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Ausführung von Bauwerken in verschiedenen Umgebungen

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SUMMARY
During the construction of bridge superstructures it is possible to come up against problems, which have not been envisaged by the designer, because no definite construction method has been assumed at the design stage. In offshore construction it is the other way round, and it can be clearly seen, that the structures have been designed for transportability or to suit existing floating construction equipment rather than for their final permanent purpose.

RESUME
Lors de la construction de ponts il arrive de rencontrer certains problèmes qui n'avaient pas été considérés par le projeteur, car aucune méthode de construction n'avait été définie dans la phase de projet. Dans la construction en mer (off-shore), c'est souvent le contraire et il est possible de constater que les structures ont été étudiées en vue de leur transport ou de leur adaptation aux équipments flottants disponibles pour l'execution, plutôt qu'en vue de leur utilisation finale.

ZUSAMMENFASSUNG
Während der Ausführung eines Brückenüberbaus kann es vorkommen, dass der Ingenieur mit Problemen konfrontiert wird, mit denen er nicht gerechnet hat, weil beim Entwurf keine definitive Konstruktionsmethode festgelegt worden war. Bei der Konstruktion von Oel-Plattformen z.B. ist es gerade umgekehrt. Es kann mühelos festgestellt werden, dass diese Tragwerke eher für ihren Transport oder aufgrund ihrer vorhandener schwimmender Bauausrüstungen konzipiert sind als für ihren endgültigen Zweck.

1. INTRODUCTION

Superstructures come in many shapes and sizes,and the nicest shape and size from a construction man's point of view is a structure which looks complicated but turns out to be simple. This does not happen too often, but the future looks brighter since I learned that the British IABSE Group last year organised a Colloqium at Cambridge on the topic "Design for Constructibility".

I have limited the talk to bridge superstructures, and limited it even further to a few types, that I know from personal experience. However, since I am supposed to deal with different environments, I will include some thoughts on offshore structures, where it is very clear to see, that it is the environment and the construction method that dictates the design and not the structural engineer. Closer to land and in a friendlier environment it is the designer who starts the creative process, and a good designer given a specific task, of course, sets out to produce a structure which functions as required, is durable and looks good and costs as little as possible. The first three criteria may be comparatively easy to achieve or at least for the design team to agree on, but in a design office separated from the commercial world of construction it is impossible to be sure, that the chosen solution also is the cheapest.

With powerful computers and an abundance of ready-made computer programmes available it is to-day possible for any designer to analyse and optimise practically any structure and minimise the material content. A great number of very important factors are though missing in these programmes; such as labour and plant content, temporary supports, construction risks and - tolerances, complexity, weather dependancy, supervision etc., and any of these factors may influence the construction cost more than any saving in material.

In the old days, when it was a tedious and time-consuming job to solve simultaneous equations, it was a natural act of self-preservation to simplify complex structures to a simple assembly of components with a minimum of indeterminate interactions. With absolutely no fear of the number of simultaneous equations required for the structural analyses there is a natural tendency to ignore the complexity of the calculations and to let every bit of steel or concrete, if possible, play a useful structural role in all three dimensions. This may produce an extremely elegant and safe final product, but during the construction phases, when some of the interacting parts are missing and replaced by temporary supports, and other parts have not yet gained their design strength, the structure may at times be closer to collapse than designers or builders have realised, and I doubt that structures have become any cheaper because of the computer, since the most important cost determining factors have not yet lent themselves to mathematical and statistical determination.

Some years back the British Ministry of Transport undertook a major study of bridge prices in an effort to establish some kind of a price list for bridges. To that end they analysed thousands of Bills of Quantities for all kinds of bridges submitted by a great number of tendering contractors. The fact, that tender prices could be vastly different from the final cost figures, was ignored and only the B.Q. figures were compared item by item from hand-railing and kerbstones to concrete and steel in all sorts of places and excavation in all kinds of grounds. The result was most disappointing. The variations of every single bill item were so great and the distribution from one end of the scale to the other so utterly haphazard that no logical conclusion could be drawn from any statistical analysis - with one possible exception. It did appear - to the complete bewilderment of the Ministry - that bridges became cheaper with increasing quantities of concrete per sq. meter of deck area. Having seen a few B.o.QS being filled in the last hour before the tender deadline, the haphazard pricing of individual bill items was not a great surprise, and the tendency to appear cheaper with increased average concrete thickness of the bridge deck was to me a clear indication that simplicity would pay off. Another member of the study team couldn't even draw that conclusion, since he could quote concrete in a 1 m thick flat slab which was priced exactly the same as the concrete in a 6 m deep web only 0.25m thick.

