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The New Storstrøm Bridge - Construction Tolerances and Precast Structures Installation Challenges

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Abstract

The construction of the Storstrøm Bridge faced and is facing a number of challenges, to ensure the alignment with design assumptions and project requirements. The main constraints related to tolerances and quality requirement are hereby described together with the strategy implemented to execute works. From the positioning of precast foundations to the erection of the girders a number of constraints pose a challenge to the general contractor (SBJV) since their fulfillment is crucial to ensure that the bridge performance standards are met, the construction program is followed and works disruption does not occur. The geotechnical settlements represent a particular challenge since the natural uncertainties related to their calculation require SBJV to adopt solutions that can accommodate any deviation from the predicted ones. In light of the above, a crucial role is played by advanced planning risk management and monitoring during construction operations.

Keywords: bridge construction, construction tolerances, foundation, precast elements, settlements

1 Introduction

The new Storstrøm Bridge will replace the existing bridge to satisfy the needs of the future road traffic and of the high-speed rail. The bridge will link the coastal location of Masnedø island in the North with the coast of Orehoved in the South. The Storstrøm Bridge stetches over a sea channel with low depth and is composed by 3 main viaducts, separated by 2 expansion joints. It is supported by 44 standard piers, 1 central cable stayed pylon and 2 abutments. The central cable-stayed bridge features 2 spans of 160m, while the typical 44 spans are 80m long. Fixed piers are the 15S, 14S and 13S (in the south) and 14N, 13N and 12N (north side) and 1C. Expansion joints are present at abutments and pier 6N and 6S.

The construction method foresees the use of prefabricated elements, produced near the final bridge location, for foundations, piers and girders; in order to limit the off-shore castings to some in-situ stiches. These are used as well for compensations of settlements and positioning deviations.

2 Typical Construction sequence

2.1 Foundations and piers

The foundation caisson of the typical precast piers and of the cable stayed pylon are prefabricated on-shore. The lower part of the pier is executed as well in the precast yard and, when the assembly of the 2 parts is finalized, they are lowered in their final position by means of a catamaran.

The construction method for the typical offshore piers is divided in three main phases, the execution and inspection of gravel bed, the placement of the

prefabricated foundation (Figure 1) and the erection of piers.

Figure 1. Placement of foundation and pier

The pier erection is carried out using 3.2m high precast segments that are made continuous through off-shore in-situ casting of joints (height 80cm). For each phase, strict tolerances and control measures are defined in order to achieve the correct rail alignment profile.

2.2 Girders

The erection of precast girder starts with the positioning of the first precast segment (*Segment C0*) on top of the pier, on temporary supports. This is 4.8m long in longitudinal direction and is limited to the central caisson (cantilevers are cast with the rear stitch). It consists of a precast concrete portion, pre-assembled reinforcement cage and pre-embedded bearings. The remaining part of the *C0* is cast off-shore and a lifting frame equipped with strand jacks is positioned on top of it.

The full-span, 73m long, precast girders are lifted from the lifting frame on top of the *C0* through retractable lifting arms positioned on the precast girder. This can extend aside the pier after the girder is in position, on the barge, allowing the lifting of the span without eccentricity with respect to the pier axis. Once in position two continuity stitches, 1.1m wide, are cast; the rear stitch casting included the casting of cantilevers around *C0*. Once continuity is made, in order to achieve the bending diagram of a continuous beam, the front end is lowered by about 250mm, imposing a negative bending moment on the rear joint.

3 General off-shore piers tolerance and settlement criteria

3.1 Positioning tolerances and off-sets compensation

The positioning tolerances foreseen in the working specifications (SAB) [1] are summarized in the following table:

Table 1. SAB positioning tolerances

	Trans. Dir.	Long. Dir.	Vertical
Foundation	200mm	200mm	N/A
Pier head	100mm	150mm	N/A
Bearings	20mm	20mm	10mm
Axis Rotat.	1/200		

Due to the pier geometry the tolerances above cannot always be applicable (i.e. for short piers compliance with 20mm off-set at bearings and 1/200 axis rotation would result in foundation allowable off-set lower than 200mm).

