

Slipforming of advanced concrete structures

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ABSTRACT: Slipforming is a method of constructing tall concrete structures based on known parameters and proven technology. The method encompasses several activities and the successful execution of a slipform operation depends on proper understanding of the mechanisms involved, careful planning and work preparation and the skills of the operator. Slipform operations are often executed by specialist subcontractors. Recent advances in concrete technology, pump line equipment and formwork design enable the method to be employed in the rapid erection of tall and demanding concrete structures, but schedule and quality advantages can also be achieved for structures of more ordinary size and complexity. The paper describes the important parameters for successful slipforming and contains some examples of slipforming of advanced concrete structures.

1 INTRODUCTION

Slipforming is a highly efficient method of constructing tall concrete structures. Rates of construction of several meters per day of varying geometrical shapes and cross sections and containing multiple inserts and openings can be achieved within strict geometrical tolerances. Slipforming is labour intensive over short periods, but when properly planned and executed it offers significant advantages with respect to overall construction time, quality and safety.

The method has made great progress during the past decades, particularly in relation to the large concrete platforms and storage tanks delivered to the oil and gas industry and for tall concrete buildings, chimneys and pylons. Progress in the field of high performance concrete, formwork design and pump line technology are some of the key elements.

Slipforming is a construction process of many inter-dependent items. The essential elements are proper planning, a well designed concrete mix with uniform and predictable properties, a distribution system ensuring uniform and timely delivery of all components, and a strong and durable slipform assembly lifted at a pre-determined speed commensurate with the setting time of the concrete mix. The system must have adequate robustness to cope with the changing conditions and occasional conflicts of interest for the many activities on a construction site.

For tall structures involving considerable overhead crane activities special attention must be paid to safety by proper fences and railings, clearly marked accesses and proper housekeeping on the work decks. In this respect a slipform assembly with a permanent lay out from start to finish offers some potential for improved safety compared to conventional forms installed in sections and served by constantly moving crews and equipment.

2 THE BASIC PRINCIPLE OF SLIPFORMING

The essential elements of a slipforming assembly are two parallel wall panels (about 1, 2 m tall) supported by steel frames and horizontal yokes connected to hydraulic jacks – ref. Figure 1. The jacks climb on vertical steel rods at a rate of some 15 mm per stroke. The spacing of the two panels determines the wall thickness and can be varied by screw type controls. The geometry of the concrete structure can vary from straight walls to circular cells and towers of varying diameter and geometrical shape. The steel reinforcement, inserts and box outs are placed inside the wall panels as they are continuously being lifted by the jacks and as the concrete is placed in layers of uniform thickness. The main key to a successful operation is the ability to synchronise and control the concrete setting time

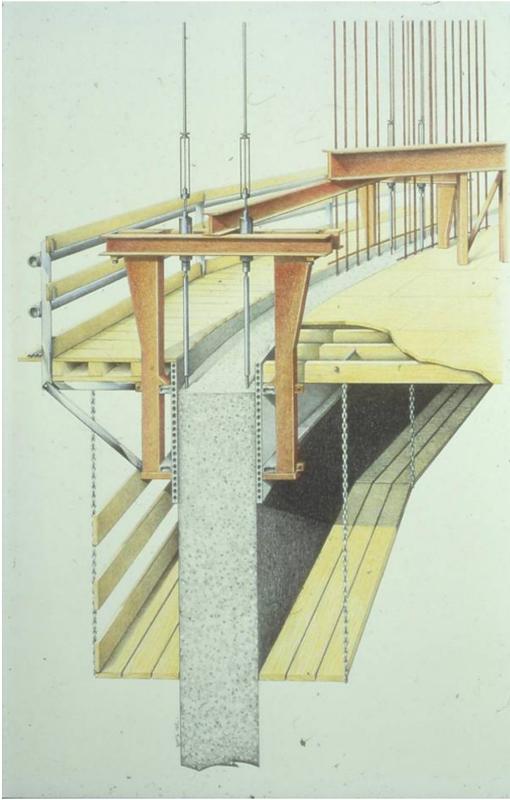


Figure 1. Typical slipform assembly.



Figure 2. Slipforming of the Telecom Centre Munich BRD (2003) showing large box outs and openings.

and the lifting rate of the assembly, so that the layers of concrete set and harden shortly before they emerge below the wall panels and not before. A faster lifting rate produces a better surface quality and less surface patching and repairs.

