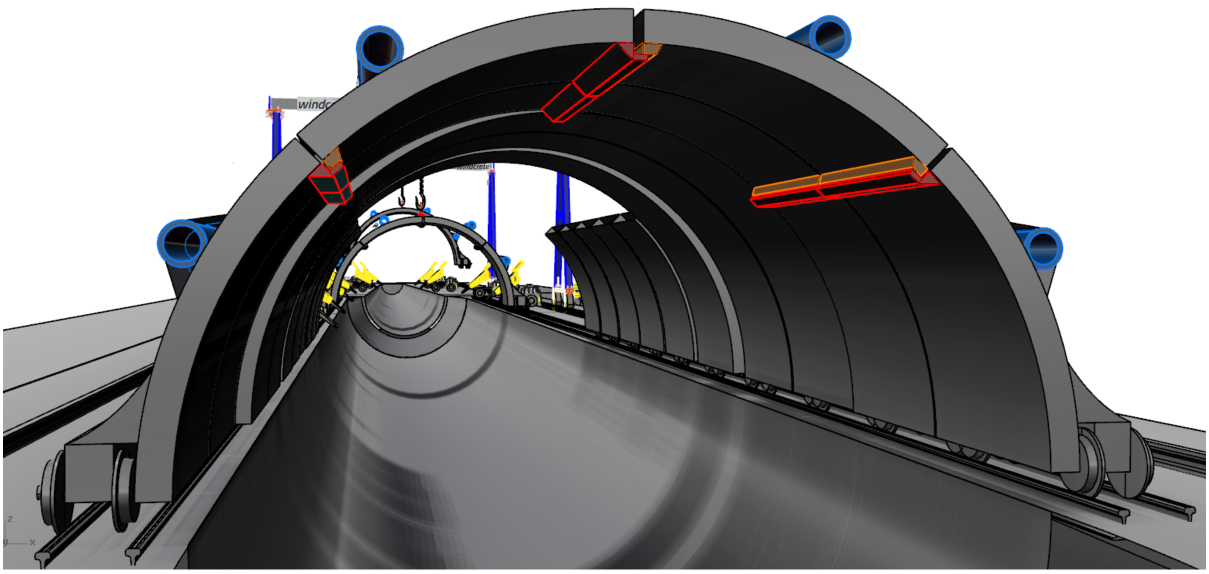


Figure 85. Inside of the semi-fixed mold.

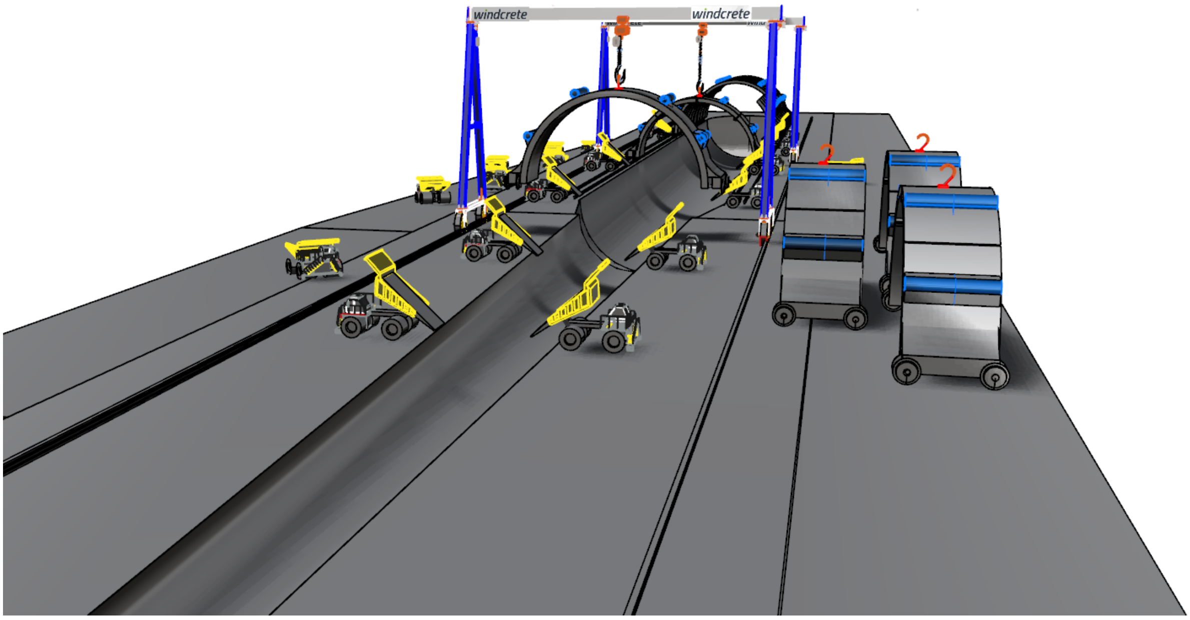


Figure 86. Birdview of fixed-mold facility with 2 gantry crane mounted on rails and dumpsters for concrete placement.

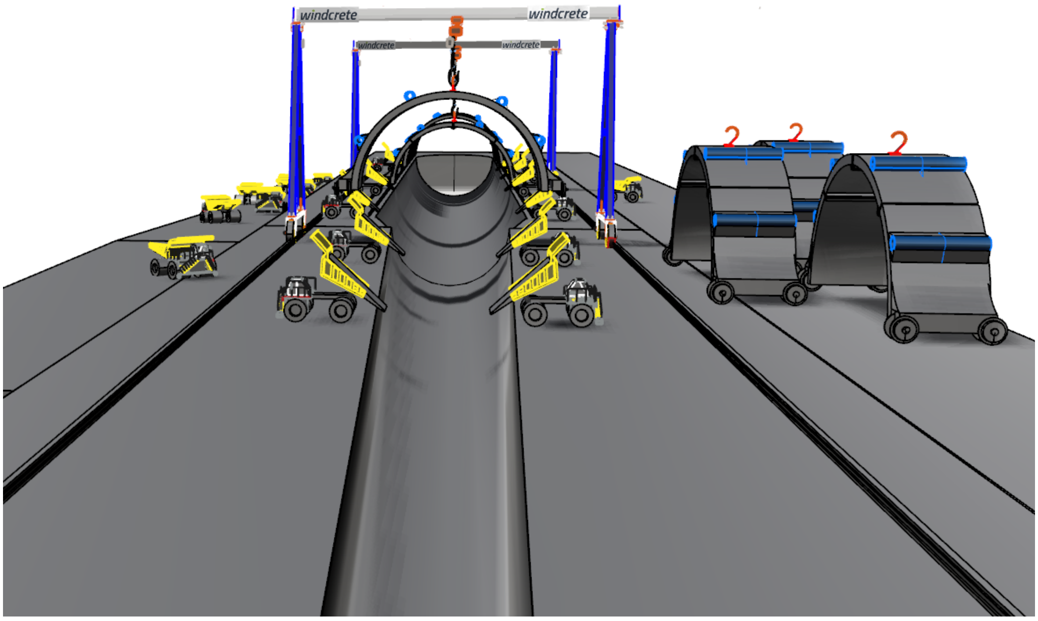


Figure 87 Initial concrete placement using dumpster trucks from diferent perspectives.

Note that the inner core and the reinforcement are not shown in the representation of the semi-fixed mold.

Comments

- Filling of the lower half of the mold can be done rapidly by directly discharging dumpster or mixing trucks resulting in highest throughput.
- Alternatively, pouring of concrete could be done through pipes distributed across the concrete slab where the mold is embedded but access and maintenance of such pipes may be difficult. Clogging of a given pipe will lead to uneven filling of the mold.

- Forms can be left in place until good curing of the concrete is achieved, resulting in high quality structures
- Refrigeration pipes must run across the entire length of the mold (across both inner and outer faces) to keep forms cool.
- Innovative solutions for the inner core may be possible like a retrievable thick rubber balloon. As the inner shape of the structure is fairly simple, a balloon could be inflated to give the desired shape to the structure and once completed, subsequently deflated and retrieved through the top opening.
- Un-casting system is particularly interesting for this construction proposal and will be developed bellow.

OPTIMIZED UN-CASTING PROCEDURE

One of the claimed advantages of this proposal is the relative ease in which finished tower can be un-casted. Up until now, the uncasting phase has not been addressed. In fact, each of the proposed construction procedures should include details on the uncasting process once the concrete structure has been completed and is ready for towing. The finished Windcrete Tower is massive and extremely heavy, using cranes to lift the structure out of the mold or formwork is close to insurmountable. Instead, this proposal (and all of the proposals for that matter) should make use of a dry dock, as water pressure can effortlessly float the structure.

What makes the semi-fixed, half-mold approach particularly interesting with regard to the uncasting stage is that the fixed installations could serve both as a permanent mold and a drydock at the same time.

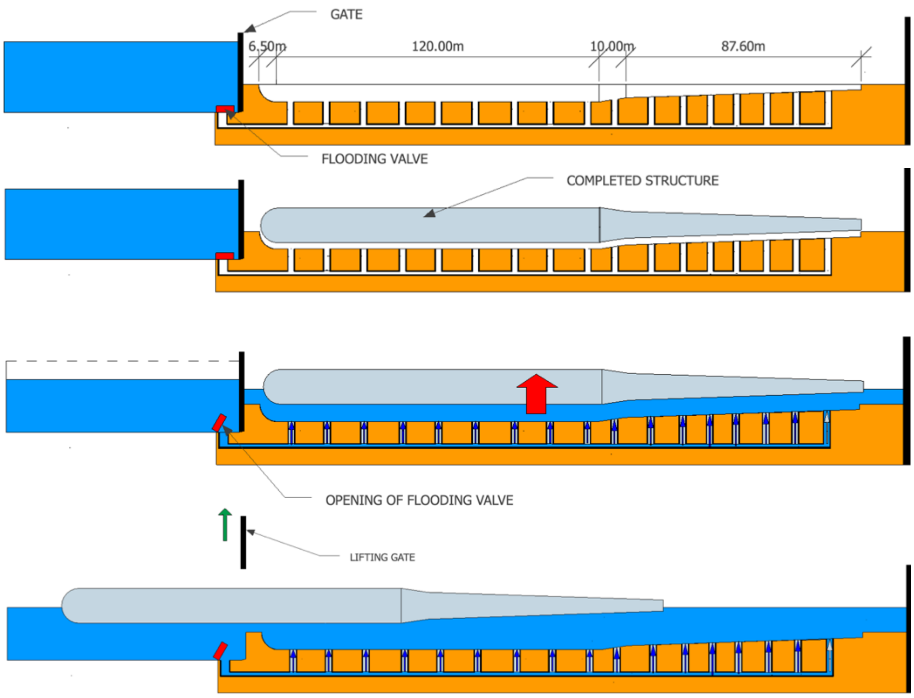


Figure 88.Optimized un-casting procedure

To reduce the time required to pump out the water once the dry-dock has been flooded, it would be sensible to minimise the size of the actual dry-dock, which ideally would be the smallest allowable volume that, once submerged, is sufficient to make the structure float. Further research would help in determining the optimal depth of this dry-dock.

By strategically equipping the lower part of the mold with openings, sea-water could be allowed to enter the mold creating an upwards water pressure. With a sufficient amount of water, uplift force could make the structure float. A valve, or a system of several valves could be provided, which can be opened to fill up the lower half of the mold. A gate at either end of the structure could then be opened and the structure floated out.

INFLATABLE MOLD CONCEPT

Figure 89. Inflatable Rubber Balloon Formwork for Culvert (900 mm diameter) manufactured by Qingdao Aorunda Rubber Industry

High quality rubber and fabric are used to produce these inflatable forms. They are used to create the cavity of culverts, concrete pipes or small bridge precast beams. This particularity of this kind of cylinder bag, is that it can expand and shrink, and offers a variety of shapes like a rectangle, octagon, hexagon or trapezoidal.

Manufacturers claim they are easy to use, economic and durable.

If such a form was employed for the inner core of the Windcrete towers it could save materials. Also, a considerable amount of labour could be saved as there would be no need to a manufacture a rigid core and would avoid the slow process of lowering this rigid core down into the mold.

CONCEPT OF A PRODUCTION FACTORY

This approach implies building a permanent half-mold at a certain location. Fixed assets are capitalized solely when they increase capacity or productivity.

The question whether we want to produce a single tower or a serial production in a fabrication plant must be addressed at an early stage, as was mentioned earlier. For this approach, it becomes even more relevant. A serial production will need a factory and large upfront costs. It should be noted that this particular kind of factory has a high degree of permanency.

If this approach was to be further developed for the commercial production of Windcrete Towers, the geographic location to construct the permanent mold should be chosen carefully.

As the possibility to tow towers produced at this facility is one of the main advantages of FOWT, this factory could serve a greater region. The size of the region it could serve would have to be analysed by estimating the maximum economic distance to tow produced towers.

Logically this Factory would have to be located in a shipyard with certain facilities and requirements (dry dock, minimum draught and near-by concrete suppliers) which may restrict the location to a certain extent. It is also very important to select the location based on market analysis and the potential future demand of Windcrete Towers. A market study, together with the most suitable dry dock facilities will yield the optimal location of such a factory. Proximity to international waters will allow easy export to the main European players.

For a fixed factory producing towers for a greater region, this construction proposal may be economical but if it is placed in a region with little demand, disassembling and transporting the mould elements may be an issue.

Another interesting factor is that by reducing the degree of permanency of the installations (subdivide the permanent mold into smaller pieces), this factory could be disassembled easier and directly shipped to a new location. Factory could efficiently be relocated without making use of roads, which in turns allows larger components.

Conclusions

High upfront capital costs involved as large investment required for facilities prior to the start of tower production. Yet if a high demand of towers is expected, large investment may be justified. Only if the goal is to produce a large number is this proposal estimated to be feasible.

Permanent mold is expensive to build but could be re-used extensively (justifying the need for high quality steel) if regular maintenance operations are carried out. Maintenance operations should be mechanized. These should include periodic cleaning and surface treatment. Rusting of the mold must be avoided at all costs. Features like a mold that serves as a dry-dock and using rubber forms for the inner core provide interesting options for cost-reductions that should be further looked into.

CONSTRUCTION PROPOSAL 6: FIXED JACKING SYSTEM

Req. 1 *Req. 2* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *YES* *YES*	*LOW*	*HIGH*	*Low*	*JACKING SYSTEM*	*FAST*	*ARCH FORMS WITH WHEELS*	*NO*

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Highly industrialized process - Seemingly reliable - Quick delivery time - High degree of automation possible - Use experience from trenchless technology	- High to very high jacking forces involved - Some technological complexity - Large up-front costs to design and build jacking-station and Concrete Eye - High-loads on form panels, buckling and damage. Early replacement of forms

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

METHOD STATEMENT

This method is based on adaptation of microtunnelling techniques. Instead of using hydraulic jacks to push precast concrete segments into the soil, a circular arrangement of jacks will launch previously filled molds into a reception lane. Forms interlock so action force of jacks can be transmitted throughout the system.

This method considers the construction of the tower by extruding its cross-section in a seemingly continuous way. The particularity of this method is that all the concreting operations are located at a single location that remains fixed during the entire construction process. This proposal does therefore not require any sort of self-propelled travelling formwork. Instead it is the actual structure of the tower that is pushed away from the concreting front as construction progresses. The fixed casting station, which concentrates most of the concrete placing equipment, will be referred to as the 'Concrete Eye' and is an essential element to this proposal

Concrete Eye

The concrete eye is a permanent reinforced concrete structure fixed firmly to the ground (shallow or deep foundations, depending on soil characteristics). The shape of the concrete eye is that of a ring and its inner diameter should approximately be 13.5-14m. The dimensions of the concrete eye are such that it can accommodate a fully mounted section of forms inside it. As the widest cross-section will be equal to 13 m (external diameter of the floater), the diameter of the concrete eye will necessarily be larger as it should account for the thickness of the forms. The concrete eye will play a similar role to the soil-shaft interphase found in microtunnelling. That is, the hole through which the pre-fabricated rings are introduced and subsequently pushed. However, in this proposal, the Concrete Eye will have an additional function which is the filling of the forms (Windcrete does not involve prefabricated rings). The forms inside the eye will be filled in-situ from the exterior through an arrangement of pumps that will be activated in ascending order. The exterior forms panels of the structure will be equipped with valves and the surface of the reinforced Concrete Eye will therefore have to include holes that match these valves in the form panels.

This concreting eye should be sufficiently long to allow several empty ring-molds to be introduced one after the other. The Concrete Eye should at least be long enough to accommodate 2 consecutive ring molds.

This concrete eye will also support all the necessary equipment for convenient filling of the forms. Concrete must be fed continuously to the pouring system.

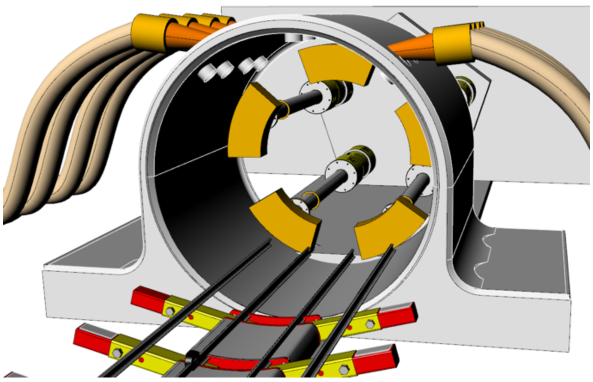


Figure 90. Concrete Eye (grey) wth circular arrangement of hydraulic jacks i

This concrete eye is perhaps the most innovative feature of the fixed casting station. The casting station also contains a system of hydraulic jacks, a pressure-ring and a reaction wall, similar to the jacking station shaft used in micro tunnelling.

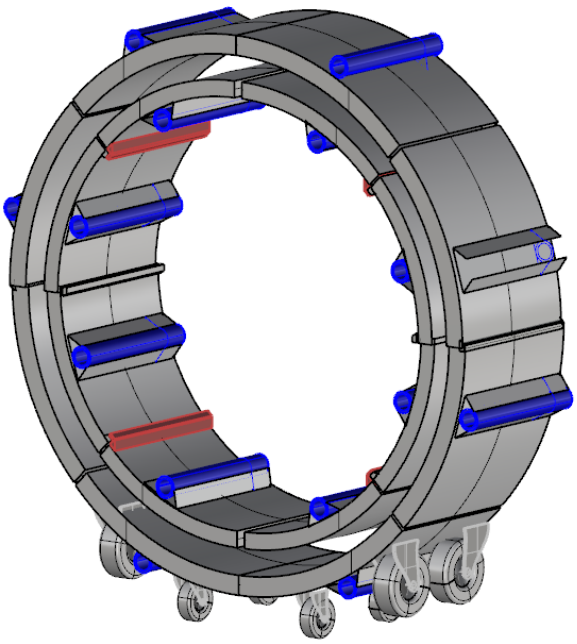


Figure 91. Lower part of the forms are equipped with wheels that match the rails inside the Concrete eye and the launching lane

Jacking-system

Jacking-system is arranged in a circle. This proposal should include an adjustable pressure ring with a diameter that can be calibrated to the varying cross section of the Windcrete Towers. Therefore, not only will this proposal require different molds corresponding to different cross sections of the tower, the hydraulic jacks will also need to be adjustable to correctly push these different sized molds.

Figure 92. Synchronous hydraulic lifting system to lift a 3500 tons mining dragline in Australia. Engineered by Enerpac.

Even if the intended purpose of this hydraulic jacking system is completely different, the circular arrangement and the scale is similar. The image allows us to grasp the possibilities with regard to size and capability of jacking-systems.

OPERATIVE CYCLE

The idea is that empty forms are pre-assembled (creating an empty ring-mold) and placed inside the concreting eye. For simplicity, here a Concrete Eye capable of accommodating to consecutive ring-molds is considered.

(a) Ring-mold #1 is assembled and introduced and pushed to the opposite face of the concrete Eye. Struts should be provided within the core of the mold to support construction loads.

(b) Ring-mold #2 is assembled and introduced into the Concrete Eye, and fastened to Ring-mold #1.

(c) Ring-mold #1 (the furthest from the jacking cylinders) is gradually filled with concrete until completely filled.

