CONCRETE IS THE FUTURE FOR OFFSHORE FOUNDATIONS

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ABSTRACT

Most offshore wind farms have steel monopile foundations, but in Denmark concrete gravity foundations have been used with success. At least two projects have tendered steel monopiles against concrete foundations and have implemented the concrete foundations that proved cheaper. No project has tendered monopiles against concrete and chosen steel monopiles.

Nysted offshore wind farm has the cheapest foundations of any offshore wind farm so far, and they are in concrete. If foundation plans for London Array West Offshore Wind Farm are based on an adaption of the Nysted solution few adaptions will be necessary. The result can be a project with the same very low foundation cost level as Nysted. Optimised design of light weight concrete constructions is the key to low cost installation, whereas cheap manufacture can be carried out far from London at little extra transport cost compared to Nysted.

The main construction of concrete gravity foundations will become half as costly as of steel monopile foundations, and though installation is more costly for the gravity foundations it seems most likely that tendering between steel monopile and concrete gravity for London Array West will prove concrete considerably cheaper. A premise for the use of concrete foundations is a more careful preparation.

Based on ENERGI E2's multi contracting concept the possibility of significant cost savings by use of concrete foundations will be exploited for the London Array West project, which is due for tender within a few months. Concrete is the future for offshore foundations.

Figure 1. Installation of Concrete Gravity Foundations at Nysted Offshore Wind Farm.

1. INTRODUCTION

Most offshore wind farms today have steel monopile foundations. All 6 UK projects, all Swedish, Dutch and Irish offshore wind farms have monopiles. Even 2 Danish offshore wind farms stand on steel monopiles. The solution is rooted in the North Sea oil- and gas-engineering tradition and uses equipment available from that industry, as illustrated in the photo of Figure 2. Low risk and use of existing practices, equipment and consultants.

In the early days of offshore wind concrete foundations were used in Denmark. At Vindeby Offshore Wind Farm concrete gravity foundations were installed in 1991, and a very similar solution was used at Thunø in 1996. In 2000 Middelgrunden followed and in 2002 the largest existing offshore wind farm at Nysted got its 72 concrete gravity foundations, as illustrated in the photo of Figure 1. Simple, safe, on schedule and very cost effective.

It seems that the oil- and gas-business is very successful in convincing the wind turbine business to use the monopile tradition and their equipment rather than develop the low cost concrete solution further. But it would be wrong to believe that there is no reason to think any more on the concrete gravity solution. Concrete foundations have an enormous cost reduction potential.

Figure 2. Installation of Steel Monopile Foundation at Samsø Offshore Wind Farm.

2. TENDER RESULTS

In two cases well prepared tendering between a concrete gravity concept and a steel monopile concept has been carried out. The two projects in question are Middelgrunden and Nysted, and in both cases market response was very clearly that the concrete solution can be manufactured and installed at lower price. Much can be argued against making too firm conclusions on this basis. The arguments should not be disputed here, but the simple fact to be underlined is that concrete gravity solutions proved cost effective when tested against market prices. Figure 3 shows the 20 Middelgrunden foundations during flooding of the dry dock used for their manufacture. ENERGI E2 believes that more thorough preparation of the tender is an incircumventable ingredient to have success with concrete foundations.

Many developers of offshore wind farms ask their consultant or engineering unit to propose a foundation concept, and in return they get an investigation that presents a steel tripod solution

and a concrete gravity solution, but ends up recommending to use a steel monopile, which is then dealt with very qualified. This solution eventually is the solution offered by all tenderers.

Economic result for the foundation works have been published for projects using concrete foundations as shown in the table below. No monopile projects implemented so far can compete with the foundation costs of the two projects.

	Year of Installation	MW	No. Foundations	Costs (m. Euro/MW)
Middelgrunden	2000	40.0	20	0.32*
Nysted	2002-3	165.6	72	0.26**

* http://www.middelgrunden.dk/oekonomi/budget2004.htm
** Ref 1.

Figure 3. Manufacture in Copenhagen of Concrete Gravity Foundations for Middelgrunden.

3. AN ADAPTED NYSTED SOLUTION FOR LONDON ARRAY WEST

This chapter is meant to illustrate how little should be changed to implement the successful Nysted concrete foundation concept for a future offshore wind farm. As an example is used the London Array West Offshore Wind Farm, which is to be installed by EON-UK and E2 in 2007. The project is due for tender within a few months.