2. CANTILEVER CONSTRUCTION

It may be difficult to decide whether a design is good or bad, cheap or expensive, and I don't think it is possible to lay down simple guidelines for good design, but based upon experience from a few bridges and offshore structures I do think, it is possible to point out at least one approach, which should lead to a competitive and rational pricing process, and that is to have a definite construction method in mind when designing the structure and preferably a method, which permits the structure to grow naturally in size and strength, reaching completion without relying on an extensive system of temporary supports and passing through vulnerable and indeterminate intermediate stages.

Constructing vertical structures as tall tower blocks or chimneys would seem straight forward in a structural sense with the main problem being the logistics of bringing men and material to the very narrow working front on the top. But there is no limit to what the human mind can work out, and there are examples of vertical structures which have been built in reverse, starting with the roof at ground level and keeping on working at ground level while jacking the structure upward; apparently the natural way for grass to grow.

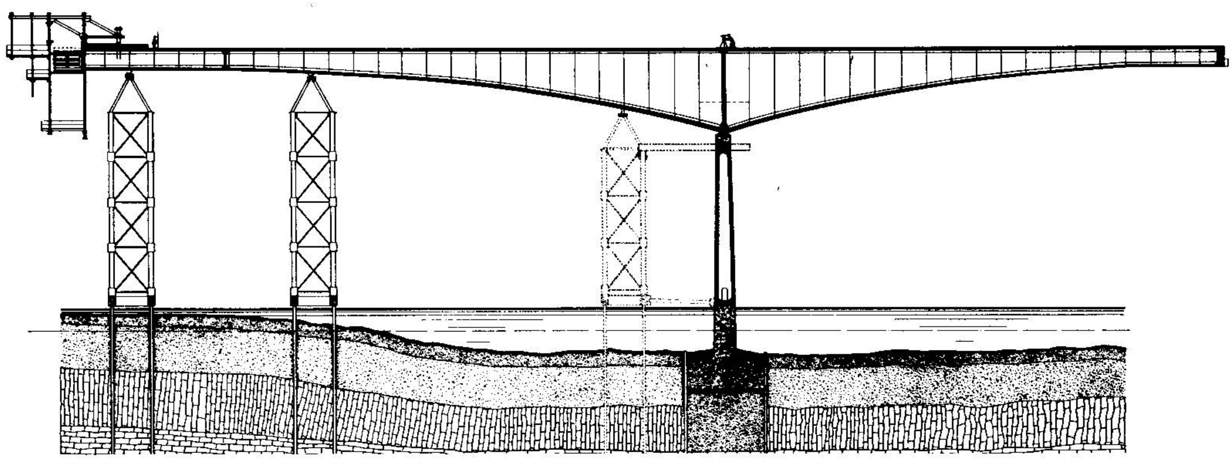
Even in horizontal construction there are examples of bridges, which virtually had to be built from the deck and downwards; but before we look at such examples, let us first look at a major bridge which could be built the right way round - more or less.

2.1 The Medway Bridge

The Medway Bridge on M2 from London to Dover was at the time of its construction the largest of its kind in the world and has been described in great detail in many technical publications. It has since been beaten several times, but there are aspects of the construction worth mentioning.

The sidespans were basically just conventional viaduct construction, albeit rather big. Piled foundations, twin columns, in-situ cross-beams, precast longitudinal beams and in-situ deck slab, with the work starting at the abutments moving out towards the main spans across the river. The edge beams were designed as concrete box girders weighing 200 tonnes. At the time these beams appeared to be super-heavy-weights, and they required purpose-made launching equipment, but it was only a matter of scale. It was exciting to push the launching girder across to the next pier and to roll the precast beams across, but theoretically there was no problem. The structure was at no time stressed more critically than in its completed state.