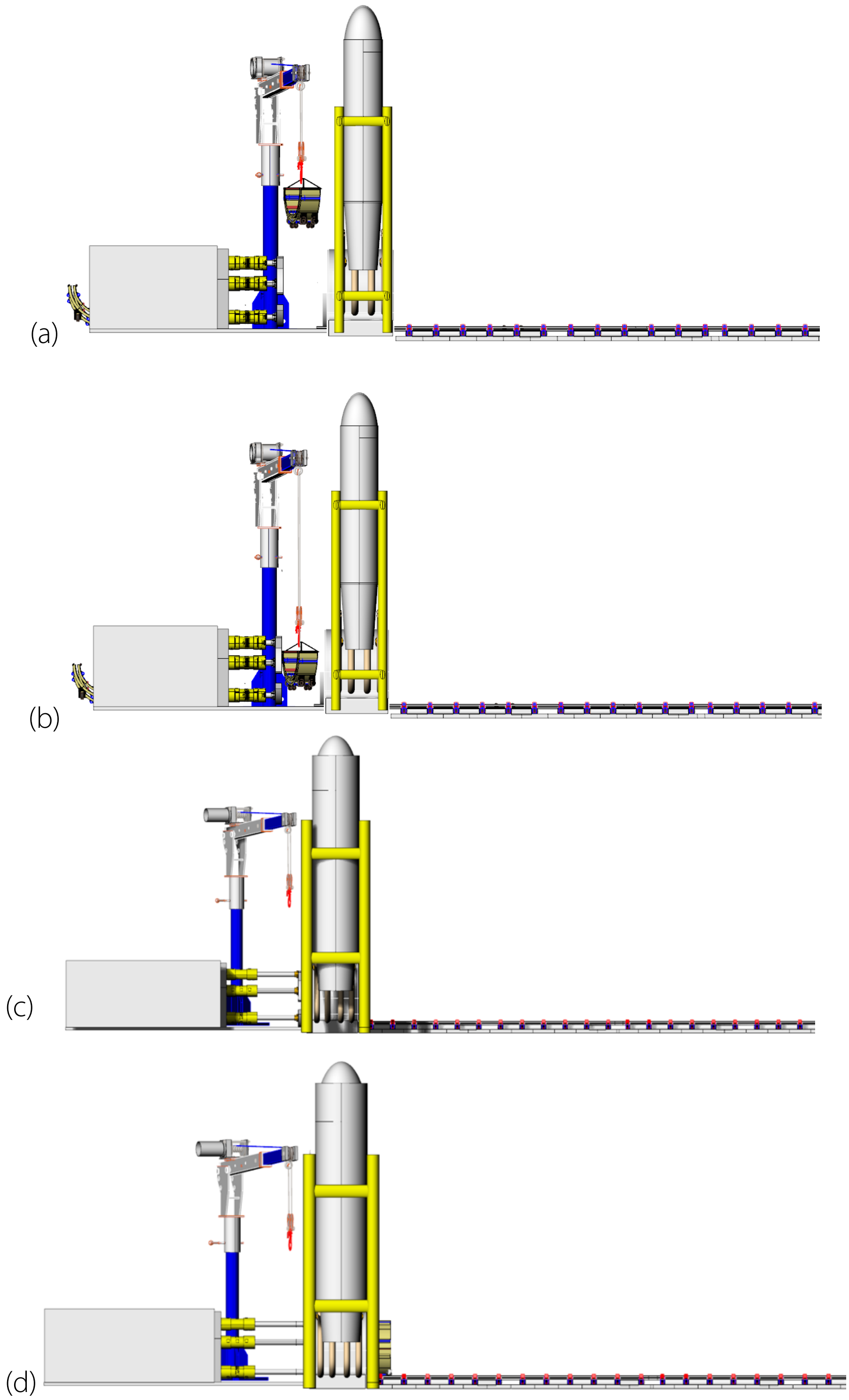
(d) Hydraulic jacks push on Ring-mold #2, which in turn pushes Ring-mold #1 out of the Concrete Eye and onto a reception lane.

(e) Ring-mold #2 reaches the former position of Ring-mold #1 within the Concrete Eye and filling of Ring-mold #2 begins immediately

- Meanwhile, hydraulic jacks retract making a gap for Ring-mold #3 to be placed in the concreting eye.

(f) During filling of Ring-mold #2, Ring-mold #3 must be assembled and conected to Ring-mold #2.

(g) When Ring-mold #2 is completely filled, hydraulic jacks push it onto the reception lane and filling of Ring-mold #3 begins.



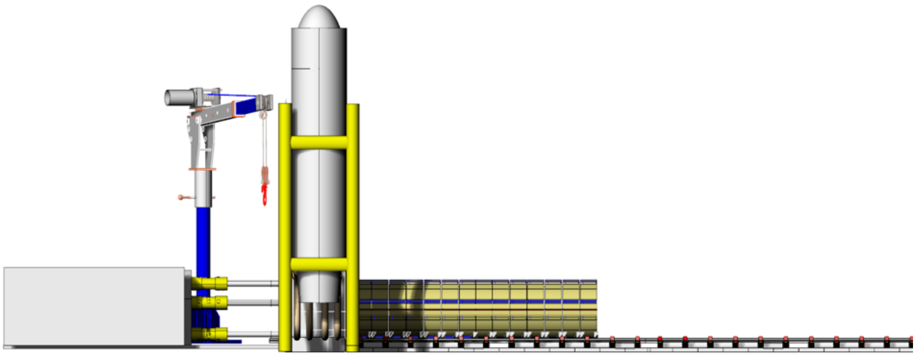


Figure 93.Operative cycle of fixed-jacking station.

Comments

- To efficiently 'extrude' rings-molds through the concrete eye, a rail or similar must be provided inside the concrete eye. The rail system should extend smoothly to the so-called reception lane. All the ring molds that will be used in this system should have the ability to slide on rails. The lower part of a standard ring-mold should therefore be made out of panels equipped with wheels.

- Jacks-will need to gradually apply more force to extrude the rings as the structure lengthens. The jacks must push not only on the molds placed within the Concrete Eye, but also on all the subsequent rings previously launched onto the reception lane.

- The highest-jacking force will presumably be realised at the end of the process when the almost entire structure has to be pushed. This fully justifies the use of a rail-like system to aid the jacking-system in moving the structure.

- If the required jacking-force is too large, additional mechanized systems could help in moving the structure. This mechanized system would have to transmit the exact same speed as the jacking system to avoid uneven movement or jerks.

- The molds should be designed to interlock with each other thus providing continuity of the mold and transmitting the jacking-force from one to another.

- The reception lane must be smoothly in line with concrete ring so 'extruded' rings can swiftly slide onto the lane with no bumps or jumps. Alignment and stability of the facilities is crucial, settlements could undermine the whole process. Ground improvement should be considered where necessary.

- The configuration of the system should be such that even during the jacking operation there would be no need to stop the concrete pouring avoiding any joints.

- Pouring-rate should be such that two entire rings can be completely filled with concrete, one after the other before the first of the two has reached setting time.

- Before filling of Ring-mold #n is complete, Ring-mold #n+1 must be fully assembled and locked to the previous ring

- An extra amount of concrete may be pumped at the interphases between two connecting rings to further ensure bonding. This additional concrete can be conveniently placed once the rings are in the reception lane.

PRELIMINARY DESIGN OF JACKING STATION

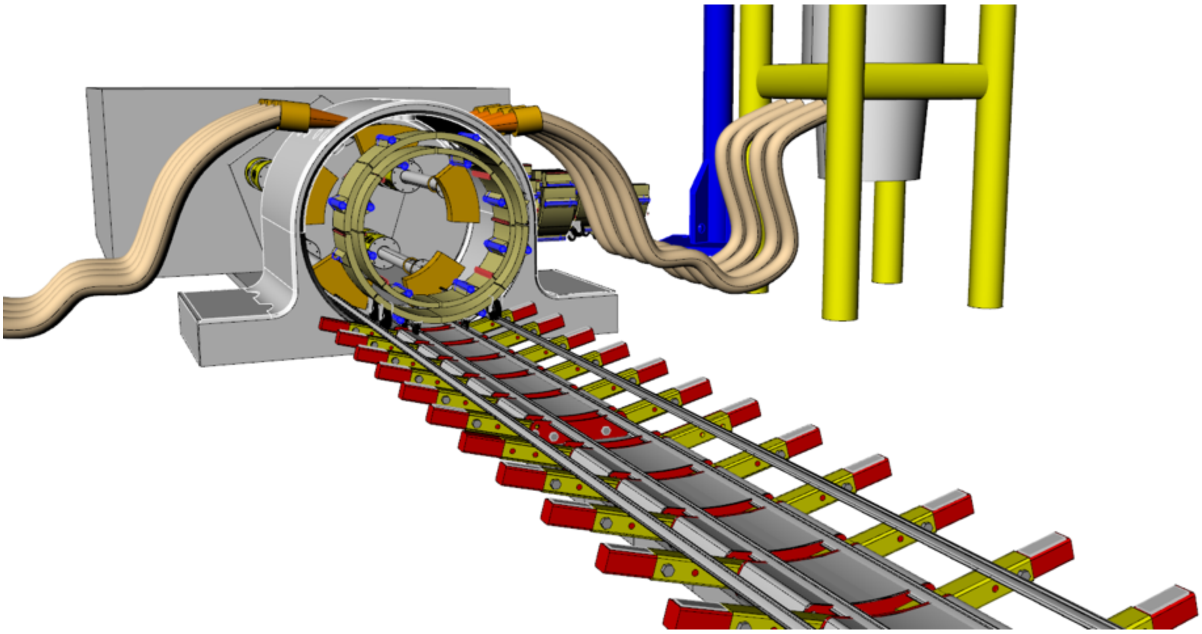


Figure 94.3D view of the assembly line with a wheeled form.

Behind the concrete eye is the reaction wall for jacks to push on. Located in front is the launching lane equipped with rails that strategically fit the wheels of the forms.

At both sides of the concreye eye, pumps (pale orange) inject concrete through valves in the forms matching holes in the concreye eye. Concrete silos are located at either side to show that feeding of concrete must be continuous.

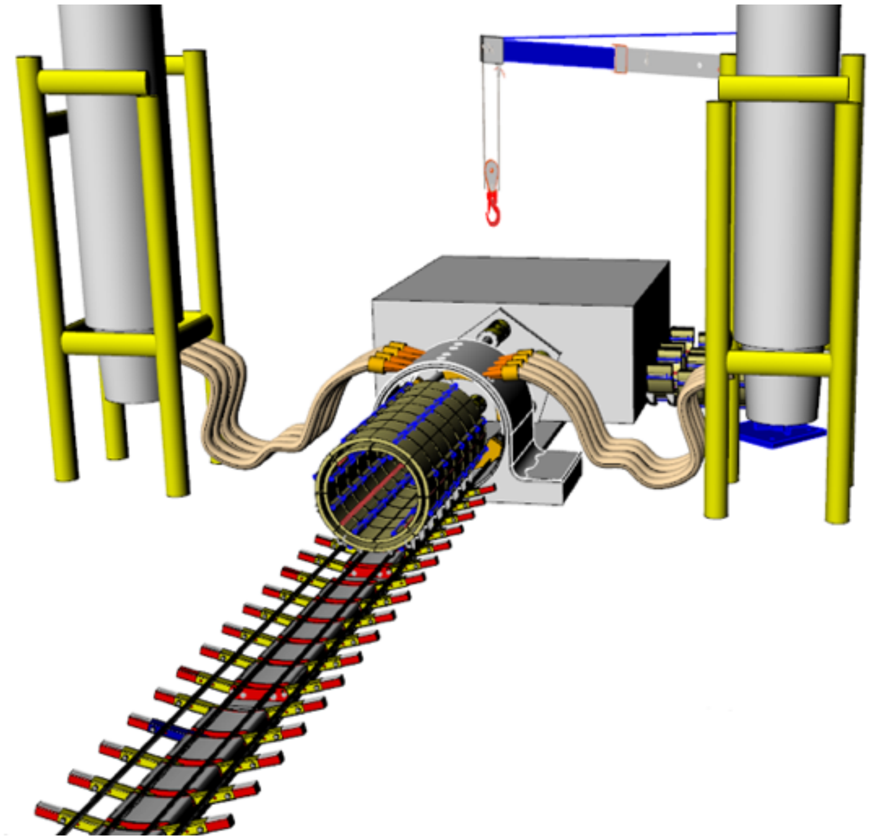


Figure 95. Front view of the fixed-jacking station

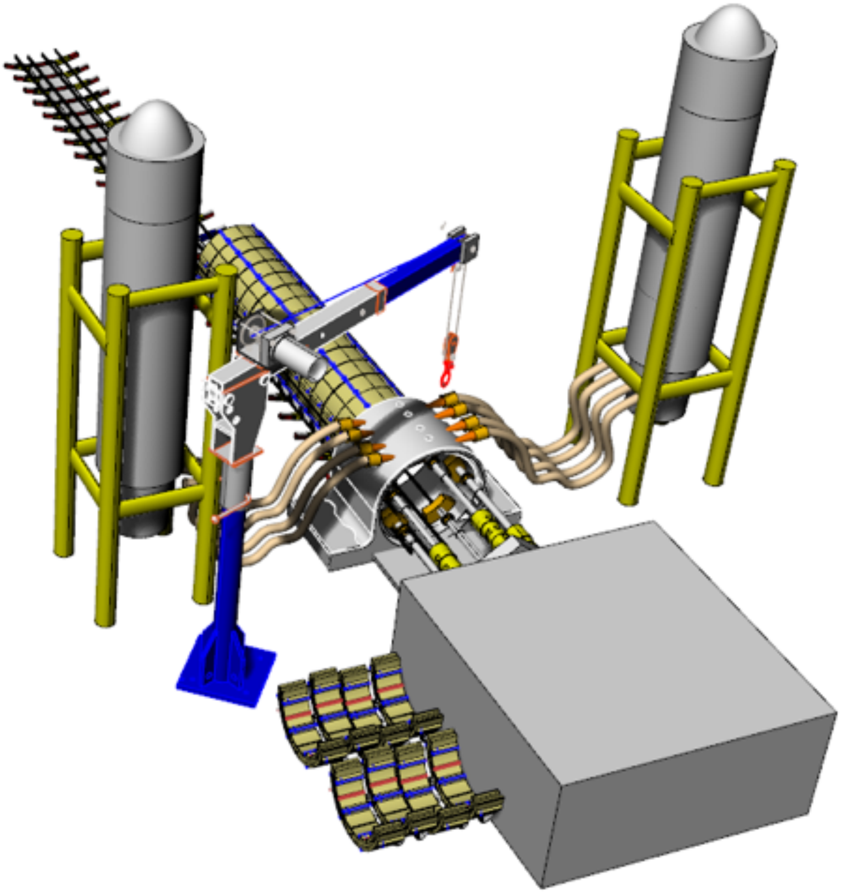


Figure 96. Rear view of the fixed jacking station

CONSTRUCTION PROPOSAL 7: SELF-ADVANCING TELESCOPIC TRAVELLING FORMWORK SYSTEM

Req. 1 Req. 2 Req. 3	**execution risk (joints)**	**innovation degree**	**techn. complexity**	**main cost driver**	**production time**	**formwork type**	**design modifications**
YES	*LOW*	*MODERATE*	*Low*	*TRAVELLING FORMWORK*	*FAST*	*TELESCOPIC FORMS ON TRAVELLING SYSTEM*	*NO*
YES							
YES							

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Highly-automated process - Seemingly reliable - Quick delivery time - Use experience from cast in-situ tunnel lining technology - Requires minimum manned machinery to strip forms - Reduces cranes on site	- Modify structural design of Windcrete to account for construction loads exerted by the travelling formwork system - Involves highly-specialized travelling formwork - Complex form design - Large up-front costs to design and build traveller - Long traveller may be required - Inner rail track must always be practicable to pass through.

METHOD STATEMENT

This method will use an automated system of telescopic forms similar to those used for cast-in situ tunnel lining.

Put simply, formwork will be in the form of a series of rings mounted on a carriage, designed so that, once the concrete has achieved sufficient strength, the first ring that was filled with concrete (located at the rear of the carriage) can be collapsed and passed through the remaining rings where concrete is still hardening/curing to the front of the carriage for the next pour. Forms will be equipped with hydraulic jacks with the ability to collapse. The formwork must be sufficiently long, or the placement rate sufficiently slow, so as to allow concrete to harden at the back of the carriage while fresh concrete is being placed at the front. Before the latest forms are completely filled, the forms at the rear of the carriage must ready to collapse and move to the front.

If this requires an unreasonably long carriage, additional separate forms can be made available, and simply placed on top of the structure before the previous section is filled. These telescoping arch forms would allow the continuous advancing of the carriage while pouring never stops even if the forms are placed in discrete steps. The formwork will be mounted on self-propelled carriage that moves on rails placed within the structure to be built. Suitable supports would have to be provided from within to sustain the weight of the traveling formwork.

Concreting equipment will mainly pour from the inside and can be mounted on the carriage itself. Additional concrete can be placed from the outside if deemed necessary.

Deploying such a carriage will induce high loads during construction due to weight and dynamic loads. These should be anticipated in the structural design of the tower by adding reinforcement where required. The travelling formwork will move backwards as construction progresses.

For the inner part, a slight modification of conventional telescoping formwork for tunnelling is necessary. This modification simply involves feeding extra forms at the casting front so concreting can go on rather than waiting for previous sections to be dry. Therefore, a combination of detachable telescoping forms seems like a suitable solution. Detachable here means that, while forms will still have the ability to telescope, they are not fixed to the travelling system, but can be individually introduced at the front of the carriage by a crane or similar.

The other modification is that the arch forms must allow for a continuous cross-section to be poured with no cross-sectional joints.

By providing a sufficient number of these detachable telescoping forms, this method will allow the continuous placing of the concrete.

COMMENTS

Once the concrete placed in the forms can hold itself to a satisfactory degree, the corresponding sections can be successively stripped or collapsed and telescoped through other sections and re-erected. To achieve this the service rail must always be practicable to pass through.

An optimized procedure will replace the actual carriage by a simple sliding beam for forms to move along. Prior to construction of the structure, suitable columns will have to be placed to support this sliding beam. Once that particular section has been completed column and sliding beam can be removed and place further ahead.

CONSTRUCTION PROPOSAL 8: SELF-ADVANCING 'CANTILEVER CARRIAGE' SYSTEM

Req.1 Req. 2 Req. 3	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES	*LOW*	*HIGH*	*Low*	*CANTILEVER TRAVELLING FORMWORK*	*FAST*	*TELESCOPIC FORMS ON TRAVELLING SYSTEM*	*NO*
YES							
YES							

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- 'Minor' adaptations on formwork for tunnelling - Seemingly reliable - Quick delivery time - Use experience from cast in-situ tunnel lining technology	- Involves highly-specialized travelling formwork - Complex form design - Large up-front costs to design and build traveller - Buckling of struts

METHOD STATEMENT

This method is similar to the previous. The main difference is that it makes no use of a conventional telescopic tunnel formwork to place the forms, instead it involves the previously mentioned cantilever carriage that is able to provide support for forms while it slides on rails that are placed strategically outside the concreting section. To further understand the reasoning that led to the concept of cantilever carriage see **APPENDIX 2- CONSIDERATIONS ON ADAPTING TUNNEL FORMWORK.**
A full circular cross-section can be achieved by placing the invert after the subsequent backwards sliding of the traveller. Thus, the rails used by the carriage do not interfere with the structure being constructed. The traveller itself does not carry the forms as it moves, instead it is designed to temporarily support the forms while concreting takes place. Auxiliary supports will gradually be put in place as the traveller moves.

The cantilever carriage, equipped with heavy counterweights to counteract the weight of the concrete, will move at a constant speed. As the traveller moves slowly backwards, the weight of the fresh concrete will be transferred to a series of hydraulic struts or another convenient support system put in place by operators. When all the concrete for a given section is placed, the traveller is gradually substituted by hydraulic struts (or other support system) so the traveller can move to the next section. Timing will be important as these two activities will require a good coordination Forms can remain in place while concrete cures thanks to these hydraulic struts.

This method allows re-stripping of the forms once concrete has attained desired strength and launching them to the front of the process for new filling.

It should ideally present all the benefits of vertical slip-forming but applied in the horizontal direction, that is continuous pouring of concrete and a fully circular hollow section. The main difference with slipforming is that in this case, the self-propelled carriage does advance at constant speed but forms are placed at discrete steps.
The speed of the travelling formwork system should be carefully chosen and not only based on the concrete pouring rate. Another important factor influencing the travelling speed is the required time for the concrete to harden so the forms can be stripped, transported to the front of the carriage and re-used for the production of the same tower. The operation should be timed such that the rear form unit is ready to be stripped when it is needed at the front of the advancing carriage. If the casting and travelling speed is low enough, more forms can be re-used per production cycle and overall less forms will be required reducing costs.