3.1. Manufacture

Manufacture for Nysted was carried out in the Polish harbour of Swinoujscie, as shown in the photo of Figure 4. 3 manufacturing teams worked at each their stage of manufacture, and the barges rotated between them. One barge was constantly at transport or anchored in Nysted. In total 4 flat top barges were used, and each barge was big enough for 4 foundations. The manufacturing barges were also used for the 36 hours transport to Nysted. If the harbour is again somewhere in the Baltic Sea it may prove necessary to use one extra barge to reach London Array through the German Kieler Channel or north of Denmark. If manufacture takes place in UK or a neighbouring country the number of barges will not change.

Figure 4. Manufacture in harbour of Swinoujscie of Concrete Gravity Foundations for Nysted.

At Nysted gravel beds were used under the foundations. Soft or semi-soft top soil was removed and divers levelled the gravel bed to a perfect base for the foundation. At London Array West the sea bed consists of sand and the conceptual foundation study carried out by E2 proposes a steel skirted gravity solution, which can be used without sea bed preparation. Figure 5 shows the proposed concept, which also shifts the ballast volume from the outside Nysted solution, refer to Figure 4, to an inside volume.

The skirt under the concrete plate necessitates a 1 m high circular 20 m diameter platform on the barge for the casting job, but does neither change the method of installation lift nor the method of manufacture. Manufacturing and transport costs for London Array West need not be higher than for Nysted.

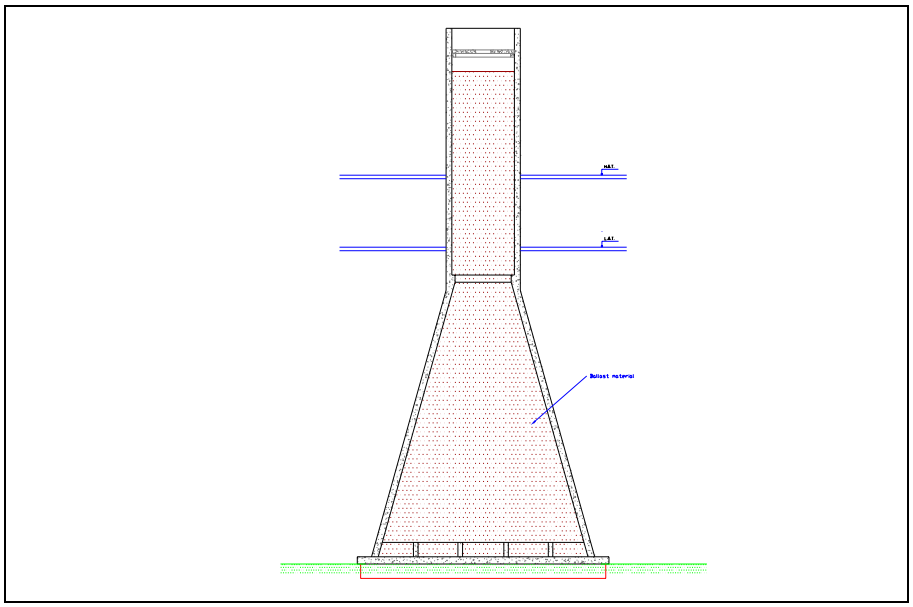

Figure 5. Optimised Concrete Gravity Foundation for London Array West.

3.2. Installation

Installation was at Nysted carried out by Eide Barge 5. The barge was originally equipped with a lifting frame for Middelgrunden, and the frame was adjusted for Nysted. Alternatively another flat top barge can be equipped with a lifting frame or for example Tacklift 4 from Smit can be used. Weight of the concrete construction is an important cost driver and fairly optimal design is thus important. The optimised concrete gravity foundation concept of Figure 5 that ENERGI E2 has developed for a 3.6 MW wind turbine for London Array West has a weight of 1000-1800 ton – depending primarily on sea depth, which varies from 0 to 25 m at London Array West. Ample time for engineering is important to reach a light weight concrete construction that can safely support the wind turbine and be cost effectively installed.