Mispositioning of foundation and lower pier can be recovered through corrections to be implemented along pier shaft and particularly at in-situ stitches.

3.2 Settlement and offsets compensation

In order to achieve the correct rail alignment after bridge completion, the designed position of the foundation accounts for the settlement that occurs due to the load induced by superimposed permanent loads. A theoretical value of the foundation settlement, d_{th}, is calculated and the construction starts at the theoretical level $+d_{th}$.

Settlements occurs mainly due to girders erection, the full load is transferred to the pier in 2 steps, corresponding to the lifting of 2 consecutive spans. Settlement development considers a relatively short consolidation window [2].

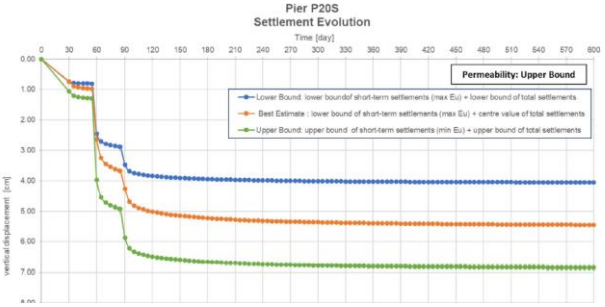

Figure 2. Settlement development

This allows for a projection of the final settlement after about 2 month from the erection of the first girder and, if needed, for a correction of any deviation from the settlement predicted during design.

3.2.1 Correction of positioning/settlement deviations

A topographical survey is conducted at every construction phase that involves the placement of a new element to any possible deviation from the theoretical position. If needed a correction is made through the application of one or more of the following measures:

1. adding/removing shim plates between pier segments.
2. adjusting the height of the bearing and shear keys after girder erection.
3. adjusting the height of the slab track at its installation.
4. adjusting the height of rail fasteners at their installation.
5. jacking of the girder and adding or removing shim plates between bearings and structure for possible deviations of long-term settlements.

Items 1, 2, 3 will be detailed in the following paragraphs; adjustment at 4. and 5. are additional contingencies reserved for the maintenance phases, during the operational life of the bridge.

4 Execution of gravel bed and screeding layer

4.1 Types of foundation

Four foundation solutions/types are encountered, namely: (i) only gravel bed (typical pier), (ii) gravel bed and inclusion piles (pylon 1C and piers 1N, 1S), (iii) gravel bed and sheet piles (piers 16S, 18S), and (iv) gravel bed, inclusion piles and sheet piles (pier 12S).

Each of the 44 typical piers consists of a caisson and a pier shaft. At each foundation the weaker upper soil layers are excavated. In the offshore excavation pits a gravel/stone bed, composed of two layers, is executed: a lower compacted layer, the gravel bed, and an upper loose levelling course, the screeding layer (Figure 3). The gravel bed consists of crushed sound rock 5/70mm (granite or similar) with an uncompacted thickness of 0.8-2m (0.5-1.6m compacted) and coefficient of uniformity, C_u>3. The screeding layer consists of ungraded crushed sound rock 30/70mm (granite or similar) with a thickness of 0.4-1.0m.

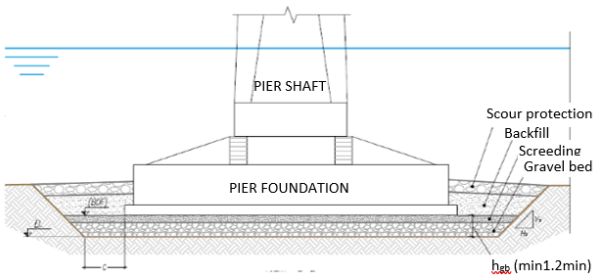

Figure 3.Typical sketch of gravel bed

4.2 Tolerances

The application of the gravel bed and screeding layer should satisfy the specific tolerances [3] that are presented in Table 2.