This method will also use similar techniques as open-cut tunnelling for the exterior part of the mold.

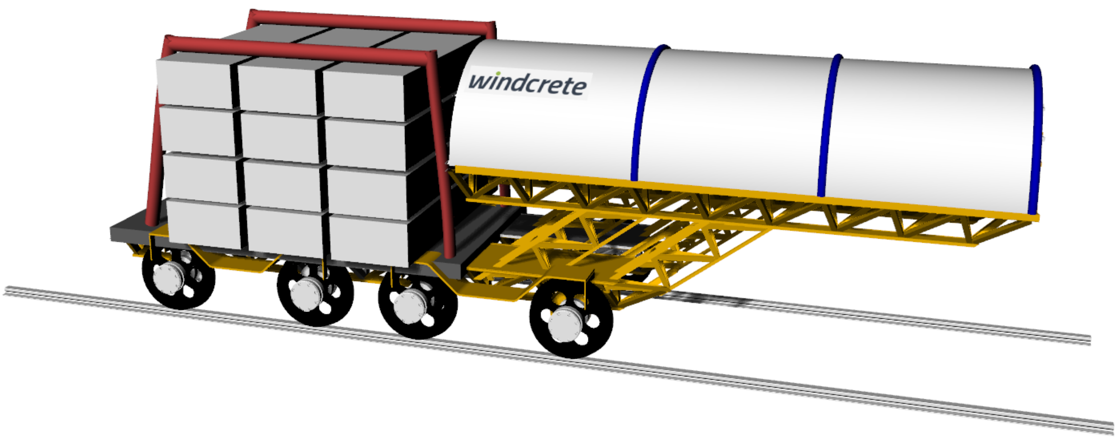


Figure 97. 3D view of the Cantilever Carriage

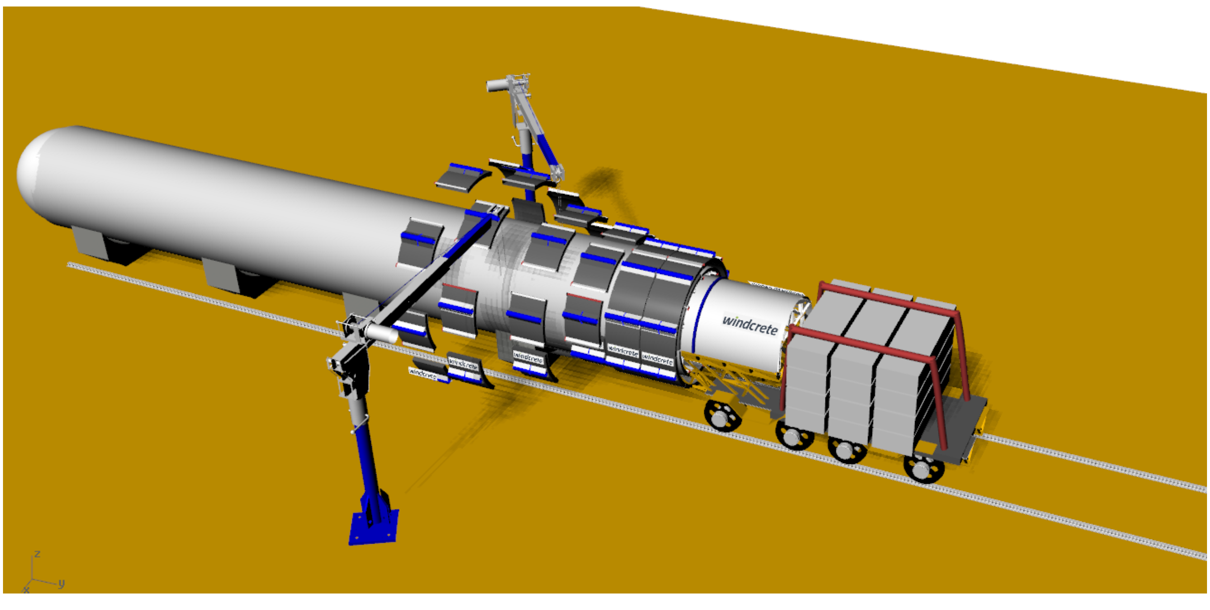


Figure 98. Cantilever Carriage during tower production.

CONSTRUCTION PROPOSAL 9: CONCRETE-CROWN

Req. 1 *Req. 2* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *YES* *YES*	*MODERATE*	*VERY HIGH*	*HIGH*	*CONCRETE CROWN*	*FAST*	*MODULAR ARCH FORMS*	*NO*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- No need for travelling formwork - No need for rail tracks - High-reuse of forms per cycle - Uses simple modular forms	- High-tech Concrete Crown - Interference between Concrete Crown and reinforcement - Unproven method of concrete placement. -May require losable mesh to keep concrete in place during filling of forms

METHOD STATEMENT

This method is the closest to slip-forming the tower that will be presented. It is comparable to slipforming in the sense that concrete is introduced axially, perpendicular to the cross-section of the tower. The fundamental difference is of course that concrete is placed whils moving horizontally instead of vertically.

The backbone of this proposal is a very specific, high-tech concreting equipment, which will be designed to suit the particular needs of the Windcrete towers: a concreting crown.
If this technology is to become a reliable way to slipform towers in the horizontal direction, extensive research will have to be carried out and ultimately a full-scale prototype will have to be tested to guarantee the requirements are met. For now, only a brief description of this technology is presented.

Concreting Crown concept

The Concreting Crown consists of a circular steel frame in the upright position fixed on some sort of carriage that supports a series of high-throughput pumps capable of distributing concrete to all points of the cross-section. The carriage and therefore the crown will move backwards as construction progresses while pumping of concrete never stops. The circular steel frame will be designed to fit the exact area of the cross-section.

The concrete crown will only be efficient if pumps provide sufficient pressure to the concrete and this across the entire cross section. The pumping of concrete should be carried out simultaneously and at a constant rate which will have to be computed. Pumps of folding distribution booms should be used to ensure good access to the entire volume of the forms and minimum free fall of the concrete. The process must never stop until the structure is finished and will require a rather fast placement rate. The speed at which the traveller supporting the crown moves backwards should be proportional to the placement rate of the pumps to guarantee perfect filling with no voids.

As one might expect, if concrete is pumped axially it will simply fall and segregate due its own weight. To address this mater, filling should create a concrete 'heap' within the forms (see Figure 98). By doing so, concrete introduced at higher levels falls on top of an existing heap of concrete. This 'heap' of concrete, providing an advancing slope, should be at angle so that freshly pumped does not slide off and concrete can accumulate while pouring never stops. To achieve this advancing slope, pumping rate should be slightly more intensive at the lower part of a section, at least at the beginning of construction, to create an adequate base for concrete placed from above to rest on.

At the time of writing, the author was unable to find any confirmation that this technology, or a concept similar to a 'concreting crown' exists and has been publically developed.

It is important to keep in mind that this method will most probably require a high placement rate that must be maintained during the entire duration of the construction of a tower. If such a throughput cannot be achieved, or is found to be uneconomical, the concept of Concrete Crown will necessarily have to be combined with other placement methods.

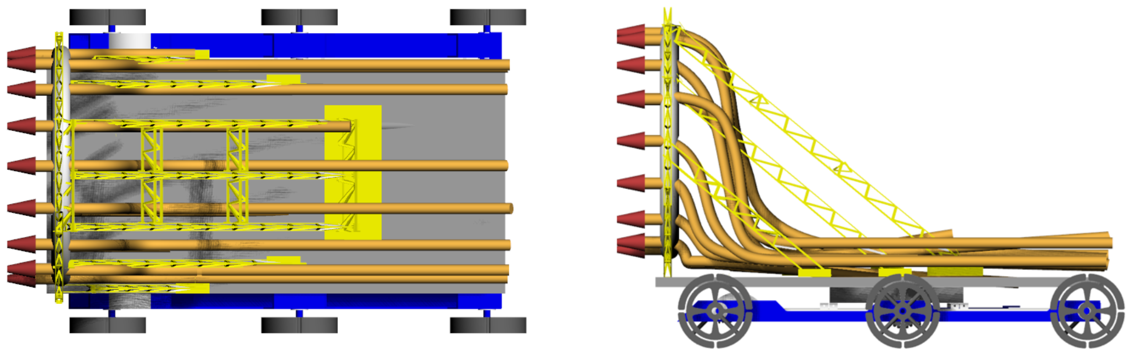


Figure 99. Side and top view of Concrete Crown Concept.

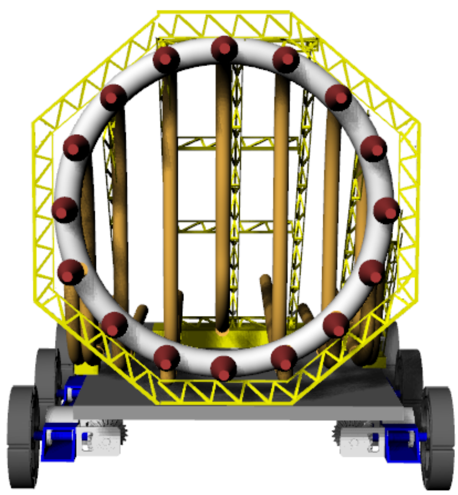


Figure 100. Front view of Concrete Crown Concept.

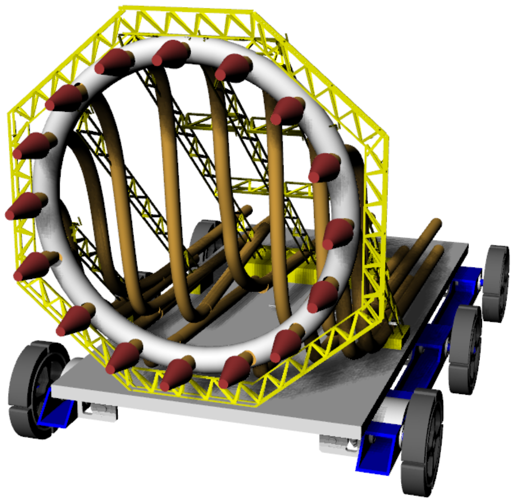


Figure 101. 3D view of concreting crown concept.

To illustrate the concept of concrete crown a configuration including 16 concrete pipelines (shown in orange) has been chosen. Each pipeline is eqquipped with a nozzle (shown in red) that must be sufficiently wide to allow a constant flow of concrete.

Note that these renderings represent only a simplified version of the concrete crown concept. In reality, to be able to properly reach the far-end of the forms these pumplines should be able to extend so that the nozzles can place concrete from short distance. The presence of the reinforcement will difficult the access for these pumplines. A simple solution is to directly use the reinforcement that has not yet been reached by the concrete level as support for pumplines. As the forms are filled and reinforcement bars are embeded in fresch concrete, these pumplines can be pulled backwards and supported by the following reinforcement bars. Concreting equipment should be resistant to friction with steel bars to reduce damage to pumplines.

OPERATIVE CYCLE

- Assembling of the concreting crown on site
- Inspection for flaws of all the hoses and connexion to concrete pumps
- Erection of first complete section of forms creating a ring
- Start of concrete pumping into the lower part of the forms at pre-calculated pumping rate.
- Concrete is poured until an adequate base is in place.
- Start of concrete pumping into the middle and higher part of the forms at pre-calculated pumping rate.
- When concrete heap at required slope is in place activation of all concrete pumps.
- Erection of second section of forms avoiding interference with the crown which continues to place concrete uninterruptedly.
- Complete filling of the first section of forms and moving on to the next.

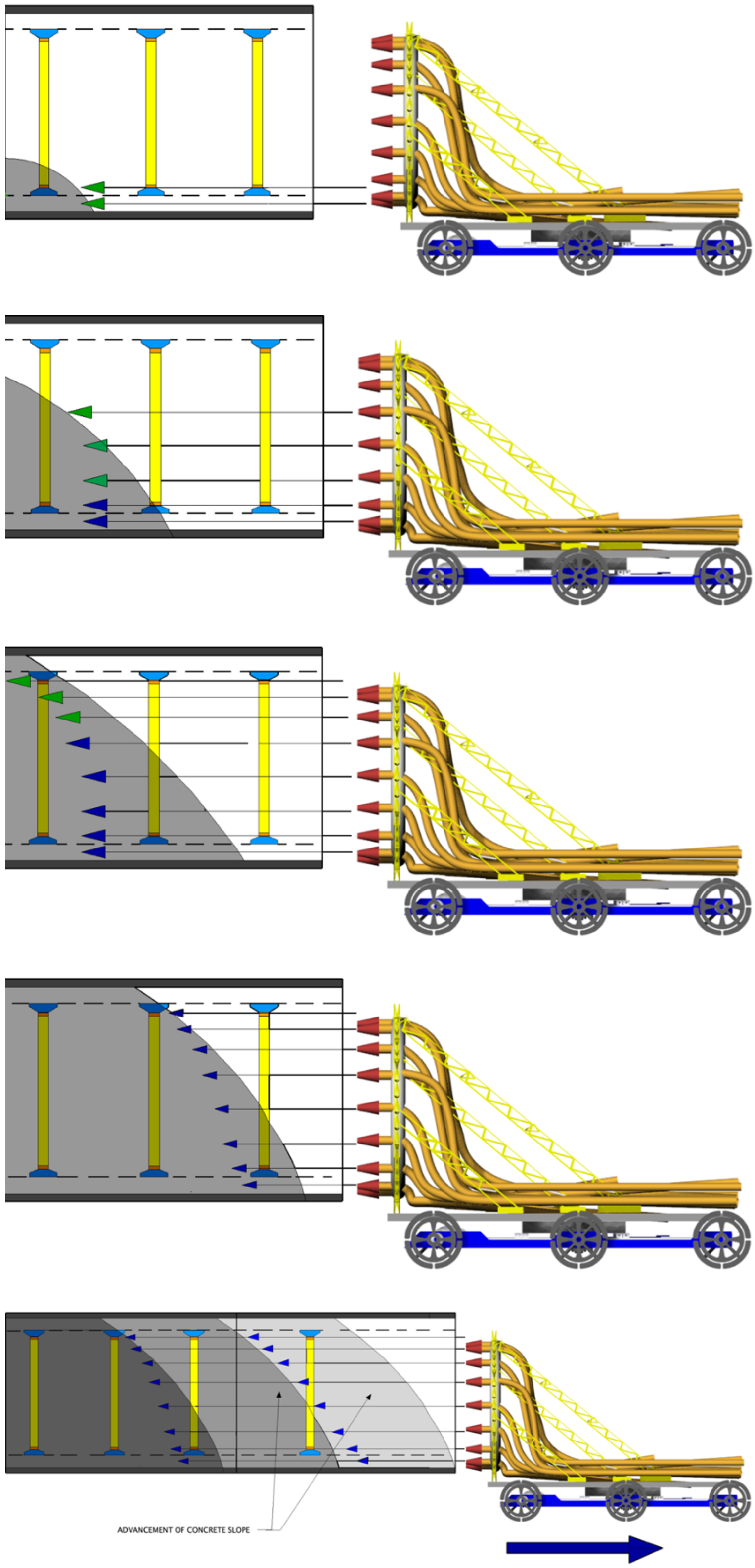


Figure 102. Concrete crown in operation, concept of advancing concrete heap

The **green colour** arrow heads represent the moment of activation of a series of pumplines at a given height. **Blue arrow** head implies constant pumping of concrete is taking place and should be maintained until structure is complete.

Note that the length of the arrows does **not** correspond to the distance over which concrete is poured. The length of the arrows just depicts the height that corresponds to each level of pumplines.

In reality the nozzles of the pumplines (shown in red) should be able to reach the volume of the forms to fill within short range in order to minimise the free fall of concrete. The type of pumplines should be of folding distribution booms so access within the forms is possible. An aspect that may hinder the operation of such a concrete crown is the reinforcement cage which will obstruct the access within the forms. The Concrete Crown concept will therefore require some further research to elaborate a circular arrangement of pumps that can extend and retract within the forms whilst avoiding the reinforcement bars.

A first attempt to reduce the interference between pumplines and reinforcement is to actually use the reinforcement bars as temporary support for the concreting equipment. Pumplines could temporarily rest on reinforcement before the concrete reaches those bars. As pumplines will have to slide in between reinforcement bars, the material used for the pumplines should be covered by a protective coat resistant to cuts.

Comments

This method may come as more of a concreting scheme than an actual construction proposal as it can be integrated in almost all the proposals that consider some sort of travelling formwork that moves backwards as construction of the structure advances.

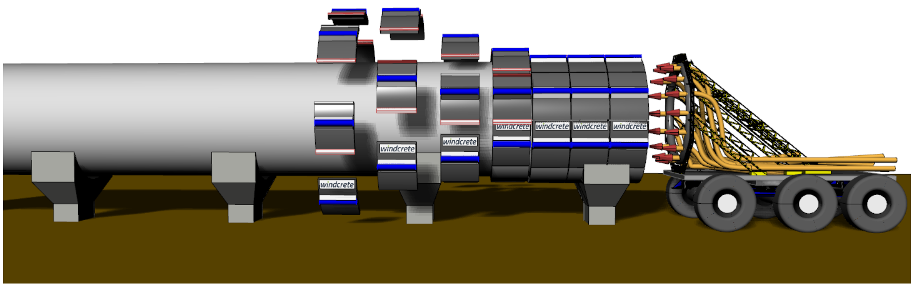


Figure 103. Side view of Concrete Crown in operation.

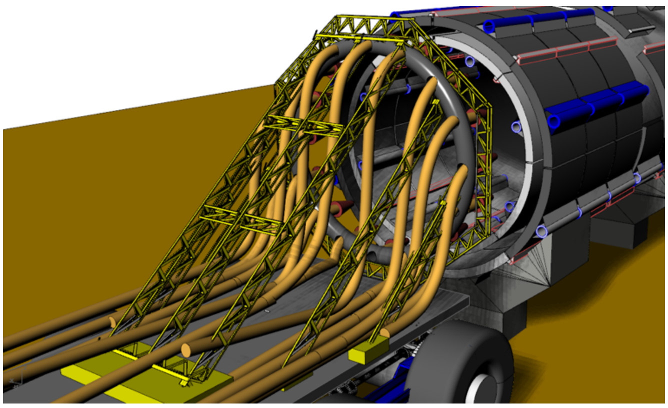


Figure 104. Concrete Crown placing concrete in the empty form

CONSTRUCTION PROPOSAL 10: TBM-ADAPTATION (ERECTOR-ARM)

Req. 1 *Req. 2* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *YES* *YES*	*MODERATE*	*VERY HIGH*	*MODERATE*	*ERECTOR*	*FAST*	*MODULAR ARCH FORMS*	*NO*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Highly-automated process - Does not involve highly-specialized travelling formwork - Seemingly reliable - Quick delivery time - Simplest forms	- Research and development on high- tech erector arm - Large up-front costs to design and build erector-arm - Will require some manned machinery to strip the forms like a crane mounted on wheels - Further research on interference between provision support systems for forms and erector arm form - Little use of TBM tunnelling experience

METHOD STATEMENT

This proposal involves a highly-automated process that hopes to bypass the use of traditional heavy travelling formwork.

This proposal sees a minor exterior carriage system that supports an erector arm which is in charge of placing the empty forms prior to filling. It will clearly seek inspiration in TBM construction methods. Concreting will be done mainly via pumplines introducing concrete both radially and axially to the cross-section as this proposal will require quick concrete placement. Additional concrete can be placed radially from the outside. As the forms are placed they will be supported by provisional structures, namely simple steel frames left in place and hydraulic struts. The carriage that supports the erector moves backwards as construction progresses. For a justification on the usage of the erector arm refer to **APPENDIX 3- CONSIDERATIONS ON ADAPTING TUNNEL FORMWORK.**

It should ideally avoid the use of inner travelling formwork mounted on rails thus efficiently achieving a circular cross-section. Concrete will be placed continuously by extendable pumps; the carriage, however, will advance in discrete steps every time the erector has placed a new section of forms.

As the placing of forms is fully automated thanks to the erector, and the filling is done by pumping concrete from a certain distance, a combination of temporary truss like supports and hydraulic struts should be enough to support the fresh concrete thus eliminating the need of heavy conventional travelling formwork systems. Forms and provisional structures will be stripped by operators once concrete has hardened. To strip the forms an inner crane mounted on wheels can move on the hardened concrete and forms can be transported again to the erector by using an adequate conveyor belt, capable of transporting the steel forms.