The main river span of 500' was designed as two cantilevers of 200' and a suspended span of 100'. The construction of the two cantilever arms were obviously intended to be in accordance with the well-established way of free cantilevering, and the suspended span was to be of a similar construction to the viaduct spans. The construction of the two 312' long anchor spans was not so well-defined and caused a few theoretical and practical problems.(Fig.1)



The free cantilevering may appear a daring way of construction, but it does in fact permit the bridge to grow in a simple and natural way. As the cantilever moment grows bigger, the prestressing force is increased, and properly designed one can maintain almost uniform stress from deck to soffit of the cross section, and thus in spite of a very large dead weight moment have rather small resulting deflections.

The longer anchor spans don't lend themselves automatically to cantilever construction, since part of the span is in positive bending in its final state. Furthermore, without the suspended span in place and in consequence without the negative moments over the main piers having attained their minimum design values, the anchor spans were hardly self-supporting. To add to the complications one had to launch the launching girder and the precast beams across the anchor spans at this vulnerable stage, which called for temporary support towers and a very careful control of the indeterminate support reactions.

A more rational and "construction-friendly" and therefore probably cheaper design would have been to eliminate the suspended span and to continue the cantilever construction right to the centre of the main span, perhaps even increased the main span to permit a balanced cantilever construction of the two anchor spans.

2.2 Taf Fawr - a smaller Medway

An opportunity to try out in practice some of the lessons learnt on the Medway Bridge appeared a short while later, when an alternative proposal for one of the bridges on the Heads of the Valleys Road in South Wales was accepted.

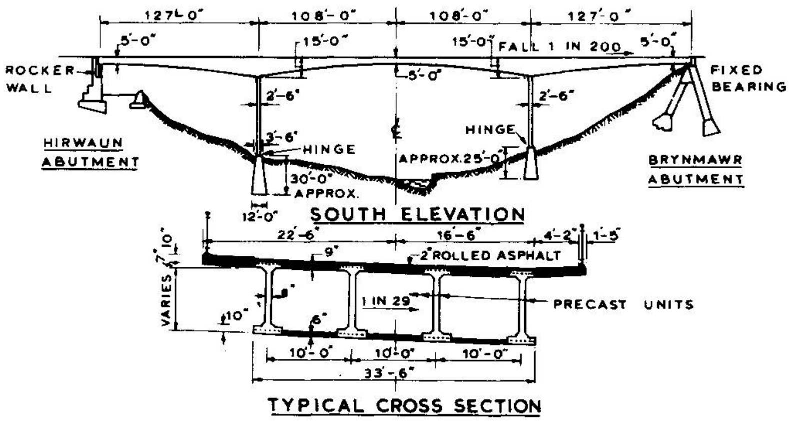
The Taf Fawr bridge crosses a 100' deep valley at Merthyr Tydfil in South Wales and it was decided to design it as a 3-span bridge, 127'-216'-127' to be constructed by free cantilevering from the two piers to meet in the middle and then be stressed together to form a 3-span continuous bridge. (Fig.2)

Another lesson learnt from concrete bridge construction was to be taken into account, and that was to simplify and reduce to a minimum the in-situ construction. The worst parts of a concrete box girder to construct are the thin webs. They are expensive,because they require more formwork than the soffit and the deck, and the concrete is difficult to place, and if anything goes wrong, it is almost impossible to carry out a neat looking repair job. Furthermore, to add insult to injury the webs constitute a major proportion of the structural weight without adding much strength, since steel generally has to take the shear.

As a first step towards the simplification of the web construction it was decided to form the box girder by having precast I-beam sections and casting in-situ only some soffit and deck slab concrete. This has certainly as a result, that the so-called cantilever carriages were reduced to simple strongbacks supporting the I-beam sections, which in turn supported a simple flat soffit shuttering and working platform.

The in-situ construction was certainly simple and the structure behaved nicely as theoretically predicted, but there was obviously room for improvements.

THREE SPAN, PRESTRESSED PRECAST CANTILEVER CONSTRUCTION 667



Each box section consisted of 4 No.I-sections and with the bridge spans being symmetrical it had been assumed there would 16 No.

identical elements in each construction sequence. That was quickly proved wrong. The bridge was on a curve and had a cross fall, and the arrangement of the prestressing tendons caused further complications, so that in fact there were very few identical elements.

