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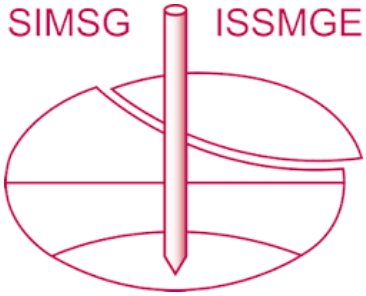

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Settlement and tilt of large-scale bridge piers based on site characterization and monitoring

Jørgen Steen Steenfelt
COWI, Kongens Lyngby, Denmark, jos@cowi.com

Per Sandgaard Kristensen
COWI, Kongens Lyngby, Denmark

ABSTRACT: Based on collective Danish experience from foundation of structures in low-plastic clay till, including heavy structures (high rise and bridge foundations), the settlements and differential settlements are small. Thus, for designs based on the ULS, with relevant partial factors of safety, the SLS condition is tacitly understood to be acceptable with no problems related to settlements, tilts and cracks in the structure. The relatively few cases with monitoring, that do exist, all support this notion. However, at the time of construction of the Storebælt Link, it was recognised that for such an important infrastructure project, it was necessary to be able to document the tacit understanding of the behaviour of the foundations by calculations and monitoring. This resulted in very extensive ground investigation campaigns with vast amounts of laboratory tests, excavation inspections and careful monitoring of all phases of the construction process (placing of gravel bed, caissons, girders etc). A long-term monitoring programme was initiated with recording of settlements and tilts of all piers. This effort has paid off as the results from Storebælt, and particularly for the 62 West Bridge piers, over a period of 25 years have formed a back-bone for assessment of settlements and tilts of large scale direct foundation on over-consolidated clay till deposits in Denmark. The paper describes the "typical" Danish clay till properties using Storebælt data as comparable experience, the predictions of settlement and tilt of the West bridge piers and the comparison with the monitoring data.

Keywords: site characterization; direct foundation; settlements; bridge piers; low plastic clay till

1. Preamble

Direct foundation seems the obvious solution, when large-scale structures may be founded on competent soils. This is often the case in Denmark, where the latest glaciation (10,000 years ago) has resulted in strongly over-consolidated soils. Very often these are low-plastic, stiff clay tills.

Although the Eurocode specifies that all limit states need to be considered in design, the Danish Practice suggests that settlements and differential settlements may be already covered when design has considered the ULS and appropriate partial factors of safety.

In cases of new structures and because of the "European Open Market", "comparable experience" is extremely valuable for contractors and consultants unfamiliar with Danish Practice and soils.

In the paper, experience with large-scale direct foundation of bridge piers on Danish clay till deposits is synthesized based on extensive site investigations and subsequent long-term monitoring. The data are primarily from the Storebælt Link Project and particularly from the West Bridge (see Figure 1).

The data have informally constituted a back-bone for the methodology to be applied in estimates of settlements and differential settlements of structures founded on clay till. The methodology was directly used by COWI in the design of the "New Storstrøm Bridge" (Storstrømsbroen) currently under construction (see Figure 2).



Figure 1. Storebælt Fixed Link; Foreground to background: West Bridge; Sprogø transition island; East (suspension) Bridge (from Sund & Belt).



Figure 2. Artist's view of the New Storstrøm Bridge (Storstrømsbroen) currently under construction between the islands of Masnedø and Falster in the southern part of Denmark.

Taking advantage of the extensive Storebælt experience, it was possible to optimize the foundation solution using direct foundation on pre-consolidated clay till at shallow depth.

The inherent variability of the clay till at both bridge sites prompted COWI as designer to consider overall soil parameters, valid over the entire foundation foot print, as detailed differentiation was not merited. This came with the caveat that the effective vertical stress due to the foundation structure would not exceed 75% of the pre-consolidation stress in the clay till. This reduces the settlements and in particular the contribution from creep.

Thus, the paper aims to provide a formal and traceable basis for the assessment of the settlement and tilt behaviour of large-scale direct foundation on Danish clay till.