DEGREE OF ADAPTATION

This construction proposal will feed on highly-mechanized excavation methods used by the tunnel industry.

Similar to the way a TBM places the tunnel linings with the help of an erector, this technology would instead be adapted to place empty forms ready to be filled. The exterior and interior form panels should be pre-assembled in a single unit will all the form ties in place before being fed to the erector arm. The erector can quickly put them in place, provisional support is provided and then forms are interlocked with previous forms by qualified personnel.

Figure 105. Erector arm designed and built by Galbiati Group, firm specialized on mechanical machines for Engineering and Construction. (Galbiati Group, 2014)

INCLUSION OF CONCRETING CROWN

This proposal is believed to be particularly suitable to deploy the concreting crown technology. If this method hopes to become a reference in mobilising the least amount of formwork systems, the placement of the empty forms can be done by an adapted erector arm and the concreting can take place from the outside of the structure, perpendicular to the cross-section by including a Concreting Crown. Concrete inside the forms can be supported by a simple mechanism temporarily left in place which will later be removed, together with the fors with a small self-propelled crane inside the structure. Once again, extensive research on high-tech Concreting Crown will be necessary.

Operative cycle

The sequence in which forms are placed will logically have to be in accordance with the order concrete will be placed. Thus, first forms from the lower part of the section will be placed. The erector should be capable of placing a complete new ring of empty forms while the concrete in the previous ring is still fresh. The size of the forms (or the placement rate) should be such that a new set of empty forms is always in place and available before the previous set is completely filled with concrete so as to allow uninterrupted pouring. Once the previous form is completely filled, a new form must already be connected, reinforcement placed and ready to be filled.

By making sure empty forms are placed as soon as possible, foldable pumps can just proceed with concreting without 'noticing' the transition from one form to another.

Backwards movement the form-placing equipment will be achieved by mounting the erector on a self-propelled carriage.

Comments

- Additional research on the capability of hydraulic struts to support forms and fresh concrete is needed.
- Struts of considerable height may not be a practical solution. Instead an intermediate support frame could be used, allowing shorter struts less sensitive to buckling, which will be a safer solution.

- Note that the erector arm would probably require a lower lifting capacity if compared to those used inside a TBM. The pre-assembled arch forms are presumably be lighter than massive precast concrete segments.

- To truly result in a highly-automated process, a mechanized method for stripping forms will also have to be designed.

CONSTRUCTION PROPOSAL 11: TBM-ADAPTATION 2.0

ADVANTAGES W.R.T PREVIOUS	DISADVANTAGES W.R.T PREVIOUS
- None	- Damaging, buckling and early replacement of steel forms - Also requires research and development on high-tech Concreting Crown and large up-front costs to design and build erector-arm - Increased technological complexity

METHOD STATEMENT

The method is fundamentally a variation of the previous, it also involves a concreting crown and an erector arm. The only difference is that this variation goes further into adapting TBM technology. The previous method considered the erector placed on carriage that was self-propelled and able to move backwards (in discrete steps) to place new sets of forms. This variation achieves movement of the carriage in a different way.

In this variation of the former proposal, the way formwork achieves this backwards movement will be directly taken from a particular aspect of tunnel construction using TBM. As one can see a ring of hydraulic cylinders pushes forward through shoes placed against the previously placed tunnel lining. (Bilgin, 2013). These hydraulic thrust cylinders are retracted separately as new segment linings are placed and after a complete cycle allow the forward movement of the TBM shield. The segment linings are placed into position by an erector, a remote-controlled crane arm, which picks them up mechanically or by suction.

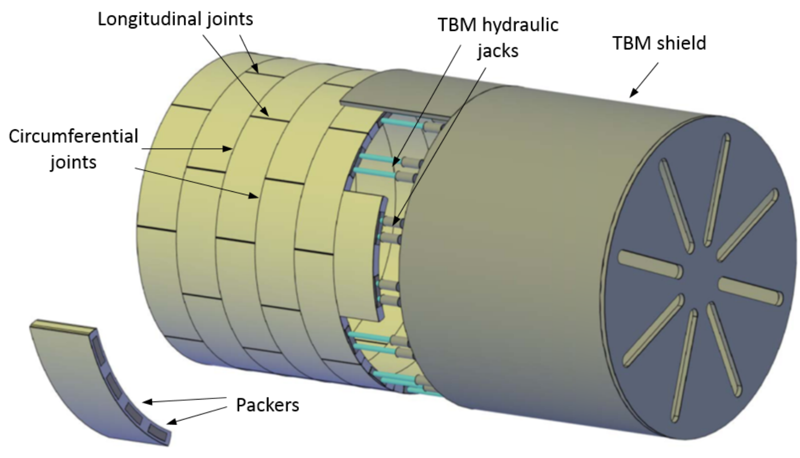


Figure 106. Segmental tunnel linings.
Source: https://oriolarnau.wordpress.com/home/segmental-tunnel-linings/

Both of these features, the hydraulic thrust cylinders and the erector arm, will be integrated in this proposal.

Movement will be achieved by a similar mechanism as that used by a TBM. As soon as a complete ring of empty forms is placed, pumps should just be finishing filling of the previous ring and reaching this new ring. At this point hydraulic jacks push on the empty ring of forms where filling has just begun and the traveller moves back leaving the sufficient space for a new ring. Once again, the erector starts to place forms and the entire ring must be in place while concrete pumps are still busy with previous.

COMPARISON WITH THE PREVIOUS METHOD

Hydraulic thrust cylinders used by a TBM normally push on high-strength prefabricated segment linings. However, if hydraulic cylinders were used in a similar way and directly pushed onto steel forms, these may be damaged in the process. Exposed to high compressive forces, they would be liable to buckle and would gradually loose their shape. Continuous damaging of forms is uneconomical and will increase costs in the long run. Forms should be treated with care for maximum number of re-uses.

The previous approach considers mounting the erector arm on a self-propelled carriage which is a much simpler way to achieve moment with no damaging of forms.

CONSTRUCTION PROPOSAL 12: EXTERIOR TRAVELLING FORMWORK – 'RING FRAME'

Req.1 Req. 2 Req. 3	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES	*MODERATE*	*VERY HIGH*	*MODERATE*	*ERECTOR*	*FAST*	*MODULAR ARCH FORMS*	*NO*
YES							
YES							

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	*(CLAIMED) DISADVANTAGES*
- Speedy process and quick delivery time - Highly-automated - Casting of large sections at once - Possibility to 'recycle' and adapt a gantry crane	- High-tech and sophisticated travelling formwork - Large to very-large traveller required - Technologically complex and makes use of unproven technology

METHOD STATEMENT

This method involves the use of travelling formwork mounted on rails designed to wrap itself around the structure as the construction progresses. In this proposal, the steel frame is considerably larger and bears resemblance with a double frame gantry crane. The estimated height of the travelling formwork is 20-25 m and should be specifically designed for Windcrete. The traveller temporarily surrounds, or envelops the forms during concreting until complete filling, only then will the sliding frame advance.

The idea is to keep feeding the ring frame modular formwork through the front of the traveller, forms are secured to the ring, filled and then detached and left in place resting on suitable supports (Figure 103).

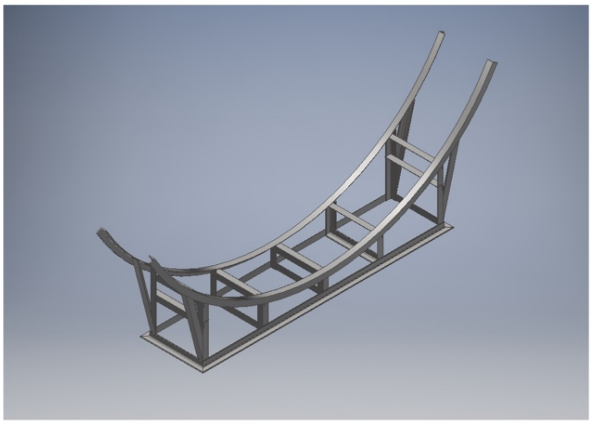


Figure 107. Standard saddle support for forms filled with concrete to rest.

‘GRIPPING’ RING

A set of hydraulic jacks arranged in circular fashion can efficiently fasten the mold while the concreting takes place. Figure. 104 aims at showing the working principle of this ‘gripping’ mechanism. Here the ring has been represented without the form panels.

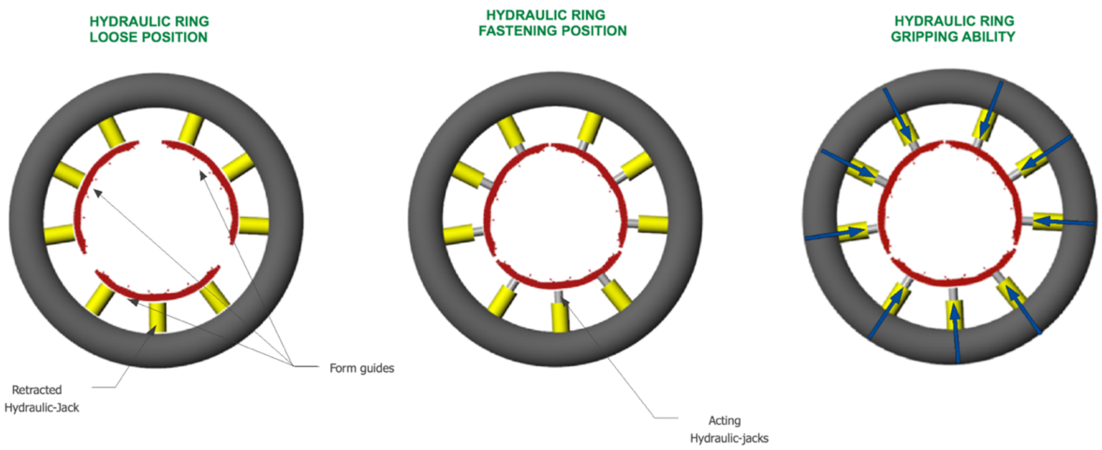


Figure 108. 'Gripping' Ring.

Figure. 105 represents the same ‘gripping’ mechanism but this time with the form panels introduced (shown in black). Once these panels are ‘fed’ to the ring, the ring can then contract and tighten the forms in place. They will then be interlocked together by an operator. Concrete placement can then begin. Concrete placement is mainly done from above as the traveller supports working decks a range of

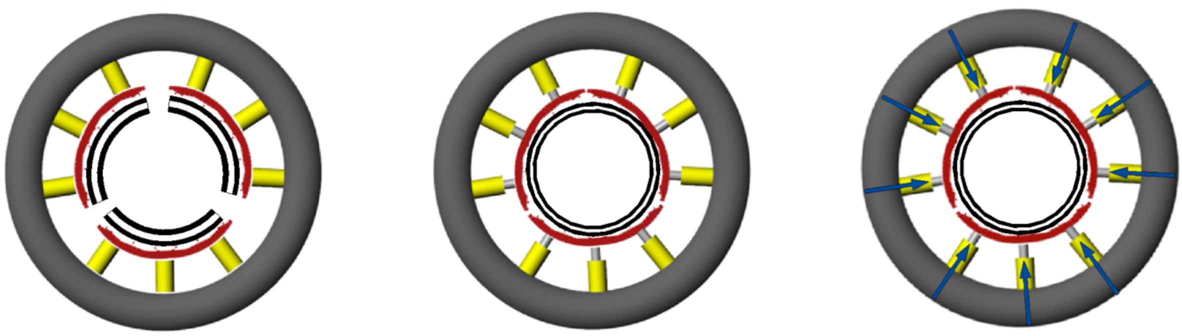


Figure 109 ‘Grippin ring’ with forms.

Note that only a simplified version of the ring is shown and that the surrounding steel frame has not been shown.

RING- FRAME

A tall steel frame mounted on rails supports a steel ring which we will call ‘gripping’ ring. As the name implies, this ‘gripping’ ring, fixed to the travelling steel frame, has the ability to extend its cylinders so as to tighten the forms that are introduced with in it. In between these two rings, working decks support all the necessary equipment for intensive pouring of concrete. The ring serves as a guide wall for arch forms. Forms are temporarily fastened to the ring and jacks can subsequently grip the forms. Intensive concreting of the volume in between the two rings begins. Once the forms are suitably filled with fresh concrete, saddle-like support structures are placed underneath the forms. The 'griping' mechanism is free to retract and the weight of the mould and the fresh concrete can be safely transferred to the saddles. Thus, the exterior steel frame can "unwrap" the forms, which are left in place, and move forward. New modular arch-forms will be fed to the rings at the end of each cycle and these will be interlocked, ´gripped´ and concreting operation can begin all over again. The steel frame will move in discrete steps, more or less equal to the length of the forms, but should provide an overlap region. By overlap it is meant that, to avoid cold joints, the last section where concrete was placed (corresponding to the boundary of a given cycle) will receive some additional concrete at the beginning of the next cycle. This means that the traveller will necessarily advance in slightly smaller strokes than the actual length of the forms to allow for this overlap.

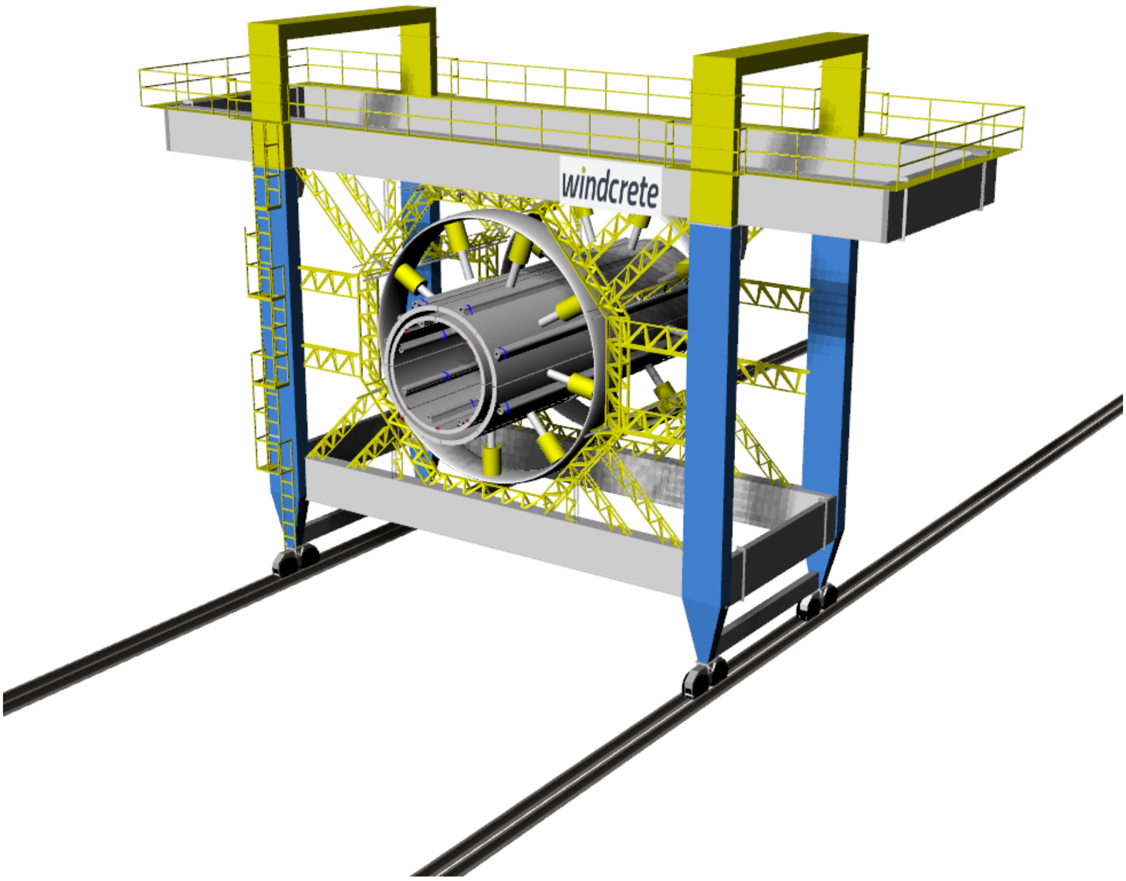


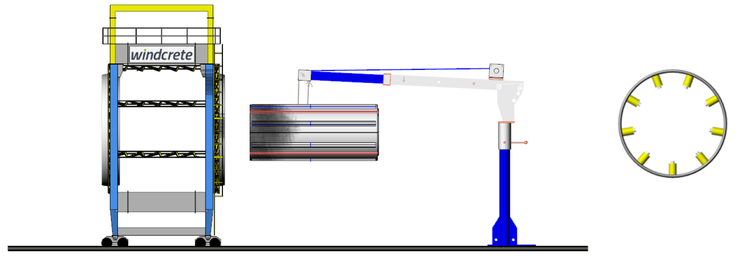
Figure 110. 'Ring Frame', novel traveller concept equipped with two 'gripping' rings

The traveller moves on rails (shown in black). The 'gripping' rings are fixed to the traveller through a steel frame consisting on a tubular truss (shown in yellow). Thus the name of 'Ring Frame'. A system of empty forms is shown kept in place by the two 'gripping' rings while pouring of concrete takes place. Placement of concrete is done from the overhead working deck that supports operators and concreting equipment (not shown in Figure. 106)

To design and construct such a specialized traveller will presumably be expensive. The size of the traveller is comparable to that of portainer cranes or smaller. A slight cost-reduction could be sought by 'recycling' and re-adapting a double frame gantry crane.

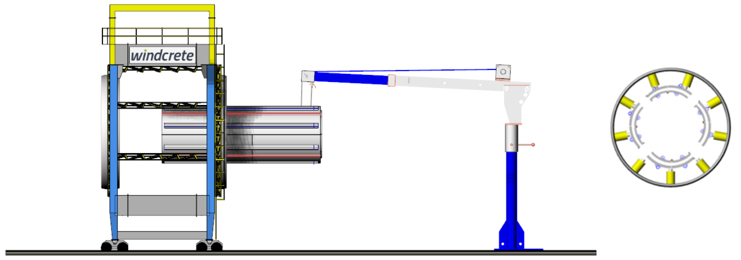
Operative cycle

The several stages of the operative cycle of the 'Ring Frame' are depicted in Figure 111. The configuration adopted by the jacking rings during each phase is also shown.



- Heavy duty lifting crane (blue) lifts modular arch-forms and places them inside the frame, on the curved guide walls of the ring.

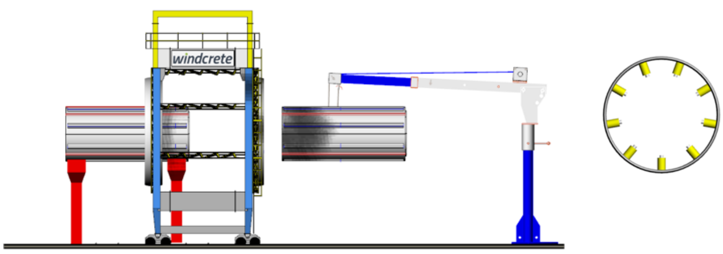
(the length of the modular forms is shown particularly long for illustration purposes)



- Once all the modular forms are secured to the rings both hydraulic-jack rings grip the forms.
- Personnel, or an automated mechanism, bolts modular forms from the same section together and also interlocks them with the previous section.

-- Placement of reinforcement.
- Concrete pouring commences from the overhead working deck (in yellow) throughout the entire length of the forms (equal to the distance in between the 2 rings).
-Tremies (shown in orange) and other high throughput placement methods

- During concrete placement, a number of suitable saddle supports are placed underneath the forms. (shown in red)
- Once suitable supports are in place and forms are completely filled, retraction of hydraulic jacks.
-forms are loosened from the ring and left resting on the saddle supports.



-Travelling system advances making room for a new set of forms.

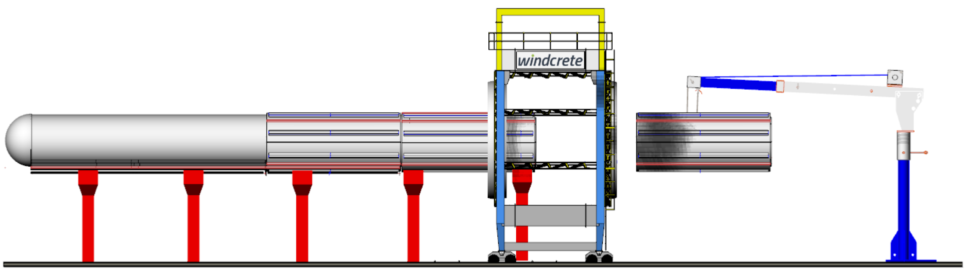


Figure 112. Operative cycle of 'Ring Frame'

More supports are successively provided as construction progresses (shown in red).
-Supports are left in place until the structure is flooded out of the construction dock.
-The bottom fraction of the forms, which is diffícut to access as the structure is being produced, are also left in place until construction is complete and they can be retrieved after flooding of dry dock.