It was decided to cast the I-sections in a casting yard some 30 miles from the bridge site, and having completed one set of 16 elements it was of course natural to cut the forms down for the next smaller section further away from the piers. Unfortunately one of the elements managed to fall off the lorry on the way to the site and had to be remade, but by then the formwork had already been modified to the smaller section. Not only became the remade section a very expensive one, but the construction of the bridge came to a standstill, while it was being fabricated.

The real lesson to learn from this bridge is not, that a precast element can be damaged en route from casting yard to the bridge site, but rather that it was a mistake to make the precast elements I-shaped and to cast them vertically. The difficulty of casting webs was not eliminated - only removed from the site to the casting yard - and the quite large proportion of precast concrete in both the deck and the soffit slab was a design disadvantage. The restraining effect of the precast concrete upon the fresh in-situ slab concrete caused tension, which had to be eliminated by additional prestressing. The obvious answer to both of these drawbacks would have been to make the precast web members flat and to cast them horizontally. Not only would that make all the concreting in the superstructure simple and reduce the prestressing but it would also make the entire method much more flexible, make room for all the prestressing tendons in the in-situ parts and permit curved alignments and crossfalls without loosing the benefits of symmetry around the supports.

It is encouraging to see, that a bridge over the river Coquet in North England just has been constructed that way, and it shall be interesting to see, if it has been a success and will be repeated. It may however have to wait a while, when we consider that there is a gap of 15 years between Taf Fawr and Coquet; and I would still like to see one more step forward.

The webs should not be made of concrete at all - but of steel, since steel in any case is doing most of the work. By making the webs of flat steel plates suitably stiffened one would on a major bridge save a considerable amount of weight and be able to span longer spans economically. The fabrication of the web members would be extremely simple and the handling and joining of the members with friction grip bolts would be equally simple, have no serious problems of tight construction tolerances, highly skilled labour content or danger of unknown built-in stresses.

External Prestressing

Still, even with the greatest simplification of concrete box-girder construction there is a limit to it's economic range, and at some stage it is easier to keep the box size constant and increase the possible span of the bridge by introducing intermediate supports from above. One has reached the range of the cable stayed bridge, which from a pure construction point of view is a simple and natural extension of the balanced cantilever method. When the cantilever moment reaches the design limit, the bridge is given a "lift" in the form of an inclined external prestressing cable, and the cantilevering can continue. The bridge is growing longer and stronger in a natural way and at no stage during construction vastly different in behaviour or more vulnerable than the completed structure. In that respect it would appear a much simpler and safer proposition than "big brother", the suspension bridge, which must pass through a whole range of varying weights and stiffnesses and corresponding natural frequences and "resonant" wind speeds.

I have, I am sorry to say, not had the opportunity to construct a cable-stayed bridge or a suspension bridge, but I have tried to support a bridge from above during it's construction.