2. "Typical Danish clay till"

Bulletin 16 *Danske jordarters geotekniske egenskaber*, under preparation by the Danish Geotechnical Society, addresses "Geotechnical properties of Danish soil deposits". The draft Chapter on Till deposits (Christensen et al. 2015) has a very extensive description of "Typical Danish clay till" (Author's translation):

"*It is surprising that it makes sense to refer to a "typical Danish clay till". From differences in depositional environment the clay tills would be expected to display very localized characteristics, varying from place to place, but this is not the case. Surprisingly, it is very difficult to distinguish samples taken at Rønne, Bornholm from samples from Kalundborg, Odense or Esbjerg. Typically, they all show a clay content of 12-15%, a water content of 10-14% a plasticity index of 5-10% and exhibit a grey colour (below the desiccated zone). With the exception of samples from Bornholm (igneous base rock) all have a carbonate content, $CaCO_3$ between 12 and 25%. This is what is referred to as A "typical Danish clay till*".

Thus, "typical Danish clay till" is also found for other large scale infrastructure projects, e.g. the New Storstrøms Bridge currently under construction. Here, the design was supported by the Storebælt data in regard to assessment of settlements and tilts of the bridge piers.

3. Comparable experience from Storebælt

A lot of the experience from the Storebælt Fixed Link ground investigations is summarized in the so-called POS Reports (POS = Project Organisation Storebælt) prepared by the Danish Geotechnical Institute. These reports draw on information from factual pier reports, and advanced laboratory and field test reports.

Based on the large number of geotechnical boreholes and CPT tests (combined with geophysical testing), the clay till deposits were classified in types, primarily based on the undrained shear strength, c_u, (see Table 2), at the time and for the location evaluated the same as the field vane shear strength, c_v.

Table 1. Clay till types according to undrained shear strength

Clay till type	Undrained shear strength, $c_u = c_v$ (kPa)
Till 0	< 100
Till 0/1	100 - 200
Till 1	> 200

In general, the average values of classification parameters for individual piers closely resemble the overall values shown in Table 2. Perusal of the extreme values reveals that these almost without exception are from samples where the geological description is ambiguous (i.e. difference between top to bottom of sample, inclusion of lumps of other materials etc.).

The large number of CPTs (~ 10 per pier) reflects the spatial variability of the soil strength. Whereas closely spaced CPTs often indicate very similar readings, significant deviations of CPTs or borings within short distances (1-2 m) are not uncommon. Whether the discrepancy is caused by heterogeneous soil conditions or inaccuracies in instrumentation, the necessity of interpreting multiple CPTs together is of great importance, as a single CPT-profile may lead to misinterpretation.

This is borne out by the monitoring results from the West Bridge piers, Sec. 4.2. Using the results from individual CPTs from say opposite corners of the foundation foot print would lead to much higher tilts than actually observed.

An example of the plots used as background for pier designs is shown in Figure 3, where the composite CPT profiles are averaged and mathematically smoothed and shown together with vane shear strength, water content and activity. The very low activity (ratio of remoulded to intact vane shear strength) is typical of Danish clay till (i.e. inactive). Both the CPT (average to average of minima) and the vane tests, demonstrate significant variation in undrained shear strength albeit with no visible consequence on settlements and tilts of the individual piers.

Table 2. Clay till types and classification parameters for clay till 0-1 for 19 East Bridge Approach Piers (after POS Report 157, 1992)

Value	w (%)	w_L (%)	w_P (%)	I_P (%)	γ (kN/m3)	ρ_s (Mg/m3)	e	$CaCO_3$ (%)	Clay (%)
Minimum	6.5	12.2	9.1	2.2	20.6	2.66	0.18	9	10
Maximum	21.9	23.1	13.2	10.8	24.2	2.75	0.59	34	29
Numbers	801	160	160	160	538	156	529	751	160
Average	11.7	17.1	10.6	6.5	22.9	2.70	0.31	17	15