It is interesting to note that the support found in between the two rings can be re-used troughout the entire cycle. This support can be integrated into the frame of the traveller.

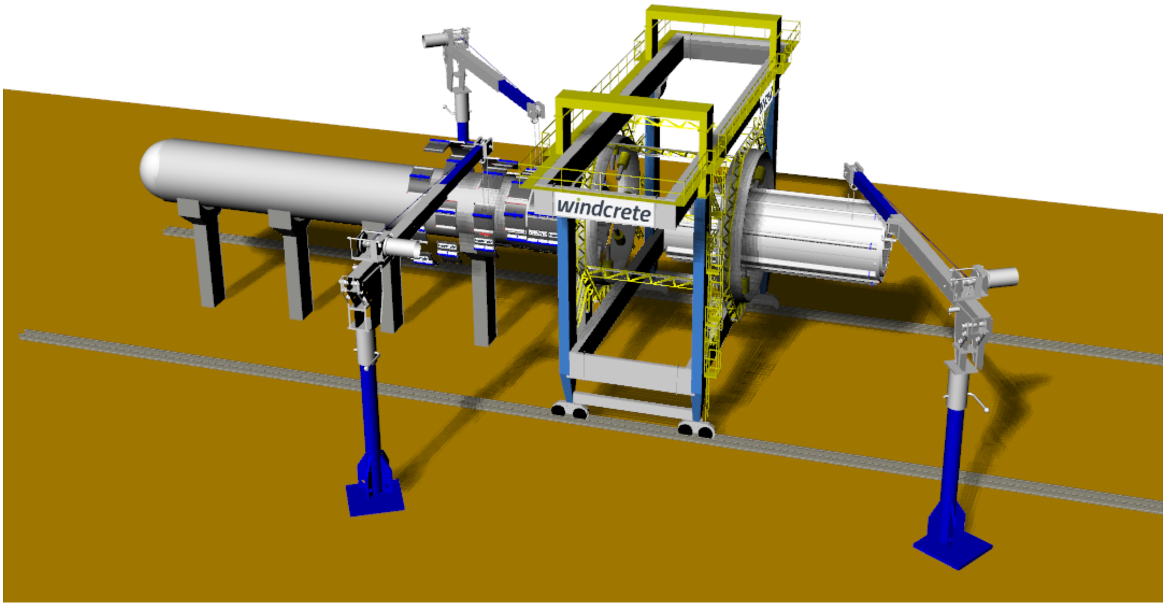


Figure 113. 3D view of Ring Frame traveller during construction.

COMMENTS

- The name travelling formwork is inaccurate, the steel structure mounted on rails is actually a guide wall and a temporary support structure for the forms, however when the traveller moves it releases the forms, which are left in place. Thus, the formwork does not move with the traveller, but rather the traveller moves over the forms.

- Forms are left in place until concrete has hardened and cured sufficiently.

- The left-in place forms can be removed once the concrete has reached the design strength and then transported to the concreting front and fed to the ring frame all over again. The forms can be re-used more than once per tower.

- The number of times a form-panel can be used per production cycle depends on the concrete placement speed, which in turn determines the. Slower sliding frame will allow higher re-use of forms in the production cycle of the same tower.

- The method cannot be considered as a strictly slip-forming technique as the formwork advances in discrete steps rather than continuously. The ring-frame advances in discrete steps but pumps pour concrete continuously.

- The alignment of all the sections of forms is a priority and should be constantly monitored. Travelling formwork must move on straight rails embedded on a reliable ground.

- The new forms will always be interlocked to the former section of forms to ensure a continuous space is available for non-stop casting.

- By adding new formwork after each concrete placement instead of sliding the forms, there is no frictional force opposing the movement of the frame.

- Access to the inner face of the structure to place/remove forms and struts must be possible.

INSPIRING EXAMPLE

Even if no direct similarities on shape, functionality or size exist, this proposal could be seen as an up-scale of slipformers used to produce cast in-situ safety barriers. The main resemblance is that this slipform machine 'envelops' the structure it produces.

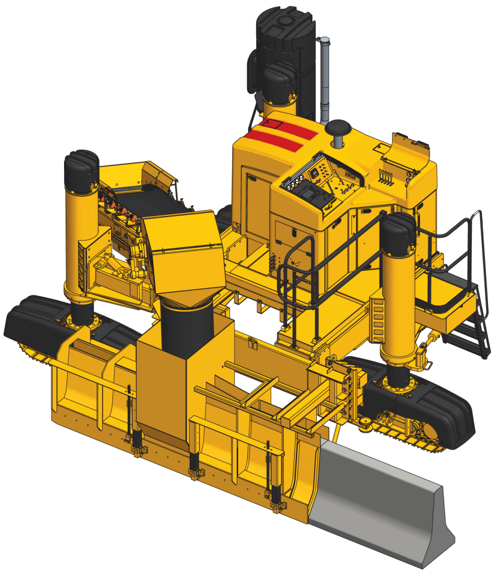


Figure 114. Safety barrier slipformer Gomaco's GT-3600. Source: https://www.gomaco.com/Resources/gt3600.html

CONSTRUCTION PROPOSAL 13: CENTRIFUGE ENTIRE TOWER

Req. 1 *Req. 2* *Req. 3*	**execution risk (joints)**	**innovation degree**	**techn. complexity**	**main cost driver**	**production time**	**formwork type**	**design modifications**
YES *YES* *YES*	*HIGH*	*VERY HIGH*	*VERY HIGH*	*UPSCALING CENTRIFUGE TECHNOLOGY*	*FAST*	*CENTRIFUGAL MOLD*	*NO*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	(CLAIMED) DISADVANTAGES
- Quick process - High to very-high quality and enhanced mechanical properties - No need for inner core - Highly-automated - Ideal for thin-walled cylinders - Simplest possible forms	- Un-reasonably expensive - High-tech and sophisticated installations - Massive (permanent) facilities - Technologically complex and makes use of unproven technology - Large up-front costs to design and build traveller - Large number of saddle supports required - Slight risk of cold joints - Will require some manned machinery to strip the forms

METHOD STATEMENT

This method proposes to use a process analogous to that used for production of Centrifugal Reinforced Concrete Pipes to construct Windcrete.

To pursue this approach, it is highly recommended to design the facilities together with a team of electrical and mechanical engineers with good understanding on this technology. Energy requirements to spin the mold are expected to be high to very-high. A way to reduce the required energy is to use a low stiffness concrete mix and by keeping the rotating mold as thin as possible.

Also to take into account is that the centrifuging should be done strictly horizontally and all the spinning mechanisms should be perfectly aligned and checked periodically. The stability of the ground should be checked prior to the construction of the facilities as well as any ground improvement if necessary. Casting a thick concrete slab to serve as a base to place the spinning equipment may be a good idea. Another aspect to consider are noise mitigation measures given that gear trains are in fact quite noisy whilst operating.

Compaction by centrifugation is appealing for several reasons:

- It uses the mold in the horizontal direction favouring horizontal casting, an elemental requirement for Windcrete construction

- Thin-walled cylinders are difficult to cast by other means, but centrifugal casting is particularly suitable.

- Centrifugal concrete is highly compact and results in watertight structures in high quality concrete with enhanced mechanical properties offering great resistance to atmospheric corrosion.

The method also eliminates the need for cores resulting in a simpler formwork with less steel which yields costs savings. Additionally, the technology is widely used, specific equipment is available and mechanical properties of centrifugal casting have been proven to be excellent.

These reasons make compaction by centrifugation close-to-ideal for Windcrete's hollow circular cross-section.

However, this technique also brings some difficulties, overcoming them is the key to knowing if centrifuging the towers is a feasible solution to construct Windcrete. The main obstacle to centrifuging Windcrete is the size of the towers. Such a method is typically done for diameters in the range of 1-2 m and maximum size limits go up to 6 m diameter and 15 m length, small when compared to the 13-m diameter of the tower. This will require complex facilities that highly increase the execution risk of the method in the event of failure.

SPINNING MECHANISMS

In order to spin the mold some sort of rotating machine is necessary. The mechanism of choice must be capable of spinning the mold to the sufficient rotational velocity that enables the compaction of concrete Several options may be considered:

Gear train

A "classic" **gear train** with gears or cogwheels with teeth that mesh together to provide rotation. They are common rotating system often used in large industrial facilities is a sequence of several gears or cogwheels

Geared devices connected to a power source transmit torque and can change the speed and direction. Gears are circular and made of metal with teeth, or cogs, which mesh with other toothed gears. Two or more meshing gears, working in a sequence, are called a gear train. In order to mesh smoothly two gears, they must have the same sized teeth. A gear train can be usually considered a fairly simple machine. However, given the large number and size of the gears, and the large torque required to reach the rotational speed to compact the concrete, makes this mechanical system rather complex.

For more information on designing a gear train, refer to **APPENDIX 3: CENTRIFUGATION BASICS**

Large rubber tires or similar

Truck wheels are hard, cheap and readily available, if equipped with some kind of teeth or grip to fasten to the mold they may be an interesting alternative. If truck-like tires could be recycled and used as turning device, it would surely lower the overall costs in comparison with conventional gears. As stated earlier, it is important to maintain the horizontal alignment of the mold while it turns. If truck tires were used, they should be inflated to an appropriate pressure and checked regularly to avoid uneven settlements.

Other possibilities for sppining devices could be a **traction driver** or a **V-Belt**

Figure 115. Spinning mechanism using a V-belt.
Source: Shandong Haiyu Industry, manufacturers of centrifugal concrete poles and machinery (Haiyu Industry, 2012)

The placement of the gears (or equivalent rotating machines) will require careful studying. Seemingly, spinning mechanisms could be placed at either sides or underneath the mold, or a combination of the two. Aspects to consider when choosing the best configuration may be:

- minimise the amount of energy required by finding the optimal number and size of the gears, as well as how to distribute them along the mold:

- ease of access for repair or substitution. If an element is damaged, access should be fairly swift to minimize the downtime and resume tower production with minimum delay;

- minimum wearing of the spinning equipment. For instance, if placed directly underneath the mold to spin, deterioration of the rotation devices is likely to occur more quickly than if placed at either side of the mold.

CHALLENGES

The real challenge lies in up-scaling this technique in terms of equipment and energy required. Facilities that are able to spin the Windcrete molds would be a remarkable feat in this sector, up-scaling this technology to unprecedented dimensions. The size of the gears would presumably be huge, and would come with great cost. Gears would have to be specifically designed and assembled to fit the needs of the project. Gears are expensive to manufacture and their lubrication requirements impose a high operating cost per hour. Such expensive equipment should be designed for maximum operating lifetime which calls for active control during operation and rigorous maintenance. The energy requirement to spin the mold would also have to be estimated in monetary terms to assess the feasibility of this proposal.

The technological complexity of the spinning mechanism is high due to the fact that all the gears must be perfectly synchronised. For a longer mold more gears will be required increasing both the technological complexity of the system and the risk of failure of a given element. As the system requires the correct functioning and coordination of all the elements, a potential failure of a single element could lead to the failure of the rest of the elements in a chain-reaction effect. Thus, an electrical or mechanical failure could have dire consequences not only for the completed concrete tower but may cause even cause substantial to the rotating system. If a single gear was to turn disjoint from the others the soundness of the entire structure could be compromised. For example, if a gear started turning in the opposite direction due to an electrical failure, it could counteract the rotation action of the remaining gears and propitiate the mechanical failure of the rest of the gears.

REDUCING EXECUTION RISK

To minimize the propagation of failure over the overall system it would be wise to mount the spinning devices on individual axis so if one device fails the rest of the devices are relatively unaffected. This will however lead to a greater technical complexity of the system and increase maintenance requirements. Additionally, a control room will be required, with specialized personnel to supervise the correct functioning of all the gears in terms of speed, acceleration rate, alignment and synchronisation. An emergency switch-off mechanism would also be a good idea to stop the system at any given moment.

The high degree of complexity of the mechanical system increases with the size of the system as does the probability of failure. The failure of a single element could cause the failure of the entire system. Due to the interdependency between elements of the system, it is strongly recommended to limit the size of the spinning system, or at the very least "split" the system into smaller distinct independent systems. This argument favours centrifuging the tower in short rings rather than attempting to centrifuge the entire tower.

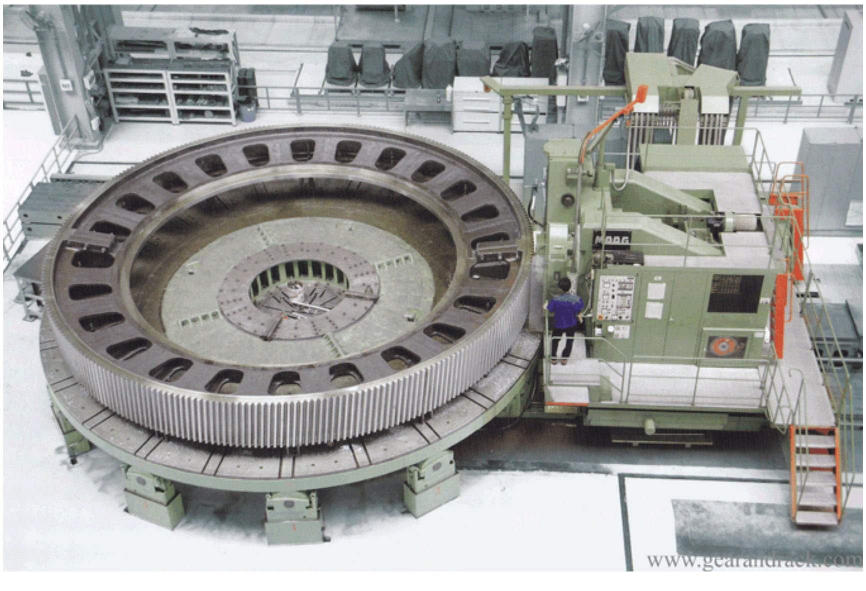


Figure 116. Large 9.936 m diameter gear manufactured by GEARX in China

CONSTRUCTION PROPOSAL 14: POST-TENSIONED PREFAB (CENTRIFUGE) RINGS- *ALTERNATIVE 0*

Req.1 *Req. 2* *Req. 3*	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES *NO* *YES*	*CONSTRUCTION JOINTS*	*VERY HIGH*	*MODERATE*	*UPSCALING CENTRIFUGE TECHNOLOGY*	*FAST*	*CENTRIFUGAL MOLD*	*YES*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	(CLAIMED) DISADVANTAGES
-Economic proposal and technically feasible -Speedy process and quick delivery time -Can get the Windcrete project running -High quality of pre-fabricated rings in factory conditions - High to very-high quality and enhanced mechanical properties - No need for inner core - Highly-automated - Ideal for thin-walled cylinders - Simplest possible forms	- Construction joints - High-tech and sophisticated installations - High energy requirements to spin large diameter - Non-monolithic structure presenting many construction joints - Major design modification - Un-known behaviour of joints during lifetime of the structure - Resin, epoxy and other sealing materials required

METHOD STATEMENT

This proposal does not satisfy Requirement [2] as it directly considers building the structure out of pre-fabricated reinforced rings. This is the first and only proposal that considers allowing construction joints in the structure, however joint sealing will have to be of the highest quality, suitable for the offshore environment.

The method is similar to that used for onshore turbines that use precast concrete towers as opposed to cast-in-place concrete towers.

Prefabricated concrete units are assembled by crane one after the other and tied together with post-tensioning tendons. The tendons are not placed in direct contact with the concrete, but are encapsulated within a protective sleeve or duct which is cast into the concrete structure. They are anchored at each end, firmly fixed to the surrounding concrete. Once the prefabricated ring elements are in place the tendons are tensioned by pulling the tendon ends through the anchorages while pressing against the concrete. The large forces required to tension the tendons result in a significant permanent compression being applied to the concrete which is transmited once the tendon is "locked-off".

The concrete units are whole rings manufactured in precast plants so that high quality and short processing times can be achieved. In this method, it has been chosen to fabricate these units using centrifugation process. It is recommended to install the centrifuging precast plant within the construction site to minimize transport distances. The concrete units can be transported by heavy-load vehicle or via a rail-track system to the assembly site. Smaller units corresponding to the tower part can be produced in adequate molds near-by the assembly-line and directly lowered to their position by a crane.

Horizontal reinforcement loops are positioned so that they overlap in the grouting areas. Longitudinal reinforcement bars are inserted between the reinforcement loops. Subsequently the grouting area is filled with flowable grout. The vertical joints of this construction method can be designed as reinforced joints, using the relevant design codes.

To produce the pre-fabricated rings a centrifugal casting process may be reasonable if the amount of energy to spin molds is within acceptable limits. As mentioned earlier, the degree of complexity of the spinning mechanism increases with the size of the system as does the probability of failure. The failure of a single element could cause the failure of the entire system. Due to the interdependency between elements of the system, it is strongly recommended to limit the size of the spinning system by "spliting" the system into smaller distinct independent systems. This argument favours centrifuging the tower in short rings rather than attempting to centrifuge the entire tower.

The enhanced mechanical and durability properties of centrifuge concrete make this process very convenient for offshore structures. The energy costs may be offset by the use of simpler forms with no need for inner core.

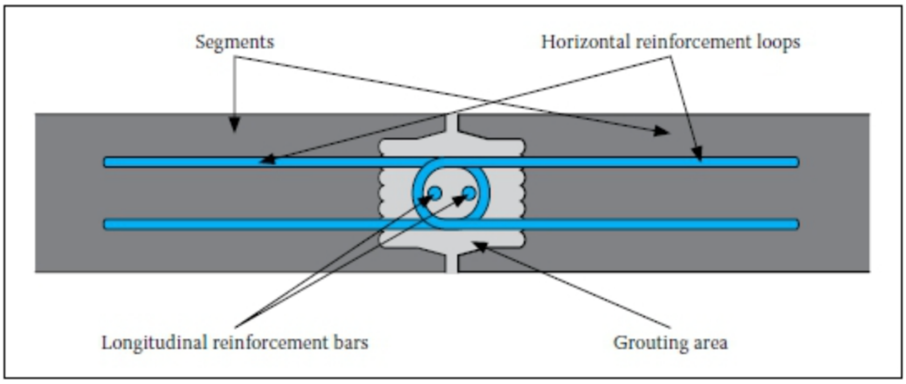


Figure 117. Connection of prefabricated elements with horizontal reinforcement loops. Source: (Haar & Marx, 2015)

An alternative connection method is joining the rings with bolts by providing special openings in the inner face of the segments to minimise risk of corrosion.

This method will of course require careful consideration on joint construction.
The construction of joints must ensure that they are capable of transmitting the required loads through the structure while remaining watertight. Different joints configurations will be assessed to identify the most appropriate. The use of epoxy joints provides lubrication to help in the fit-up and alignment of the mating segments and minimizes the effect of hard point contact between segments. (Chu, 2010)

A curved steel frame supports the lower part of the mold. Toothed gears (or wheels) are placed at both sides of the mold. The gears are fastened to the mold with some kind of gripping mechanism, for instance the mold could have a toothed section matching the teeth of the spinning gears. This technique does not require any sort of internal mold, only the outer mold is necessary. However, given the size and weight of the mold, it is a good idea to divide the mold in pieces. Once assembled, these pieces should form a ring. This ring is due to spin during the centrifuging operation, the different pieces will therefore need to be locked together and secured.

Platforms at a certain height are found on both sides where pumps can quickly pour the required amount of concrete with no segregation. Wheels placed within the steel frame, underneath the mold allow easy transport of the mold once the spinning process has been completed. Several alternatives may be considered for the spinning devices. The most intuitive is perhaps the use of a gear train.

Bellow a list of the different steps of a complete working cycle are presented:

(a) First the lower fraction of the mold is lowered or pushed into the steel frame
(b) The reinforcement and the pre-calculated amount of concrete can be placed on the open half-mold.
(c) The mold can then be closed with the use of cranes. The two halves must be bolted together and secured before spinning can begin.
(d) The spinning mechanism of choice is activated.
(e) Once the rotational velocity reaches the design value compaction by centrifugation begins.
(f) A series of secondary wheels placed under the steel frame allows the finished concrete ring to be “rolled out” of the steel frame.
(g) A new mold can be placed on the steel frame and the process can re-start all over again.