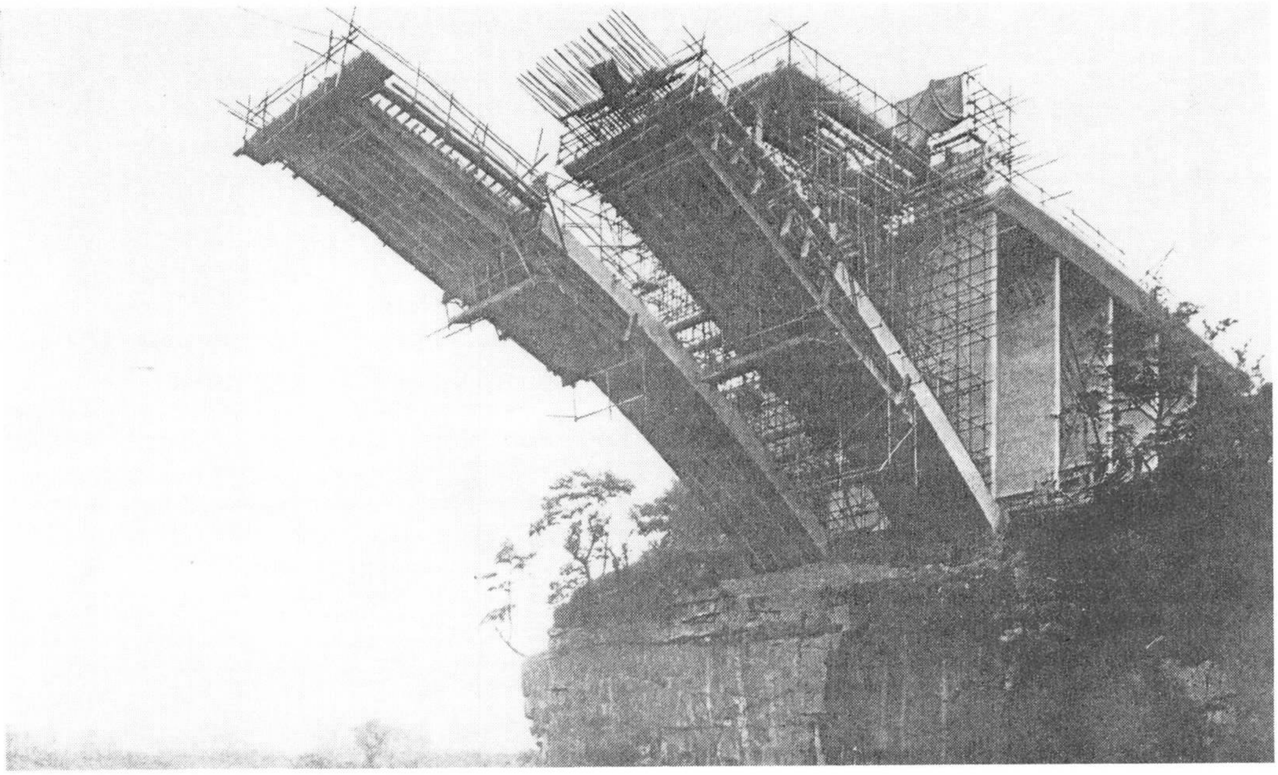
Arch bridges lend themselves best to crossing of deep valleys or rivers with steep and rocky sides, and even if many of the valleys have been very deep and quite inaccessible, there are still plenty of examples of concrete arches constructed on falsework supported on the valley floor. There are also plenty of examples where it was clearly impossible to use or reach the valley floor and the concrete arches were constructed on temporary steel or timber arches. In such cases by a carefully chosen sequence of concreting of the various sections of the arch it is possible to end up with a complete, fully fixed arch rib almost without built-in stresses in spite of considerable deformations of the falsework due to the weight of the concrete. The art is to end up with an arch with as small bending stresses as possible, after the falsework has been removed, and the entire self-weight of the structure has been transferred to the arch.

On the Heads of the Valleys road there were 3 fully fixed concrete arches, one over a water reservoir and two over deep and rather inaccessible valleys. For the largest arch and the one over the reservoir it was decided to try something new, and in the case of the third one the valley was filled up with conventional scaffolding.

The largest of the arches over Faf Fechan at Cefn Coed had a span of 236' and the crown was about 100' about the valley floor, and it was decided to construct the arch ribs by straight forward cantilevering from the two abutments (Fig. 3).

The bridge was supported on two parallel arch ribs, approx. 3 m wide and 0.6 m thick at the springings. These ribs were of course far too thin to be able to cantilever to the middle of the span, so in each construction segment of the arch rib were cast in a number of 0.5" prestressing strand anchors, and 0.5" tendons were taken to an anchor beam on a rocker bearing above deck level at the abutments. Another set of tendons were taken from the same anchor beam to rock anchors beneath and behind the abutments.

When the concrete in a section had attained the required strength, the weight of that section was "eliminated" by the stressing of some of the cast-in suspension cables and the corresponding anchor cables. The cantilever formwork could then be winched forward and another section of the arch be concreted. As the construction approached the crown of the arch, the suspension cables produced increased compression in the arch, and some of the earlier cables could be destressed and removed.



It was very noticeable that the structure became extremely flexible, as the work progressed; and as the entire construction method was a new one for everybody in the team, it caused a certain degree of anxiety, when the man on the level could see the bridge move about, when someone just walked to the end of the arch. It was, however, soon realised that the corresponding stresses were insignificant, and that the levels could be adjusted by applying just a slightly different force to some of the prestressing cables.

It might appear a little worrying, when the free end of the bridge moves, so you can see and feel it; but it certainly makes it easier to make the two halves meet in the middle, and it is very satisfying to know, that one is in charge of the stress distribution in the arch, when the final closure takes place.