Table 2. Gravel bed/screeding layer tolerances

Gravel bed	
Vertical tolerance	±0.15m
Mound height	≤0.25m
Screeding layer	
Top of screeding layer	±50mm (grid 3x3m)
Top of screeding layer	±25mm (grid 6x6m)
Global tolerance	$\Delta_{v,G,MAX}$=±50mm
Average of opposite sides	Δ<±25mm
Perimeter average/center (6x6m)	Δ<±30mm

The Except for the above tolerances, the following additional tolerances should be also fulfilled for the screeding layer:

- The pouring height should be approximately 3cm more than the final screeding height.
- The minimum thickness on the top of mounds should be 0.4m.

4.3 Onshore trial field

Before undertaking any offshore works, an onshore trial field was created by SBJV to calibrate the operation. An area was selected with the in-situ conditions similar to the ones offshore. It was then excavated and filled with water. Three small field tests with different thickness of gravel bed were performed to test the vibrator plate. For the screeding layer, a trial field was created on

Vordinborg port to check the performance of the levelling ring (Ø=3.95m and 23t weight).

4.4 Excavation procedure

First the excavation of the foundation pits at piers' locations is performed; for piers 12S, 16S and 18S the installation of the sheet piles, to retain the excavation, precedes the excavation. The BoE (Bottom of excavation) is surveyed in each of the excavated pits, and it is cleaned and reshaped, using a wire crane. A bathymetric survey is conducted to check if the cleaning criteria are met. The check of BoE is completed by CPTs. CPTs are performed using Geolight seabed CPT for every 50m^2 and for a depth of 1.50m below BoE and these are reviewed by a Geotechnical Engineer. After the CPTs, either human divers or robots inspect the bottom of excavation to check that the maximum thickness of deposited loose and softened materials on the bottom of the excavation is no more than 50 mm. The BoE is cleaned in case of the presence of soft soil with a thickness greater than 50mm; the foundation activities of the execution of gravel can then start.

4.5 Gravel bed/screeding layer placement

The execution of the gravel starts with the placing and compaction of the gravel bed up to design level except for the piled foundations (1C, 1S, 1N and 12S). The placement and compaction are conducted in layers, whose thickness depends on the total thickness of the gravel bed [4]. The maximum total thickness of loose material is 2m, which corresponds to 1.6m of compacted material. The required relative compaction of the gravel bed is D_r>65%. Bathymetric surveys are conducted before and after the compaction to ensure that the compaction required is achieved. For the special foundations 1C, 1N, 1S, 12S; firstly, a layer of 50 cm of gravel bed is placed and compacted, and then, the steel piles are installed. Before the installation of piles, bathymetric surveys are conducted before and after the compaction. Steel caps are placed on top of the piles and the remaining gravel is placed and compacted up to the design level. The compaction is checked with bathymetric surveys. At this stage, if the mounds created exceed a height of 25cm, a levelling ring is used to decrease their height so as to satisfy the tolerances.

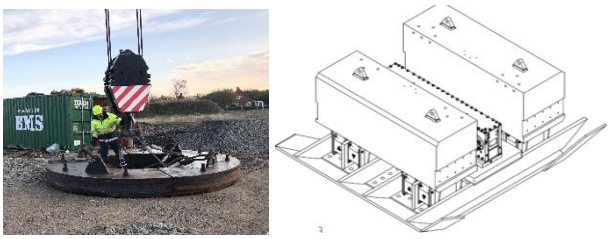

Figure 4. Levelling ring and vibrating plate

A loose screeding layer is placed and levelled through the steel ring above the gravel bed, after the compacted gravel layer is inspected [4]. Any soft soil material is removed by means of an air lifter. If new levelling is required, then the minimum thickness of 0.4m is considered. After the completion of the levelling, an out-survey is conducted to check compliance with tolerances before positioning the precast foundation.

5 Off-shore piers execution

5.1 Installation of precast foundation

Before the placement of the foundation, checks as per Table 2 are performed with bathymetric surveys for controlling the condition of the bedding plane in both the vertical and horizontal directions.