In the following representations, a configuration of 3 rotating machines at both sides of the mold has been chosen. This configuration has been chosen only to illustrate what a centrifuge station could look like. In reality the number of spinning wheels and their distribution across the mold would have to be optimized in terms of energy consumption, maximum required torque, access for maintenance purposes.

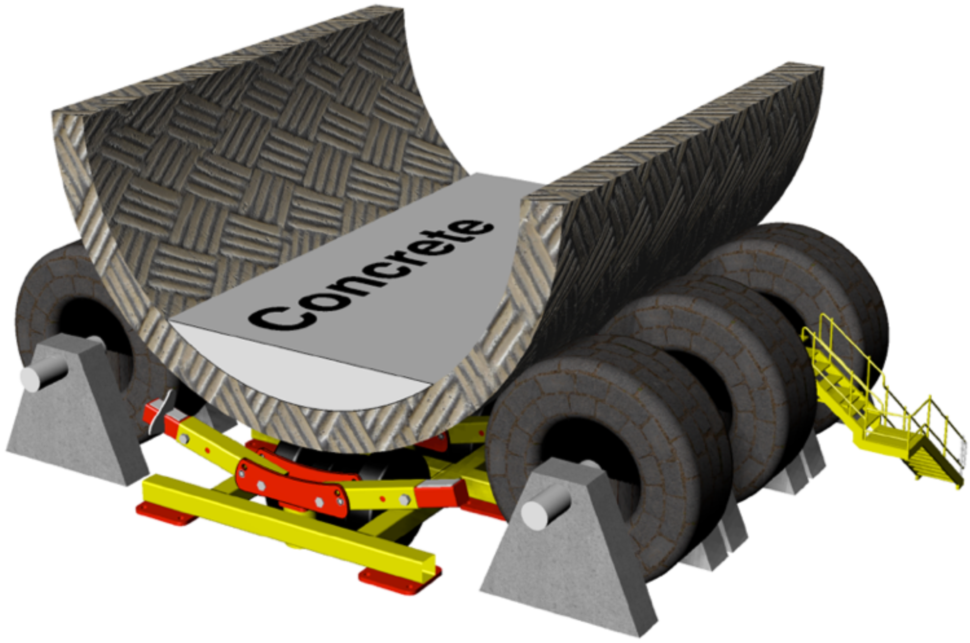


Figure 118. Centrifuge station using truck-like tires. Concrete placement on mold before closing and spinning.

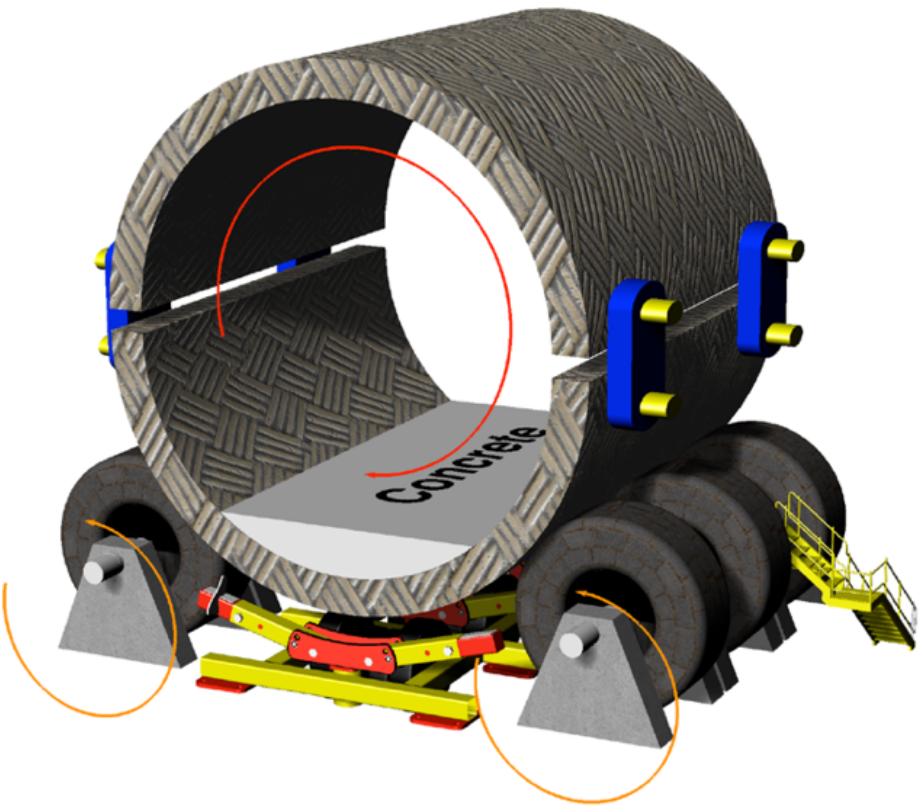


Figure 119. Two halves of the mold fastened and activation of the rotation.

The fastening mechanism has been drawn larger than in reality for representation purposes.

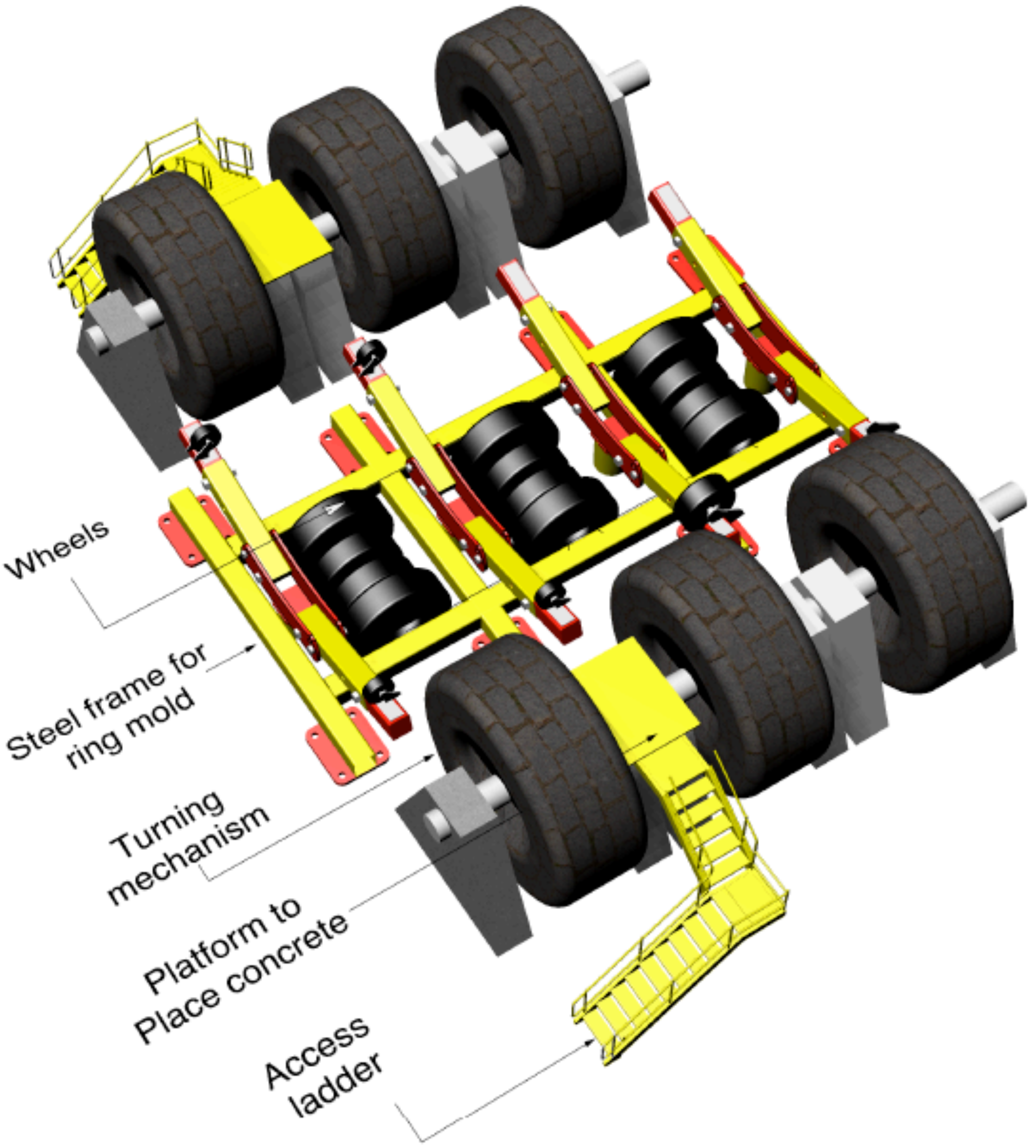


Figure 120. Bird view of centrifuge station using truck-like tires. without mold

CONSTRUCTION PROPOSAL 15: VERTICAL CASTING IN AN OFFSHORE FACTORY (O&G PLATFORM)

Req.1 Req. 2 Req. 3	***execution risk (joints)***	***innovation degree***	***techn. complexity***	***main cost driver***	***production time***	***formwork type***	***design modifications***
YES NO YES	*NO JOINTS*	*VERY HIGH*	*MODERATE*	*UPSCALING CENTRIFUGE TECHNOLOGY*	*FAST*	*CENTRIFUGAL MOLD*	*YES*

Requirements
[1] Horizontal construction
[2] Monolithic structure
[3] Suitable for serial construction

(CLAIMED) ADVANTAGES	(CLAIMED) DISADVANTAGES
- Extending the lifetime of O&G platforms due to be decommissioned - Speedy process and quick delivery time - High quality can be expected from slipforming - Minimum risk of cold joints - Minimum transport - Casting of large sections at once - Minimum forms	- Logistics in bringing all raw materials offshore - Offshore concrete batching plant - Design and construction of a specific floating platform - Instability of the floating platform - Unsafe working conditions under poor weather

METHOD STATEMENT

Two aspects make this proposal perhaps one of the most singular of the list.

First, this is the only construction proposal that considers fully vertical construction of the entire tower without a subsequent insurmountable handling operation. Secondly, this is the only proposal that contemplates construction at sea.

The concept of a Floating Factory appears as a solution, but an ambitious one. Describing the concept extensively is beyond the possibilities of this study so it will only be presented briefly.

The idea is to allocate adequate concrete casting facilities on a floating platform to slipform Windcrete towers directly into the water. The slipform will not rise at the total height of the structure but rather gradually sink the structure into the sea as construction progresses. A thorough analysis on the stability of the structure would determine the maximum allowable height of the concreting deck to ensure safe working conditions. Hydrodynamic loading acting on the platform as well as on the part of the tower inside the sea will probably be ruling, together with wind loads and currents. An in-depth structural analysis of the system will result in a reasonable height for the working deck, in line with stability and safety requirements.

What this method proposes is to by-pass the need to specifically design and build a costly floating factory by transforming an offshore O&G platform due to be decommissioned. The goal would be to convert an obsolete platform, stripping it from all unnecessary equipment, and adapt it for vertical production of towers.

Even though frail proof exists that the O&G has set its eyes on renewable energy, claiming cooperation with the wind industry any time soon is pure speculation. However, to achieve this project, it would require Oil & Gas and Offshore Wind industries to joint forces and work together.

The adaptation of the platform will depend on the platform itself. In reality the platform to be adapted does not necessarily need to be of floating type. Bottom-fixed platforms would equally provide an adequate space for an offshore production facility. In fact, and may provide improved stability with regard to a floating type.

Attempting a cost analysis is challenging and beyond the scope of this work, however, intuition leads to the assumption that the capital costs of such a concept would be huge. Nonetheless, by recycling O&G platforms the economy of such an offshore production factory does not seem so hopeless and may be worth studying further. Decomissioning an offshore platform is an expensive and time-consuming operation. If the life-time could be extended by granting the platform a new function, the residual value of the platform may increase significantly which may be appealing to the O&G industry.

Figure 121. O&G platform being decomissioned in the North Sea.
Source: https://www.oilandgaspeople.com/

9. COMPARISON OF CONSTRUCTION PROPOSALS

Accurately measuring the execution risk of some of the most creative proposals is very unreliable and would be subject to personal bias. As no factual basis to support such claims exists, instead of attempting to accurately measure the technical risk and other features, an MCA will be the best way forward to compare the 15 proposals.

The criteria, and the pertinent rating philosophy are now presented:

Each construction proposal will receive a numerical score that will indicate its overall constructability index.

A fixed set of features (10) have been considered for each of the 15 proposals. These individual features will each be awarded a score from [0-4] based on the preliminary research that has resulted from this academic work.

The constructability index (C.I) will be obtained from a very simple expression that adds up all the individual features:

$$C.I = \sum_{i=1}^{10} \beta_i f_i$$

Where f_i is a given feature- i appointed a score {0, 1, 2, 3, 4} and β_i is the weight assigned to a given feature.

For this preliminary comparison, all the weights have been set equal. $\beta_i = 1$

In future studies, it will be interesting to tweak these weights in accordance with the main drivers that impact costs. The influence of a given cost-drivers in the construction phase will be identified and understood as concrete spar-buoy construction experience increases in the upcoming years.

9.1. DEFINITION OF FEATURES

The features that have been chosen to construct this MCA are the following:

Requirement [1], Requirement [2], Requirement [3]. Horizontal construction, monolithic result and suitable for serial production, respectively

Execution risk: This feature will account for the probability of failure of a given proposal and the consequences of such a failure on the overall structural soundness of the structure as well as the risk of damage to equipment, property and facilities. It will also take into consideration safety of workers on site and suitable working conditions.

Technological simplicity: This feature will not only refer to the complexity of the equipment, mechanized formwork, concrete placement scheme, specific technology required but will also include the complexity of the proposal from a holistic perspective. This means, technological simplicity will also take into account the smoothness of transition between phases, namely transition from construction phase to subsequent transport phase. Even the simplest construction proposals will contain some complexity.

Production time: This feature will assess the estimated delivery time of a given method to produce a complete tower. Expected delivery times will range from a day to several weeks per tower. All those proposals that offer the possibility to adjust delivery speed proportionally to the initial investment will be awarded the highest mark.

Design modifications: Design modifications will induce either major or minor modifications. Major modifications include those construction proposals failing to satisfy the main requirement of Windcrete, namely achieving a monolithic structure. Segmental approaches leading to construction joints will be considered as major design modifications. Minor modifications include providing additional reinforced sections within the tower to withstand construction loads.

Optimized handling operations: Will refer to the amount of handling required, handling understood in a broad sense. Handling will refer to form handling, handling of the entire structure (either during/after construction) and handling of parts of the structure (for segmental approaches). In reality handling of some sort cannot be avoided, this feature grades the value of optimization of handling operations (if any)

(**Estimated) Econ. Feasibility**: This feature will grade proposals based on the believed cost of production. It will account for costs regarding equipment, labour, handling operations, formwork systems and specific technology development.

Technological Readiness (*): Technological Readiness is closely linked to its constructability and feasibility. It will account for both the innovation and adaptation degree of a given proposal. Those proposals relying on novel technology, highly-specific research or untested concepts will receive the lowest mark. Proposals involving some (minor) adaptation of a readily available technology will be awarded an intermediate score. Proposals requiring no (or low) adaptation of current technology will receive a high score for this feature.

(*) Most of the proposals will encourage development of a specific technology & research from early stage to become truly feasible. For this reason, the rating scheme will not be too severe with those proposals requiring specific research if they are still believed to contain a promising aspect for further development.

9.2. RATING CRITERIA

The rating philosophy will be as follows:

Table 19. Rating Scheme for the 3 construction constraints

	0	2	4
Requirement [1]	Vertical construction		Horizontal construction
Requirement [2]	Proposals that include cold joints	Proposals based on the assembly line concept (*) Proposals with high risk of cold joints	Proposals with low or no risk of joints
Requirement [3]	Little mechanization or Slow production process	Slight mechanization or Moderate speed production process	High mechanization or Fast production process

(*) The assembly-line concept has been extensively described further in *Chapter 3. 7.4 Assembly-line concept*.

Only those proposals that unequivocally produce monolithic structures will be awarded the highest rating (4)

Those proposals that involve the assembly-line process, liable to result in cold joints, will be awarded a maximum rating of two (2). They will not receive the lowest score (0) as it is believed that the assembly-line concept, if properly scheduled, has the (unproven) potential to produce monolithic structures whilst breaking down construction into smaller separate units.

The remaining criterions are presented bellow as well as the rating scheme will be as follows:

Table 20. Rating Scheme of relevant features

	0	**2**	**4**
Execution Risk	High risk	Moderate risk	Reliable proposals with no execution risk
Technological simplicity	Very high complexity	High complexity	Moderate-low complexity
Production time	Slow	Moderate	Fast or adjustable (range of a day)
Design modifications	Major design modification	Minor design modification	No design modification
Optimized handling operations	Excessive Handling	Not optimized-normal handling	Optimized handling
(Estimated) Econ. Feasibility	Unreasonably expensive	feasible	Contains one or more elements optimizing costs.
Technology readiness	New technology required	Some innovation of readily available construction technologies	Minor or no innovation required

9.3. MCA OF CONSTRUCTION PROPOSALS

Table 21 MCA OF THE 15 CONSTRUCTION PROPOSALS

Proposal	Req. [1] Req. [2] Req. [3]	Execution risk	Technological simplicity	Production time	Design modifications	Optimized Handling operations	(Estimated) Econ. Feasibility.	Technology Readiness	Constructability index (_/40)
***Proposal 1**: Vertical Casting of the Structure (on land)*	**0** **4** **0**	**4**	**0**	**3**	**4**	**0**	**0**	**0**	**15**
Proposal 2: Vertical casting of the structure in segments.	**1** **2** **4**	**2**	**2**	**4**	**4**	**1**	**3**	**2**	**25**
***Proposal 3**: Horizontal casting in assembly-line*	**4** **2** **4**	**3**	**3**	**4**	**4**	**1**	**2**	**2**	**29**
***Proposal 4:** Open-cut tunnelling method*	**4** **4** **1**	**4**	**4**	**1**	**2**	**2**	**2**	**4**	**28**
***Proposal 5:** Horizontal casting in a semi-fixed mold.*	**4** **4** **4**	**4**	**4**	**4**	**4**	**4**	**1**	**2**	**35**
***Proposal 6:** Fixed jacking system*	**4** **4** **4**	**3**	**2**	**3**	**4**	**3**	**3**	**3**	**33**
***Proposal 7:** Telescopic travelling formwork*	**4** **4** **4**	**4**	**3**	**3**	**2**	**4**	**4**	**4**	**36**
***Proposal 8:** Self-advancing 'Cantilever carriage' system*	**4** **4** **4**	**3**	**2**	**3**	**4**	**3**	**3**	**3**	**33**
***Proposal 9:** Concrete crown*	**4** **3** **3**	**2**	**2**	**3**	**4**	**3**	**2**	**0**	**26**
***Proposal 1**0: TBM–adaptation (erector arm)*	**4** **4** **4**	**4**	**3**	**3**	**4**	**4**	**3**	**2**	**35**
***Proposal 11:** TBM-Adaptation 2.0*	**4** **4** **2**	**1**	**1**	**3**	**4**	**4**	**1**	**1**	**25**
***Proposal 12:** Exterior travelling Formwork- 'Ring Frame'*	**4** **4** **4**	**4**	**2**	**4**	**4**	**4**	**2**	**0**	**32**
***Proposal 13:** Centrifuge the entire tower*	**4** **4** **4**	**0**	**0**	**4**	**4**	**2**	**0**	**0**	**22**
***Proposal 14:** Post-tensioned prefab (centrifuge) rings*	**2** **0** **4**	**4**	**3**	**4**	**0**	**4**	**4**	**1**	**26**
***Proposal 15:** Vertical casting of the structure in an offshore factory (O&G platform)*	**0** **4** **4**	**1**	**2**	**4**	**4**	**3**	**1**	**0**	**23**

[1] Horizontal construction / [2] Monolithic structure / [3] Suitable for serial construction

9.3.1. <u>JUSTIFICATION OF ASSIGNED SCORES</u>

A short description of each proposal in terms of the main features will justify the assigned scores.

Proposal # 1 →uses vertical casting, leading to maximum handling challenge (turn finished structure from vertical to horizontal) making it not suitable for serial production, economically unfeasible and technologically complex from a holistic view of the overall process (poor connection construction-transport phases). Production time is 20-40 cm/hour allowing a moderate production time.