From a purely technical point of view there can be very little doubt, that cantilevering and the use of external prestressing is a correct way of constructing an arch bridge, and the step from an arch to a straight cable-stayed bridge would appear quite natural.

From a cost point of view it is possible, that Taf Techan was too small for the method to be really competitive, but for larger spans there can be no doubt, and a much larger arch over Van Staden's Gorge in South Africa has been built since using the same method.

A concrete arch rib may not be the most difficult structure to construct an conventional falsework, but then try an in-situ multi-span continuous prestressed bridge comprising a grid of longitudinal box beams and transverse diaphragms and with prestressing tendons extending the full length of the bridge. Each additional concrete pour causes movements of the falsework, which the neighbouring green sections can't follow and haven't enough strength to resist, until at the very end of the construction the structure is provided with tensile strength through the prestressing. To control the deformations of a flexible arch rib by means of prestressed suspension tendons is absolute child's pay compared to the problem of preventing cracks in a rigid but green concrete structure on conventional falsework.

If it is necessary to cross a valley with a multispan structure and cantilevering from pier to pier may be considered too slow, it may very well be better to think big and provide travelling formwork, which can span from pier to pier and carry the entire weight of a complete span. The specialised formwork is expensive but the saving in labour and construction time by concreting a whole span in one continuous operation and having what amounts to a travelling bridge factory can still make it a competitive proposition.

I have so far concentrated my talk on construction of concrete bridge superstructures in different environments, because my own experience is limited to that field; but as far as I can see, the same principles would apply to steel bridges. If they are designed to grow longer and stronger in a natural way without relying on extreme accuracies, exceptional material strengths and a highly skilled labour force and supervision staff and - of course - without requiring a complex system of temporary supports, they are bound to be safe and cheap to construct.

I am however still looking forward to having a go at, what I would guess to be the simplest superstructure to construct, a box girder with in-situ concrete deck and soffit slabs and flat steel webs with friction grip bolted joints.

Offshore Structures

In the case of offshore structures it is a little difficult to decide what is superstructure, and what is substructure; but to give myself a chance to talk about the most interesting part I will concentrate on the section between the seabed and the water surface.

Most offshore structures are connected with oil production, and it can not be denied, that the development since the early "Texas Towers" has been quite impressive; but if we ignore the North Sea for a moment and compare the steel towers with the wide variety of bridge structures, it is quite obvious, that offshore construction still is in it's infancy. The towers have just grown bigger, until they outgrew themselves and stretched the technology to the limit, so that new ideas had to be tried. The North Sea was the limit, and the giant concrete gravity structures were given a chance.

But can it be said, that these heavy weights really represent a step forward?

To answer that question it may be useful to have a closer look at the pile-supported steel structures, to see what we can learn from them.

Steel Structures on Piles

The foundation method has always puzzled me. Why is one happily prepared to make huge piling hammers, drive piles of colossal dimensions to refusal and finally to rely on underwater grouting to tie piles and structure together instead of trying to tackle the apparently no more onerous task of digging some footings into the seabed?

But that is another story and not the subject of this talk.

Some positive lessons are however to be learnt from this puzzle, and that is, that huge piles can be manoeuvred into the pile guides, and heavy hammers can be landed on top of the piles, and later an modules weighing thousands of tons can be placed safely on top of the tower structure. There are therefore calm spells long enough to make these marriages of floating and fixed objects offshore possible; but, of course, there are also rough spells, which in one day can undo a whole season's good work. One must therefore plan the offshore work to consist of a minimum of short duration mating operations, and each operation should if possible leave the structure safe against subsequent attacks from the environment.

The installation of pile-supported steel structures does not meet this ideal requirement. Sometimes the pile driving takes too long, and the structure has to be left only partly supported, perhaps for months through the roughest part of the year.

Strangely enough, experience shows, that structures do survive such winter seasons without proper support. They have obviously been rocking about, but have remained structurally intact, so if the structure had contained some sort of living quarter, it would have been possible to stay on board, and if the foundation method had been self-contained and required only moderately sized equipment, it would have been possible to carry on working through the rough season. When one furthermore takes into account, that there generally are short calm spells even in the stormy seasons, one would not necessarily be marooned for long periods on the structure.