Modern slipform technology enables a variety of shapes and forms to be produced to within strict geometrical tolerances. In general, the walls are vertical and of uniform thickness. If required, however, the shape and wall thickness can be varied in a seamless manner as the work progresses by means of screw type controls and overlapping wall panels. A typical example of this technology is the flared shafts of the offshore platforms designed for minimum cross section areas at the water line.

From a quality point of view the method offers considerable advantage over conventional formwork by performing all operations near the top of the form, where access is easy for the operators performing the work and for inspection. The quality of the concrete is ensured through controlled placing, repeated compaction of the successive layers and systematic curing by water spray or membranes. The concrete cover to

the rebar is determined by spacers mounted on the forms and is readily controlled.

For marine structures subjected to one sided water pressure slipforming offers the notable advantage of eliminating all horizontal construction joints. Construction joints are notorious trouble spots for water leakage and durability issues, particularly for marine structures where chlorides may penetrate to the reinforcing steel, destroy the passivity provided by the concrete cover and initiate corrosion.

Slipforming offers the advantage of speed of construction, tall structures being erected in a few weeks rather than several months. Slipforming also has some inherent advantages with respect to safety as the work face never changes significantly and the operators return to a familiar workplace where safety is assured by semi-permanent stairs and lifts, proper railings, and easy access to the working areas.

Slipforms can accommodate large box outs for temporary or permanent openings in the concrete structure enabling subsequent installations of associated components or structural members, as shown in figure 2.

3 THE SCIENCE OF SLIPFORMING

A shear zone will be formed close to the slipform panel when the slipform panel is lifted. This zone consists of smaller particles (cement paste mixed with sand) and act as a lubricant during the plastic phase in the concrete. When the slipform is lifted, the lifting force is primarily affected by the particle shape of the aggregates and the workability of the fresh concrete.

In order to lift the slipform panel, the lifting force needs to overcome the static friction in the shear zone. When the panel starts to move, the friction decreases to a lower level called sliding friction. The friction can be calculated using the friction law because the friction coefficient is approximately constant for a given concrete and slipform set-up. This means that the friction force that occurs when the slipform panel is lifted depends primarily on the effective pressure between the particles. A simplified model for the relationship between the friction and the effective pressure is (1):

$$F = \sigma' \cdot \mu \quad (1)$$

where F = friction [Pa]

σ' = effective pressure [Pa]

μ = coefficient of friction

The effective pressure is the difference between the normal pressure (concrete pressure against the slipform panel) and the pore water pressure, see Eq. 2:

$$\sigma' = \sigma - u \quad (2)$$

where σ = normal pressure [Pa]

σ' = effective pressure [Pa]

u = pore water pressure [Pa]

The pore water pressure represents the pressure in the liquid phase in the concrete. The primary driving force for the change in the pore water pressure is the chemical shrinkage caused by the cement hydration. The effect of the chemical shrinkage on the pore water pressure is assumed to depend on the geometry of the pore system that is formed and the pressure equilibrium between air and water. When chemical shrinkage is developing, contraction pores are formed since the reaction products have a smaller volume than the reacting materials. The pore water pressure will decrease as a result of the developed contraction pores.

The existing air content in the concrete will reduce the effect of the chemical shrinkage on the pore water pressure because the air content in the concrete will be in equilibrium with the liquid system in the concrete.

In general the friction that occurs during lifting depends mainly of the concrete mix composition, the lifting rate of the slipform and also the slipform set-up. A concrete mix with lower air content or higher content of fines will give higher friction force. The friction

force will also increase with lower slipform rate (lower lifting frequency or lower lifting height). Also unstable concrete or heavy vibration of the concrete in the form will increase the friction force between the concrete and the slipform panel during lifting. The risk for any surface damage on the concrete structure can be assumed to increase with increasing friction force during lifting of the slipform. Poker vibrators should not be employed in the cover layer outside the main reinforcement.

4 PLANNING AND EXECUTION OF THE WORK

Most construction projects involve contributions by a number of contractors, subcontractors and suppliers. Typically concrete production (often off-site), transport and delivery into the forms, installation of reinforcing steel and prestressing, slipform installation and operation, supply of labour and site management may be performed by different companies. The properties of the concrete, the stability of the mix during transport and handling, the performance of the slipform assembly and the lifting rate of the slipform are closely interrelated so that a common understanding of the process and efficient management are key factors for a successful operation. A jointly prepared and implemented Method Statement is an essential tool to achieve efficiency and quality.

Careful planning of the logistics of all materials and components required is required. The rebars and embedments shall be lifted on to the form in the right order and so that they do not overload the slipform assembly. A lifting plan sorted by elevation is a useful tool in order to control the loads and hence the deformations of the assembly.