Proposal # 2 →relies on assembly-line concept (Req. 2=2/4) uses both vertical (pouring) and horizontal (assembly) (Req. 1=1/4). Requires 90º turning of mold making handling unpractical (depending on the size of forms) and transport of molds to assembly-line complexe. If scheduled correctly no modifications of the design required as cold joints are avoided. Equipment and energy to flip molds may be within reasonable limits. The main technology required is related to 'flipping' mold and subsequent transport. It is estimated to be a very fast method within the range of a day (depending on the size of molds and number of cranes working simultaneously).

Proposal # 3 →relies on assembly-line concept (Req. 2=2/4). Pouring and assembly is horizontal (Req. 1=4/4). Transport of molds to the assembly line make handling unpractical (depending on the size of forms), train bogies or similar required. Abundant heavy pushing of molds migh make method economically challenging. If scheduled correctly no modifications of the design required as cold joints are avoided. The main technology required is transport of freshly filled molds. Very fast method within the range of a day (depending on the size of molds and number of casting stations working in staggered cycles)

Proposal # 4 →uses readily available conventional modular formwork for open-cut tunnelling and simple (non-telescopic) travelling formwork. No complexity, but slow process that may take weeks. Many handling operations make method labour intensive, expensive and not ideal for serial production (Req. 3=1). Minor design modification may be required to include rail for the travelling formwork.

Proposal # 5 →massive (expensive) facilities, highly optimized (reduced) handling operations and novel concept for uncasting procedure (lower fixed-forms serve both as mold and individual dry-dock). Production speed is high to very-high and can be done simultaneously across the length of the entire structure. Building massive mold may induce some complexity

Proposal # 6 → significant adaptation (up-scaling a new functionality) tunnelling of micro-practices make it complex, expensive and unproven. Complexity is believed to be within reasonable limits.

Proposal # 7 → uses slightly adapted (detachable self-retracting forms not fixed to the traveller) conventional telescopic formwork for cast in-situ tunnelling lining. No significant complexity, moderate to moderate-fast process in the range of a week. Little handling operations make method good for serial production. Minor design modification may be required to include rail for the travelling formwork.

Proposal # 8 → uses novel travelling formwork (Cantilever carriage) minor adaptation from conventional formwork for cast in-situ tunnelling lining. Avoids design modifications as rails do not interfere with the structure to be built. Some technological complexity but estimated to be with acceptable limits.

Proposal # 9 → unproved novel high-tech 'Concrete Crown' (tech. readiness=0), complex, requires specific research and expensive to build. Uncertain success, requires axial pouring (creating an 'advancing concrete heap' within the forms) at a constant rate with many high-throughput pumps. Failure of a pump may compromise structural soundness of a given section. Estimated delivery speed: moderate, moderate-fast (depending on the pre-calculated placement rate).

Proposal # 10→ used uncomplicated adapted (tech. simplicity=2. tech. readiness=2) erector-arm to place forms (highly optimized handling) automated process ideal for serial production. Involves no travelling formwork, uses temporary structures to support forms from within, which are repositioned where required once concrete is hard.

Proposal # 11→ Similar to Proposal # 10 but requires significant additional complexity (tech. simplicity=1) to achieve movement (adaptation of TBM thrust cylinders) that causes wearing and early replacement of forms hindering economy (Econ. Feasibility=1) and making unsuitable for serial production (Req [3]=1)

Proposal # 12 → unproved highly complex travelling formwork (tech. simplicity=2. tech. readiness=0), requires specific research and expensive to build but high productivity and estimated delivery times may offset initial costs (Production time=4, Econ. Feasibility=2). Unproven method but seemingly simple, reliable with low risk (Execution risk=4).

Proposal # 13→Very complex facilities, interdependency of spinning mechanisms, high probability of failure and propagation of failure to structure and to equipment (tech. simplicity=0, (Execution risk=0, tech. readiness=0). Energy requirements and coordination of large number of cogwheels lead to unreasonably high costs ((Estimated) Econ. Feasibility=0). Theoretically, ideal for high-speed horizontal fabrication of Windcrete circular cross-section with enhanced mechanical properties (Req. [1] = Req. [2]=Req. [3]=4).

Proposal # 14→ Does not satisfy main construction requirement, no monolithic structure (Req.[2]=0) which induces major design modification (design modification =0). Up-scaling centrifuge technology to 13 diameter sections still uncertain (techn. Readiness=1). If up-scaling possible, high speed and quality of produced ring-segments results in a cost-effective method ((Estimated) Econ. Feasibility=4) by 'breaking-down' construction into smaller units. Individual centrifuge stations present lower execution risk (Execution risk=4) and eliminates the need for cores reducing handling operations but segments still need to be assembled and post-tensioned (Optimized handling operations=3)

Proposal # 15→ 'Futuristic', adaptation of O&G platform due to be decommissioned (techn. Readiness=0). Vertical casting of the structure at sea, requires offshore concrete batching plant, mainly unfeasible except with the cooperation of O&G industry ((Estimated) Econ. Feasibility=1). If Wind and O&G offshore industries were to work together the economic feasibility would likely increase. Uses slipform which results in good quality of structure but results in unstable platform and unsafe working conditions for workers (Execution Risk=1). Structure directly pushed into the sea as construction progresses, partially unresolved but reducing handling and making it suitable for serial production (Optimized handling operation=3, Req.[3]=4).

9.3.2. VALIDITY OF RESULTS

The results of this MCA should be treated with care and should only be seen as a preliminary classification based on the selected features. The constructability index must not be confused with the technical feasibility of a given proposal, even if the two are related. The C.I is a variable that specifically assesses the constructability of a given proposal in 'Windcrete terms', that is in terms of serial production, horizontal construction and monolithic nature of the final structure. Thus, the C.I accounts for a broader range of additional requirements, which are not indispensable for a structure to be constructible. The C.I score is better seen as the capability of a given method to satisfy the specific requirements desired from Windcrete construction rather than just the basic requirements to be constructible.

This rather simplified assessment of the different proposals hopes to account for all the main cost-drivers that are deemed of interest to define a cost-effective construction solution. However, some features include far too many variables that may react differently for a given proposal. Features should be further broken down for a finer assessment.

As the same weights have been assigned to the different features of the assessment, some results may appear surprising and even misplaced. Appointing the same weights translates in assigning equal importance to all of the features which is not necessarily correct. This may lead to disproportionate results that do not capture important particularities of some proposals.

For instance, allowing designs modifications should be considered if they lead to a significant cost- reduction. Therefore, design modifications should not be penalized in the same way when they favour cost-efficiency.

An example of this disproportion can be found when comparing constructability index (C.I) of *Proposal 5* and *Proposal 14*. From an economic and technical perspective, it seems unlikely that building a permanent massive mold is more viable than constructing Windcrete through a pre-fab ring segment approach.. In fact the estimated economic feasibility of the post-tensioned segment approach has been awarded the highest score (4), attained only by one more proposal while *Proposal 5* has scored a low score (1) for the same aspect. Yet *Proposal 5* scored a C.I of 35 while the segment approach was only awarded a C.I of 26, which may seem unrealistic.

This incoherence can be explained by the fact that all weights have been set equal and that the MCA heavily penalizes a major design modification, even if it leads to a much more-economical construction process. Appointing equal importance to all the features will be misleading and corrections to the relative importance of each feature will increase the reliability of the C.I.

9.3.3. ADVANTAGES OF PERFORMING A SENSIBILITY ANALYSIS

Often, when a MCA analyisis is performed, a sensitivity analysis is done to study the uncertainty of the output. Through a sensitivity analysis the relationships between input (features) and output (Constructability index) can be further understood and the features that lead to significant changes in the C.I can be identified. By doing so, the relevant features can be studied in greater detail or further divided to decrease the uncertainty of the MCA result. A sensitivity anlysis can be performed in a multiple of ways, perhaps the most common is the one-at-a-time method, which consists on altering one input at a time while leaving the others fixed to assess the relative impact of a given input based on the variations of the output.

To obtain a more reliable result, it would be interesting to perform a sensitivity analysis to assess the influence of each of the chosen features on the C.I. This woud provide some valuable insight on the quality of the choice of features and determine wether a different set of features will be better at predicting the constructability of Windcrete towers.

The above-mentioned sensitivity analysis and the subsequent fine tuning of features has not been realized in this academic work, but are definitively worth considering by upcoming studies to work towards a robust model to predict the possibilities of success of a given construction method. The relative importance of a certain parameter on the construction process will become easier to assess as fabrication of spar-buoys increases. The practical experience that will be gained by constructing towers will provide valuable feedback on new parameters to include, or redundant features that must be corrected.

10. CONCLUSIONS

One of the first goals that was defined at the start of this work was to assess the suitability of readily available construction technology for fabricating Windcrete towers.

Based on an extensive overview that covered a wide range of civil engineering fields, it can be said that almost no technologies can meet simultaneously all three constraints of our project without any adaptations. These three singular constraints of the Windcrete project are a large concrete structure built in horizontal position, preferably in a single monolithic pour (with high quality standards) and within a reasonable fabrication time suitable for serial prodcution.

Due to the fact that technologies in their usual context are faced with a series of unique constraints under which they have developed, it is highly improbable that a given technology directly matches Windcrete's particular construction constraints.

Therefore, if suitability was defined as the ability to directly apply a given technology for tower production, one would have to recognize that no suitable technology readily exists.

This work has found that the suitability of existing technology can really only be measured by the degree of adaptation we are willing to consider.

Generally speaking, tunnel construction methods may be seen as the most suitable as they will require the lowest adaptation when compared to technologies from other fields. However, here too it is almost impossible to directly apply inspiring tunnelling practices without some degree of adaptation. For instance, current tunnelling methods typically include at least 2 cross-sectional joints as well as a number of construction joints between different sections cast separately. Tunnelling methods will therefore need some adaptation to achieve continuous placing and avoid joints. Further modifications will be necessary to achieve the desired circular cross-section rather than the semi-circle, or horse-shoe cross-section that results from most tunnelling practices today.

Low-level adaptations, namely technology from the tunnel industry, only take us so far. If a wider range of solutions wants to be considered, broadening the scope to other civil engineering fields is necessary. The adaptation degree will vary considerably depending on the field of study. When looking at other areas for inspiration, less obvious technologies start emerging and one finds that the required amount of adaptation quickly becomes significant. Inspiring technologies begin to require more complex adaptations to become useful to the project. Higher degree of adaptation is assumed to directly increase costs.

However, choosing a technology based solely on minimizing the required degree of adaptation will not always lead to the best solution for tower construction. Sometimes a more complex adaptation, and therefore higher costs, may be justified in exchange for a significant increase in productivity. Thus, a highly-adapted technology can easily become more suitable for Windcrete production than a technology requiring little adaptation.

Besides adapting certain proven techniques, which will always lead to adaptation costs, it may be worth considering to reallocate some of these resources to develop new technologies through innovation, rather than adaptation.
For this reason, instead of only suggesting adaptations of existing technologies, this work has also promoted innovation based on the specific constraints of our project.

The costs of heavily adapting current technology should be compared with the costs of research and development of new technologies. The advantage of achieving construction through innovation rather than adaptation is that solutions can be designed to directly address all the requirements of the project. The main disadvantage of innovative approaches is that they present increased technical risks during execution. Risks, however, can be expected to decrease as construction experience increases.

What can be drawn from the findings of this research is that existing technology will only be suitable if the degree of adaptation it must undergo before it can be used to produce Windcrete towers is reasonable in terms of costs. If adaption becomes too expensive it will be more cost-effective to invest in the development of a tailor-suited technology that satisfies all of the specific requirements.
Additionally, a high degree of adaptation can be preferred over a lower adaptation level if it optimizes serial production, which will offset the increased adaption costs on the long-run.

The specific requirements that this academic work established was to develop a set of construction proposals that successfully achieve the serial producton of Windcrete. This has culminated in 15 construction methods that have been described in terms of their strengths and weaknesses, the main cost drivers involved, their operative cycle and additional comments regarding the optimization of each of these methods. These proposals have been based on four distinct logics: proposals based on minor adaptations of current technology, proposals based on up-scaling existing technology, proposals based on modifying the original use of a given technology and give it a new purpose, and proposals based on innovation. Some proposals will also be the result of a combination of these logics.

The final objective was to compare these proposals by assessing the technical feasibility of each method. Accurately measuring certain aspects related to the technical feasibility of some of the most creative proposals, such as the execution risk, would lead to unreliable results and would probably be subject to personal bias. As no factual basis exists for most of the proposals, comparison of methods was done through a MCA based on 10 features.

It must be recognized that Windcrete's construction proposals do pose particular challenges for passing the technical feasibility assessment. This is due to the following aspects:

HEAVY ADAPTATIONS HAVE BEEN NECESSARY

Existing technology has served as a starting point, but has undergone a deep adaptation process. Known technology has been adapted and integrated into tailor-suited construction proposals, some of which have taken the inspiring technology to a whole new level, beyond recognition.

The degree of adaptation is an important aspect to consider as usual technology will not be fully operational in different conditions. For instance, let's look at Proposal 6: although trenchless pipe-jacking methods are widely understood, adapting the jacking ring to push on steel molds instead of on pre-fabricated concrete segments is a whole new use of a well-known technology that is yet to be proven. Another example is Proposal 10 which considers adapting the erector arm of a TBM to place curved forms instead of pre-fabricated tunnel linings. One could argue that, through an innovative use, a verified technology may in fact become a new technology.

Assessing new usage of familiar technology is no easy task. However, this assessment is fundamental to narrow down the many construction proposals to just a few promising solutions.

UPSCALING FAMILIAR TECHNOLOGY TO NEW LEVELS

Another challenge is to assess the feasibility of proposals involving a considerable up-scale of a known technology. The main example that comes to mind is upscaling centrifugal concrete casting practices to unprecedented dimensions (Proposals 13 &14). A reliable method to produce small pipes (0.3 to 1.6 m in diameter) quickly becomes uncertain for large-scale applications and assessing whether it is technically feasible is problematic due to the lack of similar projects. Here too, estimating the energy requirements is also a major issue and will partially depend on the stiffness of the concrete available on site.

NOVEL TECHNOLOGIES

Assessing the technical feasibility becomes even more complex for those proposals that rely on technology not significantly tested, such as equipping molds with wheels and transporting them to a near-by assembly line while concrete is still fresh (Proposals 2 & 3).

Initiatives with technological complexities such as proposals that use novel technology incorporate even higher levels of technical risks. The main novel technologies that have been suggested in this work are:

-the 'Concrete Eye' that 'extrudes' the cross-section into a launching lane thanks to a circular arrangement of Hydraulic jacks and a re-adaptation of microtunnelling practices (see. *Figure 118*)

- the Cantilever Carriage (see. *Figure 119*) that is able to support forms while it slides on rails that are placed strategically outside the concreting section.

- the Concrete Crown concept (see. *Figure 120*) which inserts concrete axially while moving backwards.

- The highly-specialized 'Ring traveller' (see. *Figure 121*) designed to wrap itself around the structure as construction progresses. The traveller temporarily surrounds, or envelops the structure to construct. It holds forms in place during concreting, which are then left in place resting on suitable supports while the traveller 'unwraps' and moves on to the next section. Although these genuine technologies may hold on paper, and can be defended from a theoretical point of view, claiming that they are reliable and infallible solutions to construction would be irresponsible. Obviously unverified technology must be treated with caution and the technical risk of these devices must be acknowledged.

HIGHLY-ADAPTED AND NOVEL CONCEPTS INTRODUCED IN THIS WORK

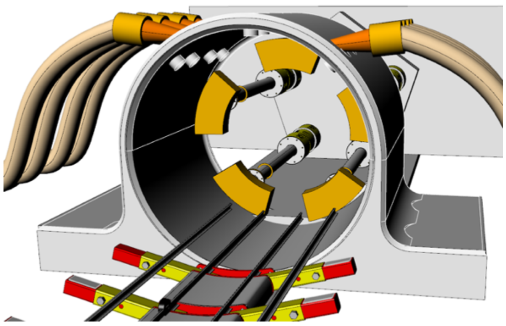


Figure 122. Adapted concept 'Concrete Eye'-Proposal 6

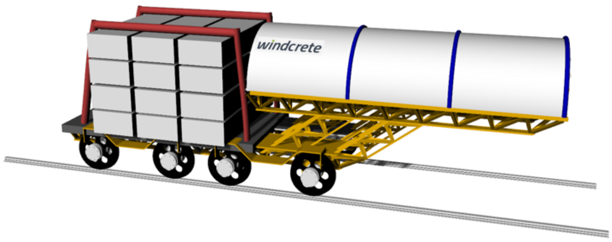


Figure 123. Novel concept 'Cantilever Carriage'-Proposal 8

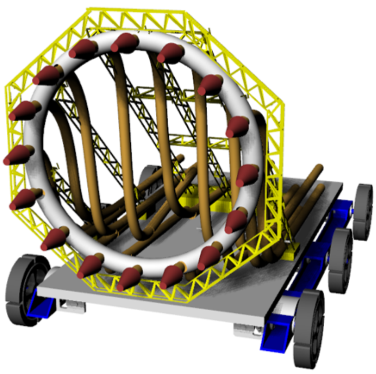


Figure 124. Novel concept 'Concrete Crown-Proposal 9

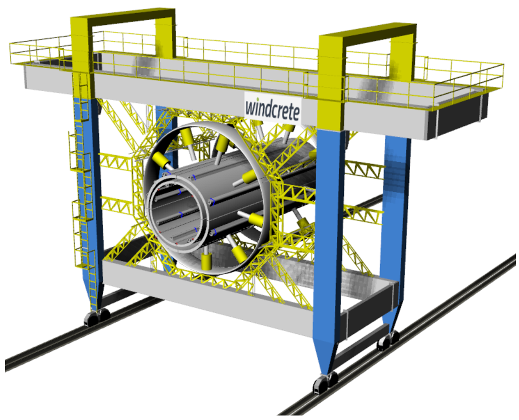


Figure 125. Novel concept 'Ring Frame'-Proposal 12

The MCA introduces the Constructability Index (C.I). The C.I score is should be seen as the capability of a given method to satisfy all of the specific requirements desired from Windcrete construction rather than just the basic requirements to be constructible. Therefore, a high-score does not mean that a certain proposal is more constructible than another with a lower score, it just means that it is more suitable in terms of serial production, horizontal construction and monolithic nature of the final structure.

Now that the limitations of a simplified MCA have been recognized it´s results can be presented and discussed. Based on this MCA, the ranking of the proposals is as follows (from highest to lowest score)

Table 22. MCA RESULTS: ranking of proposals base on Constructability Index (C.I)

Ranking	Proposal	C.I
1	**Proposal 7:** *Telescopic travelling formwork*	36
2	**Proposal 10:** *TBM–adaptation (erector arm)*	35
3	**Proposal 5:** *Horizontal casting in a semi-fixed mold.*	35
4	**Proposal 8:** *Self-advancing 'Cantilever carriage' system*	33
5	**Proposal 6:** *Fixed jacking system*	33
6	**Proposal 12:** *Exterior travelling Formwork- 'Ring Frame'*	32
7	**Proposal 3:** *Horizontal casting in assembly-line*	29
8	**Proposal 4:** *Open-cut tunnelling method*	
9	**Proposal 14:** *Post-tensioned prefab (centrifuge) rings-* Alternative 0	26
10	**Proposal 9:** *Concrete crown*	
11	**Proposal 11:** *TBM-Adaptation 2.0*	25
12	**Proposal 15:** *Vertical casting of the structure in an offshore factory (O&G platform)*	23
13	**Proposal 2:** *Vertical casting of the structure in segments.*	
14	**Proposal 13:** *Centrifuge the entire tower*	22
15	**Proposal 1:** *Vertical Casting of the Structure (on land)*	19

Generally speaking, those methods inspired by tunnelling practices have obtained high scores in the MCA (higher than 29/40) for seemingly obvious reasons. Windcrete's shape resembles that of a tunnel, cross-sectional dimensions are comparable and tunnelling formwork technology has achieved high rates of mechanization that will be preferred in a serial production. Also, the potential to use commercial products of the tunnelling industry offers the opportunity of significant cost-reduction. For these reasons, Telescopic travelling formwork and TBM erector arm adaptation rank 1st and 2nd respectively. The first will require prior construction of travelling beams inside the structure to be built for telescopic forms to slide through other sections where concrete is still hardening/curing and be re-erected in a highly-automated process. The 2nd achieves a high C.I score by optimizing form handling through the adaptation of a TBM erector arm to place and strip forms. The adaptation is believed to be acceptable in terms of complexity, which explains the high score of such a novel concept.