The precast caisson foundation and lower pier are positioned on top of the screeding layer by means of a catamaran [5], equipped with 4 strand jacks with a total lifting capacity of 2.500 tons. The lifting of the caisson is made through 4 "clamps" that are connected to 4 CHS elements embedded in the caisson internal walls.

The lowering operation is monitored through an antenna fixed to the top of the pier, which allows control of the pier top position as well as its inclination during lowering. When 80% of the foundation load is transferred to the gravel bed the clamps automatically open and release the foundation. Due to the uncertainty about possible tilts occurring after release a maximum allowable rotation of 3.5mrad has been set for this particular stage of construction.

5.1.1 Tolerance and installation requirements

During sinking the *maximum allowable error* [3] is considered. This is defined for the top of the lower pier shaft, depending on the number of pier

segments that are to be installed off-shore, and considering a maximum allowable rotation of 3.5mrad in the transverse direction and of 5mrad in the longitudinal direction. Such limitations are imposed by clashes of the headed bars in the stitch joint with precast element surface. The *maximum allowable error* for each of the 4 pier types is presented in Table 3.

Table 3. Maximum pier deviations

Upper pier type	**A** (Pierhead +C1)	**B** (Pierhead +C1 +C2)	**C** (Pierhead +C1+C2 +C3)	**D** (Pierhead +C1+C2 +C3 +C4)
Pier Numbers	19N-17N	16N - 7N 10S, 13S, 14S, 15S	6N - 3N 7S - 9S 11S, 12S	2N - 1N, 1S - 6S
Max dev.	**±50mm**	**±80mm**	**±100mm**	**±120mm**

Sinking of precast foundation is performed with wind speed less than 10m/s, current speed lower than 0.7m/s and wave height less then 0.3m.

5.2 Installation of precast pier segments

The precast pier segments are 3.2m high and include 4 pre-embedded steel profiles (HEB 340 for lower segments and HEB 240 for upper segments) that protrude outside the element. These are used to couple the segments off-shore and to achieve a nominal joint height of 80cm.

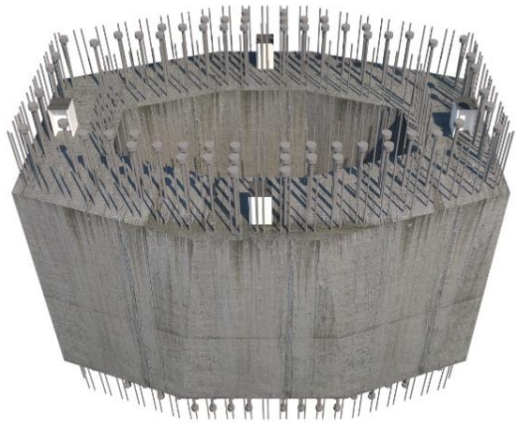

Figure 5. Precast pier segment with steel profiles

The pier bent is not precast: the last pier shaft precast segment (*segment C1*) is shipped off-shore together with the pre-assembled reinforcement cage of the pier bent and its formwork. The casting of this last part of the pier is therefore performed off-shore. Bearing plinths are not cast yet at this stage.

5.2.1 Pier shaft vertical/horizontal tolerance

During erection of pier segments the tolerances of Table 1 & 3 shall be fulfilled. Before the placement of the any pier segment the horizontal deviation of the control point (top of previously installed segment) should be known. The coordinates of this point are derived from the topographical surveys at different phases of pier erection. These surveys give the exact actual deviation of the control point from its design calculated position. Considering this deviation as a starting point for the erection of each pier segment, a correction is applied by adding or removing shim plates at pier segment joints.

The shimming at steel profiles flanges is performed during pier erection and allows recovery for both vertical and horizontal misalignments, through imposed axis rotation. A nominal gap of 30mm is considered between the flanges of the profiles, this can be either reduced or increased by ±20m for HEB 240 and ±22m for HEB 340, in order to achieve the necessary compensation of vertical and/or horizontal deviations.