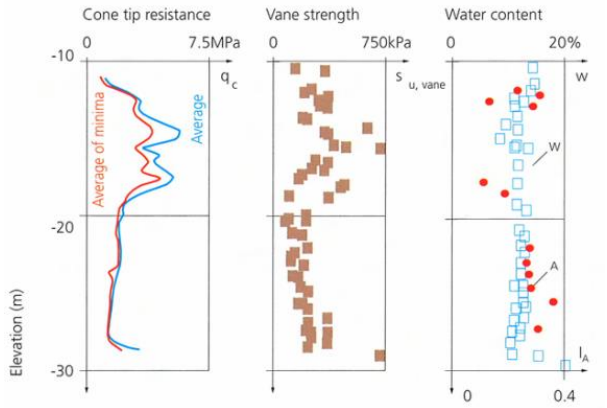

Figure 3. Example of variation with depth of (smoothed) cone tip resistance, vane shear strength, water content and activity for East bridge approach pier (Sørensen, Steenfelt and Mortensen,1998)

Many classification tests were carried out, but not systematically (say per one metre) in each borehole. Hence, plots of water content and plasticity index with depth by necessity involves several boreholes.

4. Comparable experience from Storebælt West Bridge

4.1. Pier foundations and soil strata

The 62 offshore piers and the two abutments of the West Bridge, have been monitored from handover by the Contractor in January 1994 to the most recent readings in October 2010. These data allow comparison of settlements and rotations of all bridge piers, reflecting the power of prediction and the influence of variation in soil properties across the pier footprints.

The prefabricated caisson bridge piers are founded directly on a 1.5 m thick stone bed in glacial till deposits (post-glacial and other deposits with inferior strength and deformation properties removed by dredging). The foundation bases vary from 17.25 m by 29.5 m to 22.5 m by 34.0 m with total loads of the order 186 to 251 MN. Thus, the foundation pressures are of the order 325 to 500 kPa.

The geology and soil strata are described in detail by Foged et al. (1995). The water depth varies from shallow depth to approximately 30 m along the alignment.

The predominant soil units are clay till and sand till with interlacing of meltwater sand. The Upper till shows undrained shear strength increasing with depth from 50 - 250 kPa, whereas the Lower till is generally stronger and stiffer with undrained shear strength of the order 200-300 kPa. Marl (Kerteminde Marl) and Danian limestone form the base of the glacial deposits.

The plasticity index of the clay tills varies from 4% to slightly above 10% and the carbonate content is typically below 25% but slightly higher, above 30%, for the Lower till.

Large variations in the undrained shear strength were observed both vertically and horizontally by eight to 15 CPTUs and two boreholes carried out over the foundation footprint.

Examples of superimposed CPTs from West Bridge pier are shown in Figure 4, clearly illustrating the variability of CPTs within a small pier footprint. Pier 6 shows almost 5 m of gravelly/sandy soil for half of the CPTs recorded for this footprint; Pier 8 shows a general high variability and Pier 19 shows a very distinct CPT outlier.

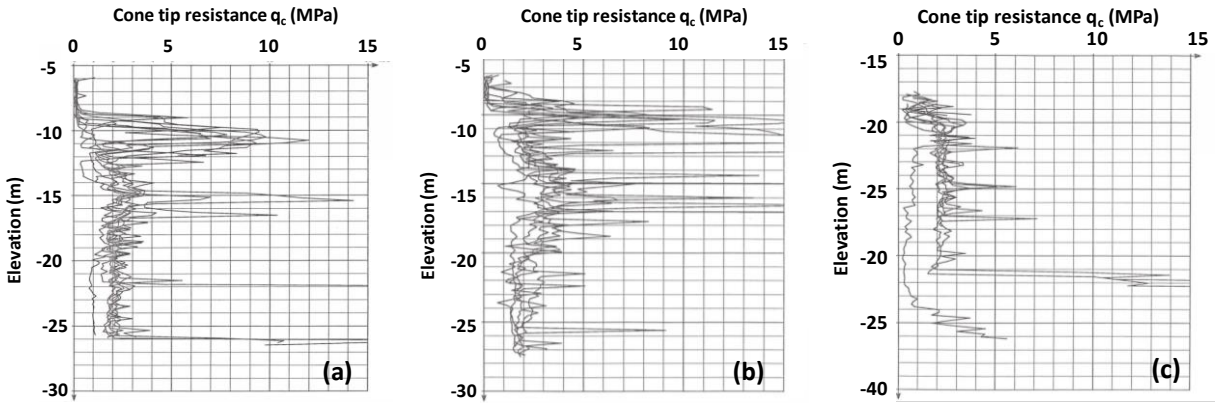

Figure 4. Examples of composite CPTUs from (a) Piers 6 (b) Pier 8 and (c) Pier 19 of the West Bridge (horizontal axis is tip resistance q_c [0-15 MPa] and vertical axis is elevation [-5 to-30 m; -5 to -30 m; -15 to -40 m])