The installation operation at Nysted lasted 24 hours for the first installations, against only 6 hours for the last of the 72 foundations. This compares well with the well known driven and grout-connected steel monopile installation. Eide Barge 5 worked at Nysted at significant wave heights of up to 0.8 m, but this could be improved with better winches and anchors – and other installation barges may work at severer conditions. At London Array significant wave height is less than 1 m for 80% of an average summer, which means that including weather delays the average installation time per foundation will be 7.5-30 hours – not significantly worse than at Nysted. At Nysted 12 months was used for installations, but the installation barge spend much time waiting for the manufacturing in Poland. For London Array the 86 foundations can comfortably be installed during the 6 summer months in a worse than average year – including time for unforeseeable delays.

The skirted concept will need no sea bed preparation. After lowering the construction onto the sea bed possible water pockets below the skirt can be filled with concrete grout, as was at low cost done at Nysted between gravel bed and concrete bed plate.

Installation at 0 depth is impossible, but tidal variation is significant. HAT to LAT is 5.4 m at London Array and installation of a skirted foundation is at the low depth positions possible within the 6 hours of high tide, when properly planned.

Ballasting will have to be carried out offshore, as was the case for Nysted. At Nysted ballasting with sand inside the hollow shaft proved cost effective, whereas the three-layer outside ballasting with careful placing of wave-protecting boulders on top along the concrete walls proved rather costly. The proposed concept for London Array West has all ballast inside the construction. For the deep water sites the use of heavier olivin sand for ballast might prove cost effective compared to a constructional change with wider bed plate or larger ballast volume.

Scour protection can for concrete foundations be implemented with the same method and equipment as for monopiles, and at only slightly higher cost due to increased amounts.

3.3. Conclusion on adapted Nysted solution for London Array West

The Nysted methods can be used with few adaptions. Manufacture at low cost in harbour far from site of installation is again feasible. Installation by means of low cost flat top barge is also feasible. Careful design of optimal structure and sufficient preparation effort in general are preconditions - as for the use of concrete gravity for any offshore wind project.

Compared to Nysted few extra problems and costs will be found if using as much as possible from Nysted.

4. COST DISTRIBUTION

4.1. The Possibility of Concrete Foundations: Very Low Cost of Main Structure

Costs for main structure are very different for concrete gravity and steel monopile. For London Array West the weight of the average foundation will be around 450 ton for steel monopile and 1350 ton for concrete gravity. This corresponds to very different main structure costs of 0.7 m. and 0.3 m. Euro - concrete being the cheaper.

The basic idea behind the use of concrete is evident: Concrete supplies the necessary strength at much lower cost than steel does. As shown in Figure 6 costs of concrete structure will be around half the steel structure costs.

	Average Depth (m)	Weight (ton)	Cost (€ pr ton)	Cost of Construction (m. €)	Cost of Installation (m. €)	Special Installation (m. €)	Other Costs (m.€)	Total Costs (m.€)
Steel Monopile	10	450	1500	0.7	0.3	0.0	0.2	1.2
Concrete Gravity	10	1350	200	0.3	0.3	0.1	0.2	0.9

Figure 6. Cost estimates for the London Array West Foundations.

4.2. A Challenge of Concrete Foundations: Keep Installation at Low Cost and Risk

The basic challenge of using concrete is now to install the concrete foundation at low cost and low risk.

The assumption is that a concrete structure and a steel monopile can both be installed within the same time-frame of around 24 hours. This of course is valid only if things go as expected. For the monopile foundation a pile is hammered, a transition piece is grouted on the top of the pile and the installation is ready. For the gravity foundation a transport vessel arrives, the installation vessel lifts off a concrete structure and lowers it to the sea bed where the skirt penetrates a meter into the ground and the concrete installation is ready. Day-rates for the two different set of vessels and equipment are not much different.

Scour protection and mounting of appurtenances is basically the same for the two concepts. The concrete structure will have to be ballasted offshore. The conical gravity structure will allow the use of cheap sand for ballast and costs will be limited.

So installation costs are about the same – as long as the main solution can be used for the gravity foundations.

4.3. The Real Challenge of Concrete Foundations: The few problematic locations

The site assessment will normally show that gravity foundations cannot easily be used at all locations. Soft sea bed soil is normally the main problem as was the case in Nysted Offshore Wind Farm. Global erosion, sloping sea bed and liquefaction risk are other trouble makers.