6 Sinking of foundation 1C

6.1 General description and tolerances

The plinth 1C (Figure 6) is the foundation of the cable-stayed pylon and is itself a special case. The foundation is 42mx34m in plan, about 10m high (at connection with pylon shaft) and features a portion of pylon shaft of 12.7m height. The pylon concrete shaft is 250mm thick to reduce the overall weight at float-off and features 2 levels of temporary struts to limit the inwards deflection due to water pressure.

Four additional floating tanks (in red in Figure 6) are installed at the corners for buoyancy during sinking operations, a steel structure (in blue) supports the in-situ casting of the first part of cable-stayed girders. There are 24 ballast tanks inside the plinth, 4 ballast tanks provided by the stability towers and the void space inside the pylon shaft.

The total weigh of the foundation, steel structure and pylon shaft reached about 12.000 tons; it was

been cast and assembled on-shore and then loaded on a submersible barge (BOA barge 34) using a skid system. The caisson float-off was made at the location of final installation; the mooring and sinking operations lasted 5 hours (max).

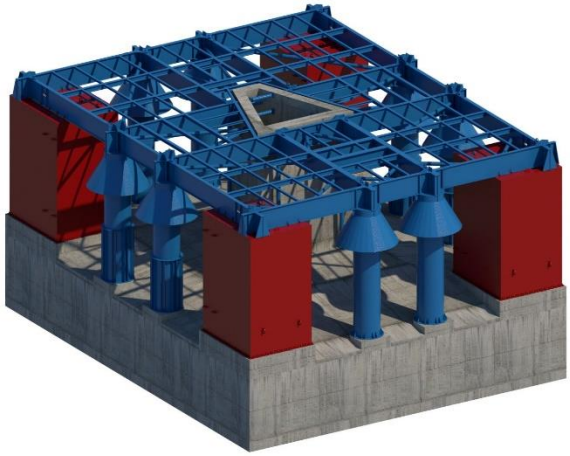

Figure 6. 3D view of 1C.

6.2 Mooring, sinking and laying of Plinth 1C

The mooring is conducted using 176kN winches, all the mooring equipment is fitted for this load. After the mooring is completed the sinking of the plinth starts. The ballasting of the plinth is realised by filling successively the tanks and the towers using pumps. At the final position the tanks are ballasted by gravity and the pylon shaft by pumping [6].

6.2.1 1C vertical/horizontal tolerance

The final position of the plinth 1C must fulfill a tolerance of 50mm (in horizontal direction) from the design position. In order to achieve this accuracy, the operations require specific weather conditions: wind speed (<10m/s), current speed (<0.5m/s) and wave (0m).

The 4 steel towers installed at each corner of the caisson are used for refloating in case the required tolerance is not met. Air is pumped into the towers to allow the floating of the foundation 30-50cm above the screeding layer. After 1C repositioning water is re-pumped into the floating towers to complete the sinking. The re-floating operation can be performed till the required tolerance for positioning deviation is achieved.

7 GIRDERS CONSTRUCTION

The first 2 spans in the north and in the south are cast-in-situ, starting from the abutments. Following the completion of these spans the precast girders are erected in sequence following the sequence outlined in paragraph 7.2 and 7.3.

7.1 In-situ girders: construction sequence

The 2 span that start from the abutment in both Falster (south) and Masnedø (north) are cast-in-situ. A temporary embankment stretches from the coastline towards the sea to allow the positioning of the falsework, these are supported on a concrete slab cast on top of the embankment. The embankment is built with sand (BLII) and a 0.4m layer of SGII (sand and gravel) on top; both with compaction 95% in modified proctor test. The foreseen settlement of the falsework foundation for girder casting (at midspan) was set to be within 8mm, the one measured by monitoring system achieved 5mm after the completion of first girder casting.