The cantilever carriage, a 'minor' adaptation of travelling formwork for in-situ cast linings and an adaptation of traditional open-cut tunnelling practices rank 4th and 7th respectively. The appointed score of these methods is proportional to their degree of mechanization. The proposals will not lead to any significant design modifications, mainly just some additional reinforced sections to anticipate construction loads exerted by travelling formwork, which has also been accounted for by the MCA.

The massive permanent mold has obtained a surprisingly high score. Although it is economically challenging to develop such facilities, which would presumably become the biggest mold ever created, the execution risk is so low and delivery time so fast that the C.I becomes appealing. Additionally, the complexity of the method is not significant and the quality of the structure produced is estimated to be high. A very high demand for Windcrete towers and allocating the factory at a suitable location may be the ruling factors that determine if this method is economically feasible.

A traveling engineered formwork system in exchange for greater productivity is practically unavoidable as demonstrated by the tunnel-inspired proposals that lead the ranking with high in C.I. In this same line of reasoning, an Exterior Travelling formwork, a novel concept designed to achieve the specific dimensions of Windcrete, was awarded the 5th position. Despite the unproven technology, the potential of such a sliding system to reduce costs by maximizing productivity is considered promising. One must accept that a very start large upfront costs to design such a sliding systems will be offset on the long-run by serial production. The size and complexity to build the Ring traveller are significant, but once these obstacles are overcome, the operative cycle is fairly simple and allows casting of large sections at once.

Another genuine idea is the implementation of a highly-optimized schedule of staggered production cycles involving several identical casting stations. As it is yet unclear whether these methods can truly avoid joints, the assessment has chosen to be conservative. Those proposals involving the assembly-line concept have been ranked according to their estimated risk of producing joints and the amount of handling required. Horizontal assembly-line method and the vertical assembly-line method ranked 7th and 12th respectively. The main advantage of staggered cycles is that production rates are high to very-high and with the sufficient amount of casting stations a complete tower can be fabricated in a day. The execution risk is deemed high due to the extreme time-sensible nature of these proposals which must maintain a strict schedule.

Other innovative proposals have been assessed more severely, such as the Concrete Crown, that involves novel technology and an uncertain concrete placement scheme. This method is ranked 8th as it relies on several assumptions that have not been tested. Additional research may rule it out as unpractical or on the contrary increase its C.I score.

The remainder of the proposals score low in C.I mainly due to high execution risks and costs related to building the facilities (Proposal 15 & 13I) or to unreasonable handling operations (Proposal 1).

Apart from the essential construction constraints, the major design drivers for the construction process are:

- The general complexity of the proposal from a holistic perspective (smoothness of transition between construction and subsequent transport phase)

- The specific complexity of the technology involved in terms of necessary research, fabrication complexity, size and type of facilities, energy requirements and maintenance.

-The execution risk in terms of probability of failure, consequences of such a failure, safe working conditions, risk of damage to structure, equipment and facilities. A main aspect to include in execution risks is the likeliness of undesired joints occurring during construction.

- The amount of form handling operations, the degree of mechanization and the delivery time to complete a structure should all be optimized from the perspective of serial production.

- The flexibility of the facilities, that should be suitable to deploy in a wide range of coastal locations instead of locations of exceptional nature. Norwegian fjords are a convenient location to upend the spar platform by introducing ballast. However Norwegian fjors, deep, enclosed and nearshore represent a unique worldwide exception (Joao Cruz, 2016). Decomissioned offshore platforms are also too scarce to design a construction proposal based on such locations.

Finally, a low technological readiness for a given proposal should not be seen as a drawback but rather an opportunity to create value through new technology and optimize productivity in tower production.

The balance between innovation and adaptation will be at the core of defining a cost-effective construction process. Existing technologies for tower production will certainly need to be adapted from their usual context if they are to satisfy the desired features of Windcrete, however some adaptations may be less feasible than developing novel technologies. Coming up with the right technology will only be possible through the combined efforts of civil, as well as mechanical and electrical engineers.

Emphasis on Design for Construction

The design of Windcrete, has been considered fixed throughout this academic work particularly regarding dimensions. However, it frequently is possible to modify the design slightly to achieve economy in construction without impairing the functionality of the structure (Robert L. Peurifoy, 2011). Windcrete designers must integrate constructability at the core of the concept as often two or more designs will meet the design objective equally well, however, one alternative may be significantly less expensive to construct. "Design for construction" should remain a priority when designing the structure even at the earliest design stage.

Thus, one must recognize that for constructing Windcrete, the design process will have a major impact on the construction possibilities and both need to be addressed simultaneously. A coupled design-construction approach leads to certain interesting remarks.
Some elements required to aid construction, such as additional reinforced sections to carry construction loads or rail-tracks used by travelling formwork may find their place in the permanent structure.

In a similar way that reinforced sections are considered to support the mooring lines (Figure 117), these sections could also be designed to previously accommodate a series of rails for self-propelled formwork systems. Note that it would be interesting to integrate these rails into the final structure. These rails could become useful to lower equipment into the base of the tower for ballasting the structure through self-discharging trolleys during the installation process or even better, to install the elevator that provides access to the nacelle.

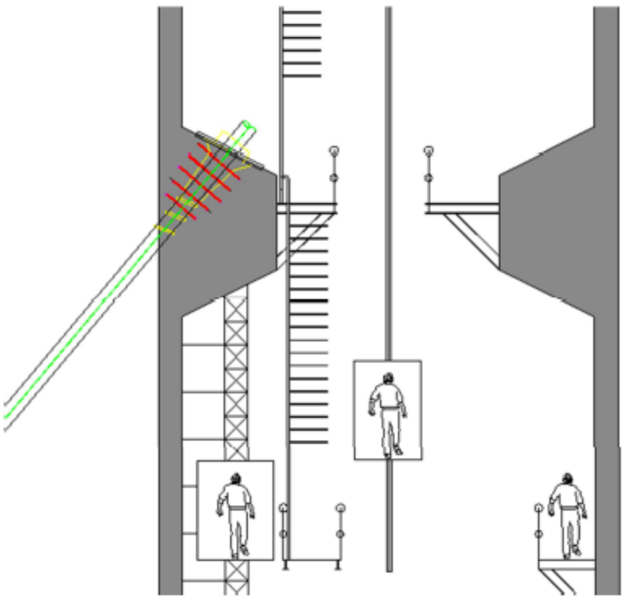


Figure 126. Table 25. Reinforced sections for anchooring of mooring lines. Source: (Campos, 2012)

In this sense, the structural design should remain open to certain modifications that will both aid construction and lead to practical applications during the operational lifetime of the structure.

Even if will be clearly advantageous to modify the interior of the tower to a certain extent, all these modifications are liable to alter the stiffness, weight and stability of the completed structure, which will have to undergo a new dynamic analysis.

- Specific research on allowing construction joints

Initially, to get this project running a cheaper construction process may be the best way forward, even if this means modifying the design. It is believed that tolerating a few construction joints should be considered if it drastically reduces the cost of producing towers. Under this assumption, detailed investigation on joint technology capabilities and durability in offshore applications is fully justified.

If segmental-precast construction is chosen as the preferred manufacturing method there will be concrete-to-concrete or concrete-to-steel joints (for hybrid designs) that require careful consideration. Different joint configurations will be assessed to find the most appropriate solution that fulfil the stringent requirements of offshore structures and without compromising durability. In a full-concrete structure, the interface between segments should be rough enough to provide adequate adherence and ensure high-resistant bonding of the wet joint. Wet joint construction should be done using high quality concrete such as HPC or UHPC to guarantee the structural integrity of the structure and the durability of the joint. Strengthened epoxy bonds will also have to be considered. Additionally, joints should incorporate mechanical connections to transfer loads between different segments (N. Khosravi, 2015). Flat faced bonded joints without mechanical considerations, which are cheaper, are likely to not be suitable for such an offshore project. The durability of the bond between segments is a prime concern and no cost savings should be sought in the design of these joints. At interface between segments, stainless reinforcement bars will be preferred. Post-tensioning will be crucial in a segmental-precast support structure to increase the shear capacity.

The underlying idea behind ***Proposal 14:*** Post-tensioned prefab (centrifuge) rings, which has also been refered to as *Alternative 0* is precisely to suggest breaking up construction into smaller units, thus not satisfying the requirement of a monolithic structure, to reduce construction costs. The advantages and disadvantages of such a segment approach will need to be further understood and weighted out, particularly with regard to increased maintenance costs and the impact on the life-time of the structure.

- Specific research on minimising the effects of cold joints

If a monolithic structure with no construction joints is preferred, a lot can be gained by investigating an allowable time limit for successive concrete placements. A good understanding on the time before cold joints forms and their structural repercussion will alleviate the stringent requirements of monolithic pours. A new family of approaches could obtain a seemingly monolithic result by producing discrete segments that are swiftly assembled while still fresh. Specific research on avoiding cold joints and/or minimising their effect on the finished structure may provide valuable feedback and lead to a game-changing construction philosophy. Assessing the resistance of cold joints in the offshore environment should be carried out with the aid of Finite Element Method analysis. The results of such a research will determine whether cold joints are appropriate for transferring the dynamic loads occurring offshore whils maintaining a watertight structure.

- Establishing a suitable framework to assesss constructability

A sensitivity analysis and the subsequent fine tuning of features has not been realized in this academic work, but are definitively worth considering by upcoming studies to work towards a robust model to predict the possibilities of success of a given construction method. In addition to the features that have already been integrated in the MCA, further research must identify other drivers that will be relevant in defining a cost-effective construction process. A sensitivity analysis of the MCA presented in this work will help identify main sources of variability and will find that a different combination of features may lead to a more reliable assessment of the Constructability Index. Establishing a robust model to assess construction options will become useful to narrow down candidate solutions whilst accounting for all the main drivers of a cost-effective solution and the specific requirements of the project.

The relative importance of a certain parameter on the construction process will become easier to assess as fabrication of spar-buoys increases. The practical experience that will be gained by constructing towers will provide valuable feedback on new parameters to include, or redundant features that must be corrected.

- Research on new technologies

As innovation is at the core of FOWT design, it should come as no surprise that innovative construction procedures may have to be developed.
Coming up with the right technology will only be possible through the combined efforts of civil, as well as mechanical and electrical engineers. This multidisciplinary task is due to be complex and will require extensive research. It will also provide an interesting space for academia and contractors to work together towards a suitable formwork engineered system. Re-thinking concrete placing schemes and an industrialized outlook on the construction process will also benefit finding a cost-effective solution.
New techniques will have to be developed for solving a highly specific challenge such as the ones mentioned throughout this preliminary analysis of construction proposals. Thorough investigation will almost certainly lead to new and different alternatives to those presented in this document.

Finally, the author would like to state that Future FOWT will need to remain flexible with increasing depth and be ready to accommodate larger turbines. The offshore industry is willing to assume greater implementation costs in exchange of generating more energy. Everything seems to indicate that turbine rating will continue to increase as the industry deploys more structures at sea. Turbines up to 20MW rated capacity will be a reality and are expected to enter the offshore wind energy market on the medium- to long-term scale (Vries, 2011)
Being well aware of the market trends, namely up-scaling, and keeping in mind the industry's future demands is the only way to submit a future-proof solution.

The views that have matured from this academic work regarding optimizing Windcrete construction is that the tunnel industry_seems like a very reasonable place to start.

Independantly on the proposal, curved form panels that suit Windcrete's dimensions are readily available in the form of commercial products offered by the tunnelling industry. The tunnel industry also offers a valuable range of opportunities regarding highly mechanized engineered formwork systems that should definitively be explored for Windcrete constructon.

However, on the long term, the Windcrete project should aim at developing new techniques and specific equipment that satisfies all the particularities of a singular structure whilst maximizing productivity.

Windcrete's unique constraints can play a special role in creating value, as drivers of discovery and invention.
Promoting creativity and innovation may be the best way forward for this novel monolithic concrete-spar-buoy to go from a promising concept to a fully operation utility-scale FOWT at sea.

Windcrete has the potential to increase the lifetime of the support structure like no other existing concept whilst offering a practically maintenance-free design, a cost-effective installation process and reducing material costs. These unique features will bring down the costs of offshore wind in a whole new way, which gives Windcrete the upper hand over other FOWT concepts. Windcrete presents series of cost advantages that can offset the technical complexity of building a monolithic spar-buoy horizontally and fully justify large investments on specific research and construction technology to optimize tower production.

11. REFERENCES

4C Offshore, 2015. *www.4coffshore.com.* [Online]
Available at: http://www.4coffshore.com/windfarms/eneco-luchterduinen-netherlands-nl32.html
[Accessed 7 March 2017].
Acciona, 2014. *Acciona.* [Online]
Available at: http://www.acciona.us/projects/industrial/adriatic-lng-terminal-caisson/
[Accessed 4 March 2017].
Acciona, 2014. *Experiences Acciona.* [Online]
Available at: https://experiences.acciona.com/2017/01/25/kugira-giant-artisan/
[Accessed 3 March 2017].
ARPA-E, 2011. *Rare Earth Alternatives in Critical Technologies (REACT).* [Online]
Available at: https://arpa-e.energy.gov/?q=arpa-e-programs/react
[Accessed 11 June 2017].
Böhmeke, G., 2013. *Samsung Heavy Industries comments on gearbox vs direct drives,* Berlin: nternational Quality & Productivity Center in Germany.
Bamforth, P., 2003. Concreting large-volume (mass) pours. In: B. S. C. John Newman, ed. *Advanced Concrete Technology Set.* London: Butterworth-Heinemann, p. 1920.
Bilgin, N. C. H. B. C., 2013. *Mechanical Excavation in Mining and Civil Industries.* s.l.:Taylor & Francis Group.
Butterfield, S., 2013. *Drive Train Innovations for the Next Generation of Wind Turbines.* Boulder, Big Energy Seminar Series. The Department of Electrical, Computer, and Energy Engineering and the Renewable and Sustainable Energy Institute (RASEI).
Butterfield, S., Jonkman, J., Musial, W. & Sclavounos, P., 2005. *Engineering Challenges for Floating Offshore Wind Turbines.* Maine, U.S. Department of Energy.
Carter, B. R., 1982. *Concrete construction using slipform techniques,* Gainesville: University of Florida.
Chu, V. T., 2010. *A Closer Look at Prevailing Civil Engineering Practice – What, Why and How.* s.l.:s.n.
Cruz, J. & Atcheson, M., 2016. *Floating Offshore Wind Energy: The Next Generation of Wind Energy.* s.l.:Springer.
Dalgic, Y., Lazakis, I. & Turan, O., 2013. *Vessel charter rate estimation for offshore wind O&M activities.* A Coruna, University of Strathclyde Glasgow.
Deo, M., 2013. *Waves and Structures.* Mumbai: s.n.
European Wind Energy Association, . ., 2009. *Wind Turbine Technology for Offshore Locations: Availability, Reliability and Access.* s.l.:European Wind Energy Association.
EWEA, 2015. *The European offshore wind industry - key trends and statistics 2015,* s.l.: EWEA.
EWT Direct Wind, 2015. *Direct drive technology.* [Online]
Available at: http://www.ewtdirectwind.com/technology/direct-drive-technology.html
[Accessed 23 May 2017].
EWT, n.d. *Direct drive technology.* [Online]
Available at: http://www.ewtdirectwind.com/technology/direct-drive-technology.html
Galbiati Group, 2014. *http://galbiatigroup.it/custom-built-machines/category/tunnel-boring-machines/page/2/.* [Online]
Available at: http://galbiatigroup.it/custom-built-machines/category/tunnel-boring-machines/page/2/
[Accessed 11 May 2017].

Gilman, P. et al., 2016. *National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States.* s.l.:U.S. Department of Energy, U.S. Department of the Interior.
Gurley, E., 2010. *Hot weather concreting.* [Online]
Available at: http://precast.org/2010/05/hot-weather-concreting/
Haar, C. v. d. & Marx, S., 2015. *Design aspects of concrete towers for wind turbines,* Cape Town: Journal of the South African Institution of Civil Engineering.
Haar, C. v. d. & Marx, S., 2015. Design aspects of concrete towers for wind turbines. 57(4), pp. 30-37.
Haiyu Industry, 2012. *Manufacturer of Concrete Pole.* [Online]
Available at: http://hypolemachine.com/3-2-centrifugal-concrete-tube-machine
[Accessed 14 May 2017].
Hurd, M. K., 2005. *Formwork for Concrete.* s.l.:American Concrete Institute.
Kuranovas, A. & Kazimieras Kvedaras, A., 2010. Centrifugally manufactured hollow concrete-filled steel tubular columns. *Journal of Civil Engineering and Management,* 13(4), pp. 297-306.
Lönker, O., 2004. *Operation offshore,* Osnabrück: New Energy.
Maritime Denmark, 2013. *Maritime Denmark.* [Online].
Matha, D., Fisher, T., Künh, M. & Jonkman, J., 2009. *Model Development and Loads Analysis of an Offshore Wind Turbine on a Tension Leg Platform, with a Comparison to Other Floating Turbine Concepts.* Oslo, NREL.
Molins, C., Campos, A., Gironella, X. & Trubat, P., 2016. Spar concrete monolithic design for offshore wind turbines. In: *Open PDF Proceedings of the Institution of Civil Engineers - Maritime Engineering.* Barcelona(Catalunya): Institution of Civil Engineers, pp. 49-63.
Morris, L., 2011. Direct Drive vs. Gearbox: Progress on Both Fronts. *Power Engineering - Barrington then Tulsa,* 115(3), pp. 38-42.
N. Khosravi, L. B., 2015. Use of concrete as the primary construction material for the Prelamis wave energy converter. In: C. G. Soares, ed. *Renewable Energies Offshore.* London(London): Taylor & Francis Group, pp. 305-311.
Newman, J. & Choo, B., 2003. *Advanced Concrete Technology Set.* London: Butterworth-Heinemann.
Office of Materials and Road Research, 2003. Chapter 6: Placement Operations. In: M. D. o. Transportation, ed. *Concrete Manual.* Minnesota: Minnesota Office of Materials and Road Research, p. 458.
Okumoto, Y., Takeda, Y., Mano, M. & Okada, T., 2009. *Design of Ship Hull Structures: A Practical Guide for Engineers.* 2 ed. Tokyo: Springer.
Portal, T. C., 2012. *The Concrete Portal.* [Online]
[Accessed 14 May 2017].
Rabbat, B., Asce, M. & Russell, H., 1985. Friction Coefficient of Steel on Concrete or Grout. *Journal of Structural Engineering,* March, 111(3), p. 124.
Rijkswaterstaat, 2016. *The storm surge barrier in the Eastern Scheldt,* Rotterdam: Ministry of Infrastructure and the Environment.
Society, The Concrete, 2014. *http://www.concrete.org.uk/.* [Online]
Available at: http://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=370
[Accessed 3 May 2017].
The constructor, n.d. *https://theconstructor.org.* [Online]
Available at: https://theconstructor.org/concrete/pumped-concrete-pump-types-selection/6081/
[Accessed 5 May 2017].

The Seasteading Insititute, 2010. *https://www.seasteading.org/*. [Online]
Available at: https://www.seasteading.org/2010/05/cocrete-structures/
[Accessed 23 March 2017].
Utsunomiya, T., Sato, I., Shiraishi, T. & Ishida, S., 2015. Floating Offshore Wind Turbine, Nagasaki, Japan. In: *Large Floating Structures*. Singapore: Springer, pp. 129-155.
Veers, P. S. & Butterfield, S., 2000. *Extreme Load Estimation for Wind Turbines: Issues and Opportunities for Improved Practice*. s.l.:United States. Department of Energy.
Vries, W. d., 2011. *Support Structure Concepts for Deep Water Sites,* Delft: Delft University of Technology,
Wang, C. & Wang, B., 2015. *Advances, Large floating structures: Technological*. s.l.:Springer.
Wankhede, A., 2016. *Dry Dock, Types of Dry Docks & Requirements for Dry Dock*. [Online]
Available at: http://www.marineinsight.com/guidelines/dry-dock-types-of-dry-docks-requirements-for-dry-dock/
[Accessed 8 February 2017].
Watson, G., Hill, B. & Courtney, F., 2005. *A framework for offshore wind energy development in the United States,* Washington: U.S. Department of Energy, General Electric.
Yee, S., 1977. *Operational experience with pre-stressed concrete barges.* London, Royal Institution of Naval Architects, pp. 71-82.