At Nysted 5 positions had more than 4-8 meters of soft top soil, which had to be removed. It was replaced by correspondingly thick gravel beds in order to avoid a major reconstruction of the installation-barge due to the wide ice-breaking cone in top of the foundation.

At London Array West a handful of positions have thick layers of soft top-soil, a handful of positions have risk of more than 4 meter of global erosion and a handful of positions have sea bed slope of more than 1 degree.

Monopiles can most likely be used on all these 15 sites. Costs for these monopiles may be some twice as high as the marginal costs for concrete foundations, corresponding to 15*0.3 m. = 4.5 m. Euro. In Figure 6 this cost is named “Special Installation” and shown as average extra cost for 86 foundations. Figure 6 show that this number corresponds to only a quarter of the extra main structure costs of the steel monopile.

The special installation costs may be even less serious than this assumption. Global erosion risk will hit both foundation concepts with extra costs, and thus not make the assumed difference. The use of extra scour protection might well prove a more cost effective solution than the use of monopiles for protection against up to 7 meters of global erosion, which would mean for all positions.

For the positions with sloping sea bed it may prove cost effective to manufacture foundations with bed plate slope corresponding to the sea bed slope of each of the few critical positions.

This will imply that the concrete solution can simply be placed at the sea bed by means of the generally used simple installation method.

In conclusion the costs for special installations at London Array West will only be a fraction of the difference of costs for main structures of the concrete and the steel monopile.

4.4. The Complete Cost Picture: Concrete Gravity is Considerably Cheaper

Other Costs than main construction and installation are in Figure 4 estimated to be the same for the two concepts. This amount covers design, supervision, on-shore mobilisation and appurtenances as well as a number of other minor costs.

In conclusion costs of a concrete construction is only half the cost of a steel construction, and though installation costs are likely to be higher for concrete the complete cost picture is clear: Concrete Gravity Foundations will be Considerably Cheaper than Steel Monopile Foundations.

5. WHERE ARE THE RISKS

Manufacturing concrete constructions in harbour is a low risk task. Design is also fairly well known and though more time for the design work is needed there is little risk associated with the task.

The serious risk of the foundation works is associated with installation. Installation of concrete foundations is less well known to all involved than the steel foundation installation. It is also potentially more complicated.

The construction is by means of the floating lifting barge lifted off the floating transport barge. The two barges are separately rolling and pitching on the sea and swells can, if they occur during the lift, cause problems. At Nysted the lifting operation was carried out 72 times without serious problems. The risk seems small, but should of cause be planned for.

Moving the lifting barge away from the transport barge and lowering the construction to the sea bed is not of significant risk. Lowering the skirt 1 meter into the sea bed by means of the weight of the construction is sensitive. The skirt must penetrate vertically and thus simultaneously over the complete length, even if soil is harder in one side than the other. There is a risk that skirt penetration stops at one side and leaves the construction inclined with skirt only partly in the ground. If this occurs the construction will have to be lifted and re-lowered. Experience from bridges and oil-platforms show that the operation in practice can be handled safely.

The real risk is probably found where conditions differ significantly from the general pattern, and where solutions differ from the preferred solution. Proper preparation and design can solve this problem if given sufficient attention. The risk is that the design and preparation is underestimated, which may end with very costly trial and error events with very costly offshore equipment. Using a few monopiles for these sites will always be a safe alternative, though maybe more costly.

Weather delays also constitute a serious risk, which basically shall be treated the same way for any offshore foundation concept. The weather can be statistically well described and plans can be prepared accordingly. Statistically worse weather than average should be planned for, and plenty of time for delays of the foundation works should be allowed for before initiation of turbine installation is planned.

In general plans shall allow for unexpected delays in the offshore works – due to weather or technical problems. Plans shall allow ample time between the end of foundation works and initiation of turbine installations – to eliminate risk of consequential damage on other contractors works.

6. RISK PREVENTION AT ENERGI ENERGI E2

ENERGI E2 uses the multi contract system, whereby E2 signs separate contracts on wind turbines, foundations, inter-array cabling, grid connection and possibly other bits of work. The principle provides direct contact between E2 as project coordinator and the foundation contractor. This enables E2 directly to inject knowledge in the project – and take quick risk-preventing steps within and outside contract as the project develops. The intention is the risk sharing between E2 and contractor, which best places the risk on the part who can best reduce it. In some cases E2 carries the risk and often the contractor is payed to carry the risk. A lot of effort is spend in E2's preparatory works to create a set-up that reduces risk and carefully splits risk between contractors and E2.