When the oil in the Northern North Sea was discovered, and it was realised, that one had to build bigger and heavier structures than ever before and during a shorter "working window" than before, it was feared, that existing designs and construction techniques would prove inadequate, and for the first time a completely new approach was considered.

Gravity Structures

From one extreme of having too much offshore work one went for the other extreme of having no offshore work at all, and the aim was now a structure, which could leave the inshore fabrication base complete in all respects and ready for production, as soon as it touched down on the virgin seabed. The concrete gravity structure was conceived, and a variety of proposals were produced, out of which only 3-4 solutions have been successful, in so far as they have been built and installed.

But have they really been successful? Are they really the natural next step forward from the pile-supported structures? Is it sensible to cut the offshore work out all together, when it is an established fact, that there are spells of calm weather offshore, where it is possible to bring a large floating object safely in position on a bottom-supported fixed object?

Some 15 years ago I had the experience of designing and constructing a gravity structure in the Irish Sea off Dublin. It was the Kisk Bank Lighthouse, and it was telescopic and attracted a certain attention at the time. The telescopic design was introduced by necessity to obtain floating stability during all stages afloat from the inshore construction base to the final touch-down on the seabed in 20 m water depth. Floating stability depends upon the relative position of the centres of buoyancy and gravity and upon the "water-plane'inertia". For the lighthouse to be stable in it's extended form it required a large "water-plane-inertia"; i.e. large diameter at water surface level. By pushing it together telescopically the centre of gravity was lowered, and stability could be achieved with a smaller water-plane-diameter, which in turn meant, that the structure attracted smaller wave forces and thus become better suited for the permanent design conditions. One could therefore say, that the telescopic feature was a good idea since it improved the structure for its permanent purpose; but by no means did it make it ideal. So although I am in 100% favour of "design for constructibility", I could not accept, that the design was dictated entirely by the temporary conditions and only afterwards just was checked to see, that it was adequate for the permanent - and very severe environmental conditions. So therefore, having completed the Kisk Bank Lighthouse I thought, I was going to keep a unique record, and that nobody would pursue the gravity principle into deeper water.

It did take me by surprise, when the Condeeps and the Seatanks were accepted by the oil companies; but I did though find some mitigating circumstances, when I got the opportunity to look at the problems a little closer. In very deep water it is possible to lower the centre of gravity so much without telescoping, that stability can be obtained even with a small "water-plane-inertia" and a heavy payload above water. The design is however still governed by the temporary floating conditions, and the price for stability is exceedingly high. For every tonne of payload above water it is necessary to place as much as 10 tonnes below the centre of buoyancy to keep the balance, and the base structure in consequence becomes extremely bulky. This in turn even in deep water attracts large wave forces and imposes high stresses on the seabed, and we are in the same situation as on Kish Bank, that the structure certainly is not the best answer to the permanent design conditions.

Only the fear of too short a "weather window" for the offshore construction and the prospects of enough oil to pay for any structure could make the "heavy-weights" acceptable, and probably only Norway with the ideal conditions for this construction will continue to use them.

After the initial shock from the arrival of concrete on the offshore scene the established offshore contractors have recovered, and now with much larger and more stable floating cranes to rely on the pile-supported steel structures will be pushed into still deeper water and shorter weather windows, until at some stage fixed structures are out, and compliant structures become a must. It would appear, that one oil company already seriously is planning a tension leg platform in the North Sea; but if this plan is carried out, and one jumps straight from the scaled-up Texas Towers to the TLPs leaving the concrete Dinosaurs as a dying-out species, there is most certainly some missing links in the offshore chain of evolution.

"A Missing Link?"

Foundation-wise there must be some stages in between 100 m or more long piles driven to refusal and nothing at all apart from some tiny shear keys biting into the soft surface layers, and structurally there must be some sensible solutions between the towers with their multitudes of braced tubular members and the "Dinosaurs" with their three unbraced cantilever columns. There must also be some safe and practical compromise between a lengthy offshore operation which hardly can be fitted into the "working window" and one single touch-down of a completed structure including all top-side installations.