The choice of distribution system for the concrete is important. For a conventional crane and bucket delivery the crane capacity must be adequate to avoid bottle neck situations in other areas. More advanced systems of distribution by pump lines into hoppers on the deck or by pump lines with vents discharging straight into the form offer significant advantages, but are vulnerable with respect to unexpected stops and slow deliveries causing changes to the concrete properties and blockages in the system. In a well managed slipform operation pipeline delivery into the form will reduce manpower requirements and improve the overall performance.

The lifting rate must be determined with regard to the supply of all the components and the availability of manpower, so that interdependent activities can proceed without hold ups. The concrete properties can then be chosen to match the chosen mode of delivery and rate of lifting. The setting time of the concrete can be adjusted within wide limits (up to 24 hours) by means of chemical admixtures and temperature

control, and the clue to success is to fully synchronize the prescribed setting time of the concrete and the lifting rate of the form.

The temperature of the fresh concrete can be adjusted by cooling or heating systems at the batching plant and the curing conditions for the slipform can be adjusted by wind or sun shields or by external heaters. The total temperature regime will have a bearing on the all important concrete setting time, additional to what can be achieved by chemical admixtures.

A mock-up should always be considered when new materials, methods or systems are being employed. A mock-up will pay dividends for the training of inexperienced crews. If pipe line distribution is adopted, pumping trials in advance will assist the concrete mix design and prevent problems.

5 CONCRETE CONSTITUENTS AND MIX DESIGN

Successful slipforming depends on the delivery of a high performance concrete with uniform and predictable properties. Essentially this means high binder content, well graded aggregates with adequate fines, and admixtures ensuring high workability and controlled and adjustable setting time. Supplementary binders such as fly ash and silica fume often prove advantageous, particularly if the concrete is delivered by pump lines. Concrete mix design and full scale site trials are essential elements in the planning process; several examples of less than successful operations can be attributed to unsatisfactory concrete properties and absence of site trials. The minimum material requirements stipulated in the mandatory Codes will not be adequate to assess fitness for advanced slipforming.

Uniform and predictable properties can only be consistently delivered by an efficient batching plant with automated batching of all components and monitoring of workability and temperature.

The essential slipform properties of the fresh concrete can be defined by 3 s's;

- Slump (or workability)
- Setting time (at all times tailored to the intended lifting rate)
- Stability (absence of segregation)

A high slump, approaching that associated with self compacting concrete (240 mm), is commonly adopted and promotes easy handling of the concrete on site. The stability item refers to the need for the mix to remain workable also during stops in the pump line delivery. Air-entrainment, which may be a requirement for durability in cold regions, has proven to be beneficial also to the pump line performance of the concrete.

Tests on drilled out cores from several projects have shown that the slipform methodology of concrete

layers being placed in the top of the form and repeatedly compacted by poker vibrators can yield up to 20% increase in the obtained in-situ strength, compared to a conventionally placed concrete (2).

6 THE SUCCESS CRITERIA

As discussed above, it is convenient to consider the slipform operation as consisting of three main elements:

- a) The concrete
- b) The batching, transporting, placing, compacting and curing of the concrete
- c) The shape, size and speed of the slipform.

The properties and performance within each of these categories impact significantly on the other two and determines the robustness of the operation. Recognizing this relationship is important and will govern a series of decisions in the planning process. High performance slipform concrete is not a standard product available from a regular all purpose plant, but requires detailed mix design and testing before it can be accepted. There are some clear examples of the concrete mix not being compatible with the chosen equipment and methods, resulting in lifting cracks and surface imperfections and costly repairs. Such imperfections are generally confined to the concrete cover, seldom extending beyond the main reinforcement or creating doubts about the structural integrity of the wall in question.

An inherent advantage in a slipform operation is that, in principle, the slipform never stops. Once the operation has started and the form has had lift-off the work goes on and problems get resolved, unless they become insurmountable and a stop and a very undesirable cold joint occurs. The slipform thus provides an indirect driving mechanism to the construction schedule by virtue of the non-compromising need for all parties to meet their part of the contractual obligation. Cold joints can be managed but require extensive cleaning of the joint and additional starter bars. Back up procedures for unexpected stops should therefore be included in the Method Statement.