E2 prepares a certified site assessment covering waves, wind and geotechnical investigations. E2 also on top of DNV's J101 prepares a certified design basis, which guides the contractors designer to a safe detailed design of the foundations. E2's considerations have led to the split of tasks, where E2 is responsible for the site assessment and the design basis, and contractor is responsible for design, manufacture and installation.

During preparations E2 carries out a thorough conceptual study, where potential design problems are tackled. Examples are liquefaction, skirt penetration, combination of wave and wind loads, scour protection, extreme wind conditions, global erosion, system eigenfrequency and conceptual optimisation of concrete structure, where E2 in all cases has involved the highest available expertise to find optimal solutions and in some cases has had the solutions certified by DNV to enable the immediate use by contractors designer.

E2 has in preparations gone very far in discussions of possible practical solutions to many problems with potential contractors and sub-contractors. This has prepared the in-house engineering staff with deep insight into potential problems and possible solutions of these. An insight to be used during contract negotiations, at design-reviews with contractors designer and at subsequent supervision of contractors manufacture and installation works.

E2 has no fear of involvement in risky parts of the foundation work, and does not leave risky parts of the foundation works to a contractor alone – E2 involves its experienced staff and contributes as much as possible to prevention and solution of any upcoming problem.

7. CONCRETE FOR LARGER TURBINES FAR OFFSHORE

The example above with and adaption of the Nysted works for London Array does not take the steps to larger turbines far offshore. Though the referenced turbine is a 3.6 MW, which is today state of the art.

E2 has carried out a conceptual study for concrete foundations for the same turbine for Borkum Riffgrund at 25 m water depth 40 km offshore in the North Sea, see Ref. 3. The only major change from the above example for London Array West is that foundations are slightly heavier due to larger design waves, and that weather conditions provide less offshore working days making the simultaneous use of two installation vessels necessary.

For larger turbines of 5-7 MW at larger depth concrete gravity foundations are still an obvious solution. They will be heavier and costlier and the installation vessels will have to be larger. But plenty of flat top barges are available and can at modest cost be equipped with a lifting frame to lift heavier constructions in line with the creation of Eide Barge 5 for Middelgrunden.

Scaling to the next generation of offshore wind farms will not change the game between steel monopiles and concrete gravity foundations.

8. CONCLUSIONS

Costs for main structure of concrete gravity foundations are only half the costs for steel monopile foundations. This is the core reason why concrete gravity foundations potentially will outdo steel monopiles.

Costs for installation of concrete gravity foundations will roughly be the same as for steel monopiles if the geotechnical conditions are fair and installation goes as planned. For turbine sites with soft soil or liquefaction risk gravity foundations may have to be adapted or even replaced by monopiles, and the cost savings by using the concrete solution will be reduced. For London Array West and most other offshore wind farms the extra costs for special installations will not be as high as the savings on the main structure.

Simple considerations suggest that an adapted Nysted gravity foundation solution can be used for London Array West with little extra costs – which means considerably less than the alternative costs for a monopile solution. And which also means the lowest cost level of foundations for any offshore wind farm so far.

Risks are high for any offshore work, and this is also valid for steel monopile and concrete gravity foundations. Basically installation of concrete gravity foundations have the same risk level as installation of steel monopile foundations. For sites with soft sea bed or other special geotechnically difficult conditions insufficient preparations will cause higher risks. Thus more preparatory work is needed for the gravity solution to reach the same risk level as for monopiles.

E2's multi-contracting philosophy with sufficient time for thorough preparations, design reviews and implementation of changes as well as planned separation of foundation works and turbine works is believed to be the key of the Nysted success. It is also believed to become the key of success for future projects - whether they use concrete gravity foundations or steel monopile foundations.

There is a huge potential cost saving to be harvested by the use of concrete gravity foundations for offshore wind farms, and ENERGI E2 intends to exploit this potential.

9. ACKNOWLEDGEMENT

Most of the results presented here were prepared by colleagues and they deserve the honour.

10. REFERENCES

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