The construction of the in-situ girders consists of the following phases [7]:

1. **Installation of formwork**: the panels are installed taking account of settlement compensation at abutment and piers as well as according to pre-camber for girder deformation;
2. **Positioning of bearing and shear keys**: these are positioned through dedicated frames and are cast together with the girder bottom slab; the lower plate is not grouted on top of pier/abutment in order to allow final elevation tuning. Temporary jacks, with an overall capacity of 3.200t (4x1000t jacks), are installed at abutment/pier diaphragms for this purpose.
3. **Temporary Restrains Installation**: Between the backwall of the abutment and the edge diaphragm of the girder a temporary restraint system consisting of high strength bars and steel profiles is introduced.
4. **Casting of girder:** the girder is cast in 3 main phases: (i) bottom slab and webs up to 1.5m from girder soffit (top of lower blisters); (ii) webs up to top slab soffit and finally (iii) the top slab. While the whole span is cast for the fist 2 stages the casting of top slab is divided into segments about 30m long.

After girder completion and upon achieving the

required strength for PT stressing (f_{ck} 38MPa) the longitudinal post-tensioning cables are stressed, grouted and the falsework removed.

The girder position is adjusted by the jacks according to the projected settlements of the abutment and the pier (see paragraph 7.2.3). The ducts for the shear key anchorages and the concrete blocks of the bearings are cast. After reaching strengths of 50Mpa for the grout and 40MPa for the bearing plinth concrete, a force is applied in the jack; the safety collar is released and the girder is lowered on the bearings.

7.2 Precast girders: construction sequence

The construction of the typical precast girders starts from an already constructed girder (i.e. cast-in situ spans). The erected precast girder foresees the need for 2 stitches to be cast off-shore: 1 towards the already completed span (rear joint, full section to be cast) and 1 towards the segment *C0* positioned on top of the pier (front joint, box cast without cantilevers).

It is worth noticing that the Initial restraint configuration (longitudinal restraints imposed at abutments) is significantly different from the final one (fix piers at 15S, 14S, 13S and 14N, 13N, 12N).

7.2.1 Positioning of segment 0

The pier head segment (*segment C0*) is partially precast on-shore (for a height of 1.4m from the girder soffit), with pre-embedded bearings and shear keys. It is then shipped and positioned on top of the pier, on temporary bearings, in a position 250mm higher than its final one.

The pier top is also equipped with temporary restraints as well as horizontal (2 sets of opposed 2x200t, in green in Figure 7) and vertical jacks (4x1000t in blue in Figure 7). These are used for the adjustment of *C0* position in order to achieve the required pre-set and vertical alignment position. After positioning the remaining part of the C0 is completed for both steel fixing and off-shore cast.

The horizontal position of the C0 is determined in terms of the diaphragm off-set in respect to the pier axis (pre-set) [8]. The value of pre-set is the combination of an irreversible component (shrinkage, creep) that is fixed and a reversible component (temperature) that depends on the environmental condition at the moment of girder lifting. Due to the non-negligible time elapsed between the positioning of precast *C0* and erection of precast girder, a system with horizontal jacks, steel sliding plates and reaction frame is foreseen for pre-set adjustment.

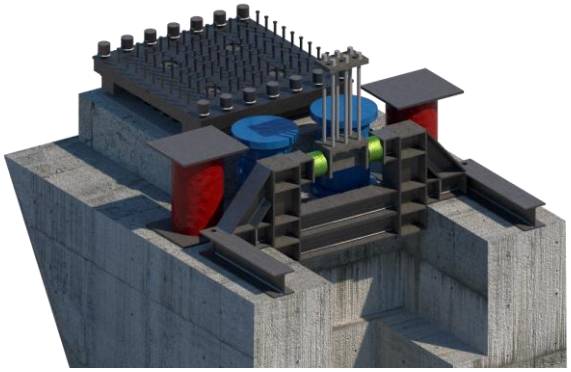

Figure 7. Frame for temporary restraint and preset adjustment

7.2.2 Erection of precast girders

The precast girders are cast in 73m long sections onshore; after completion of the girder PT the precast element is shipped off-shore for erection.