The simple control procedure of measuring the depth of wet concrete in the form (ideally 80 cm) decides if the concrete setting time needs to be adjusted or the lifting speed has to be altered. A uniform and predictable speed and depth of wet concrete improves the overall efficiency of the operation. The general rule is: a fast and uniform lifting rate gives the best quality and few surface repairs. Any repairs, surface installations or applications of coatings should be performed from the suspended working decks (ref. Figure 1) as the work progresses, thus eliminating the need for costly access at a later date.



Figure 3. Mondriaantoren, Amsterdam.



Figure 4. Snøhvit LNG Tanks, Hammerfest.

A smooth running slipform operation is an inspiring experience, the daily progress can be measured directly in meters and the crew takes great satisfaction from a tangible team effort.

7 CASE RECORDS

The examples below illustrate the versatility of the slipform method:

North Sea platform Oseberg A (1987). The 92 m tall flared concrete shafts were slipformed at a rate of about 3 m/day. Internal diameter varied from 25 m at the base to 12 m at the water line, flaring out to 16 m at the top, where the outside was transformed from a cylindrical to an octagonal shape to match the footprint of a module support frame.

North Sea platform Draugen (1992). The single shaft was slipformed to a height of 242 m. The diameter varied from 41 m at the base to 15 meter at the water line and flared out to a rectangular shape 22 × 22 m at the top. Ref. Figure 5.



Figure 5. Draugen Platform. North Sea.

North Sea platform Gullfaks C (1987). The largest slipform ever; the 26 no. 28 m diameter cylindrical cell caisson made up a gross area (footprint) of 16 000 m². This was lifted through a height of 56 m by a total of 1800 hydraulic jacks. The operation lasted 42 days, consuming 1 14 000 m³ of 65 MPa concrete, 24 000 tons of reinforcing steel and more than 7000 steel embedments.

Snøhvit. 4 no. concrete LNG storage tanks of 75 m diameter (2004). The slipform incorporated a unique (prototype) pipe line system with automatic vents enabling concrete delivery straight into the form.



Figure 6. Spinnaker Tower, Portsmouth.

The rate of slipforming was 2.5–3 m/day within strict geometrical tolerances. Ref. Figure 4

Mondriaantoren, Amsterdam, Netherlands (2000) A building 115 m high and incorporating 280 prefabricated beams installed during the slipform operation. Concreting was deliberately stopped from 10 pm to 6 am every night. Ref. Figure 3

Spinnaker Tower, Portsmouth, England (2003). A spectacular 143 m tall concrete tower with an hexagonal base and a main inclination of 5,5°. The geometry changed continuously all the way to the top. Ref. Figure 6

Sakhalin GBS platform, Vladivostok, Russia (2005). Close to the top of all 4 shafts, a “Leg Mating Unit” was established to support the Topsides. For this purpose the wall thickness was increased in a small sector from 60 cm to 6 meter with a slipform angle of 23°. Above this massive cross-section a new slipform was established with a diameter of about 4 m within the existing slipform. This was connected to and followed the main slipform to the top.

Hibernia GBS platform, Newfoundland (1996) Due to extreme ice loads heavily reinforced cross sections

containing more than 700 kg/m³ of steel reinforcement were slipformed on this project. Good planning and logistics made this possible. The slipform was built-in during the harsh winter season with often –10 to –15°C in longer periods. Heaters were used to keep the working and hanging deck warm. Hatches were installed on top of the working deck to enable reinforcement to be lifted in.

Adriatic LNG Terminal, Algeciras, Spain (2006).

Slipforming was performed during the hot weather periods in the middle of the summer season. The interior faces of the smaller cells were cooled by air condition systems installed on the working deck. By using this system, the ambient temperature inside the smaller cells was kept between 20–25°C and this enabled satisfactory control of the concrete setting time and successful completion of the work.

8 SUMMARY AND CONCLUSIONS

Slipforming can be used for a large variety of concrete structures, most spectacularly for tall and elegantly shaped buildings, towers and oil platforms, but also for smaller and less glamorous structures where speed of erection, absence of cold joints, good control of workmanship and enhanced safety are important merits. Recent advances in concrete mix design, formwork design and performance and efficient pump line delivery systems give scope for improvements in quality, including geometrical tolerances, and savings on labour.

Successful slipforming depends on efficient management of the 3 main parameters; the concrete, the delivery system and the formwork. The key is control of the setting time of the fresh concrete so that the forms can be lifted at a predetermined speed and the concrete sets and hardens at the desired depth in the shallow forms. Control of the setting time is accomplished by chemical admixtures and management of the temperature regime at the batching plant and at the work face.

Mock up tests and pump line trials are recommended when unfamiliar materials, methods and systems are being employed and for training of inexperienced crews.

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