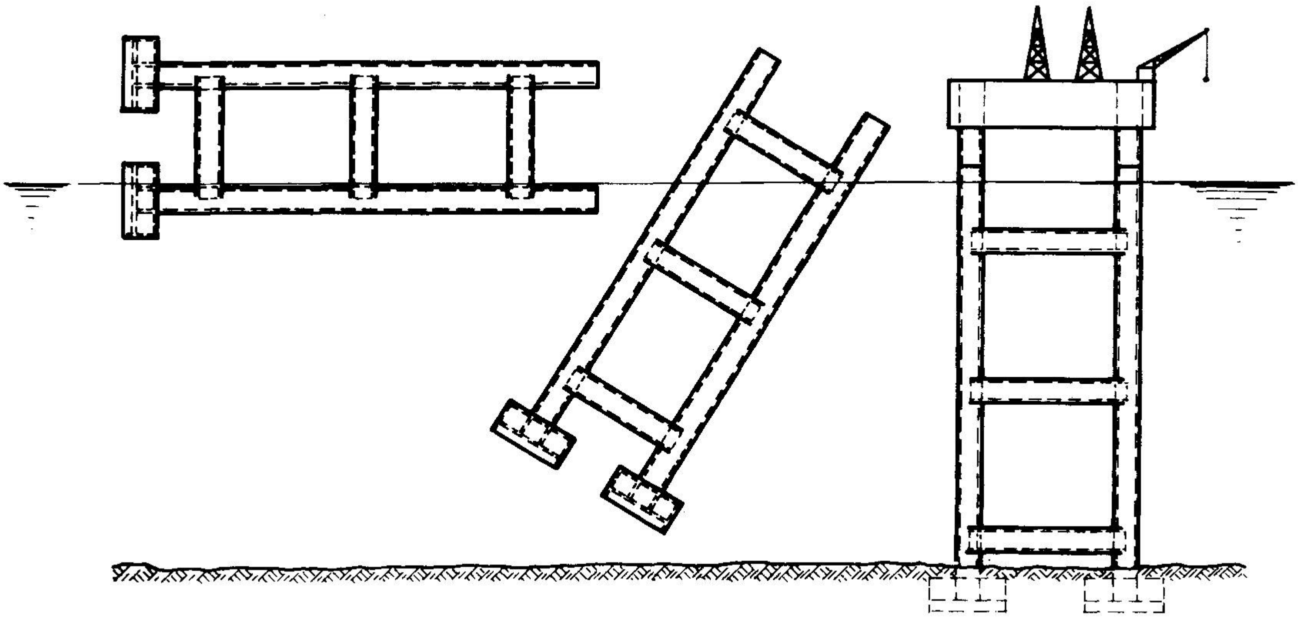
"Design for Constructibility" is a most commendable aim, but in offshore structures it has been taken to such an absurd extreme, that the design has been permitted to be dictated by the transport to the site and not by the permanent purpose of the structure. This is obviously a completely unacceptable situation - and unnecessary, if we only use the experience already gained, imaginatively.

The design and construction of the tower structure is a civil - and structural engineering task and should be completely detached from the design and construction of the top side, which is not a structural design or an offshore problem, but entirely an oil production task.

A tower structure can be designed to float horizontally in shallow water, and vertically in deep water, without getting into conflict with the requirements for the final fixed position.

From the development of jack-up structures it is obvious, that even the most extensive and heavy top-side installations can be housed in a stable and buoyant hull and in just one short spell of calm sea be landed on a previously installed tower structure and jacked to safety above the waves.

Combining the tubular design experience with the knowledge gained from the gravity structures it is obvious, that the tower design could be simplified in the extreme and be reduced to three vertical columns braced together at 2-3 levels by horizontal tubular numbers. This may not lead to absolute minimum material content, but it provides as compensation useful interior living and working space, and knowing that the structure is perfectly safe just resting on the seabed, it should not be beyond the wit of man to devise a practical foundation method. (Fig. 4)



The tower may rock about a bit in the waves; but it is possible to live and work comfortably inside the structure from the moment of touch down, and it would not appear too difficult to develope a firm foundation somewhere between huge piles or nothing, which would make sense in ordinary geotechnical terms. This may require some new and specialist equipment, but surely nothing as outrageous as hammers weighing hundreds of tons or cranes with capacities of thousands of tons.

I do hope that civil and structural engineers will take up the challenge of the sea. Sailors and oilmen are also important; but without a more forceful input of civil and structural design, some of the missing links in the offshore construction evolution will remain missing for a very long time.

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