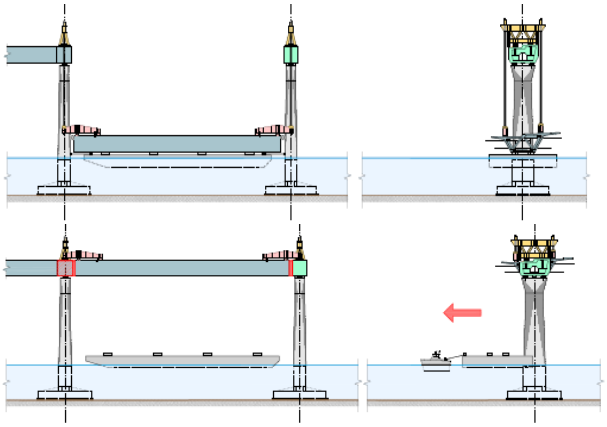

Figure 8. Phases of girder erection

Lifting operations require: wind speed (<10m/s), current speed (<0.7m/s) and wave (<0.3m).

This is completed in six phases, that are shown in Figure 8 as described hereunder [8]:

1. The girder is towed to the lifting site and it is moored to the piers and adjusting the horizontal position.
2. The strands are lowered and anchored at the lifting arms; lifting is performed by computer controlled hydraulic strand-jacks.

3. At the last stages of erection a centering device placed on the girder engages a guide positioned on *C0*, in order to ensure the span alignment. Specific elements are introduced between *C0* and the span in order to connect the 2 without bringing forces into the lifting equipment.
4. Continuity is then completed with steel fixing, casting and post-tensioning (with f_{ck} 38MPa) of continuity cables: (full prestress of the rear joint; partial prestress of front joint).

After the completion of prestressing, the front end of the girder is lowered by jacks to its final position.

7.2.3 Tolerances and settlements compensation

The tolerances for the girders concern the girder *Segment C0* and the girder of a span between two piers. The prescribed tolerances are the following:

- girder segment 0 on pierhead: $\Delta 1 \leq 10$mm (horizontal) from BGE (Bottom Girder Elevation)
- location of lifting arms on girder: $\Delta 2 \leq 10$mm.

The control measure taken for achieving the tolerances is related to the presence of the 1.10m wide stitch joint between *C0* and the precast span, that allows for compensation of possible deviations of the final position of the pier top.

After lifting the precast girder about half of the final permanent weight is induced on the foundation. Most of the consolidation settlement occurs within 2 months from load application. The settlement for half of the load is, therefore, monitored for both the immediate and consolidation components and projection is made for the final one, due to the load of the second span. The deviation between the design settlement and the projected one is then compensated through jacking of the girder up or down. Typically design settlement is about 50mm.

Adjustment of bearings is possible by means of the adjustable reinforcement cage of bearing plinths (±50mm); shear keys elevation can also be adjusted (for the piers where shear keys are present) although to a limited extent (20mm). The long anchors resisting overturning moment are pre-embedded in empty boxes at the pier head that allow for ±20mm vertical adjustment. These are connected to the Shear Key base plate when the front end of the girder is lowered to induce negative moment in the rear end (shear keys and bearings are cast in the Segment 0 bottom slab).

It is also possible to recover additional -25/+40mm, through the reduction/increase of the slab track bedding. This allows an extra buffer if the deviation exceeds 20mm, for piers where adjustment is limited by the presence of shear keys.

The above is applicable for both precast and in-situ spans. For the in-situ work the settlement on piers/abutments is monitored after longitudinal post-tensioning and falsework removal, instead of after lifting.

8 Conclusions

The construction of the Storstrøm Bridge is subject to several variables in terms of settlements and installation accuracy. Structural monitoring is therefore performed throughout the construction operations and deviations are measured by regular topographical surveys. A set of strict tolerances is defined for every particular construction phase of foundation, piers and girders. Possible deviations from the nominal position, outside prescribed tolerances can be recovered at specific locations through the implementation of corrective measures during the construction process, in order to achieve the design rail alignment.

9 References

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