The variability of soil strata and overall soil properties is a general feature of Danish clay tills. Very similar conditions were found for the current Storstrøm Bridge (Figure 2 and Sec.5) albeit the undrained shear strength seems to be slightly lower at the latter.

This variability in strength and deformation properties is likely due to the erratic glacier movements during the latest Weichel glaciation causing the observed heterogeneity of the deposits (also manifesting itself by distribution of clay mineral constituents, Ernstsen, 1998).

The geological setting and the methodology applied for settlement and tilt prediction for the West Bridge are e.g. described in Foged et al. (1995) and Kristensen et al. (1995).

4.2. Settlement and tilt prediction West Bridge

Due to the high overconsolidation ratio the settlements were calculated for the additional stresses from the

foundation loads under the centre of the foundation assuming an isotropic, homogeneous, linear elastic soil.

Thus, an overall model was used except for the weakest parts of the Upper till where a 1:2 distribution of the additional stress was assumed. For each of the 10-17 investigation points the overconsolidation ratio was determined per metre and equivalent "springs" were assigned. Settlements (at the centre) and tilts in two directions were then assessed for the different load events. The tilts were caused by asymmetric loading, as the road girder was placed before the railway girder, as seen in Figure 5.

The initial tilt (~ 0.1%) towards south was only partly recovered after the placing of the railway girder. Importantly, the stiffness applied for the pre-consolidated glacial deposits was based on the oedometer tangent stiffness, $E_{oed,t}$, for the West Bridge (in accordance with general Danish practice):

$$E_{oed,t} = E_{oed,t,0} + \Delta E_{oed,t} \times \sigma'_{red} \quad (1)$$

where σ'_{red} is the minimum vertical effective stress after glaciation.



Figure 5. Construction of the West Bridge (a) The giant floating crane "Svanen" is transporting a railway girder for final placement, with a time delay relative to the road girder; (b) Placing of girders near completion (road is south of railway)

Importantly, the stiffness applied for the pre-consolidated glacial deposits was based on the oedometer tangent stiffness, $E_{oed,t}$, for the West Bridge (in accordance with general Danish practice):

The oedometer sample is initially typically loaded to the in situ stress, and then unloaded (in order to compensate for sample disturbance and fitting to the oedometer ring). Even for poor samples, this may change these in fair to good sample quality. Then the sample is loaded to 85% of the preconsolidation stress (in order not to destroy the "structure" achieved by the ageing process since glaciation) and then unloaded-reloaded to increasingly lower stress levels (σ'_{red}) to allow determination of the constants, $E_{oed,t,}$ $\Delta E_{oed,t,0}$ in Eq. (1).

For the West Bridge till deposits, values of $E_{oed,t,0}$ was in the range 15 to 50 MPa, and for $\Delta E_{oed,t}$ in the range 1500 to 3000.

The creep (rate of secondary settlements) was determined from oedometer tests. However, based on the overall data, it was pragmatically decided to assess the rate of creep for the over-consolidated state as 10% of the sum of initial and primary consolidation settlements per log cycle of time. The creep calculation was initiated one month after placing of the railway girder, i.e. at the time of completion of the primary consolidation. The latter reflected the observations from the groundwater lowering project MOSES for the East tunnel of the Storebælt Link project (se e.g. Steenfelt and Hansen, 1995), and other in situ observations, for which the coefficient of consolidation, c_v, for the clay tills was found to be a factor 10-100 times higher than observed in the oedometer tests (POS Report 157, 1992). However, large scale block samples can provide realistic values, demonstrating that the hydraulic conductivity is completely controlled by fractures in the clay till (exacerbated by increasing undrained shear strength) bypassing the matrix (e.g. Baumann, 1997).

Thus, the erratic occurrences of sand seams/layers and sand pockets together with cracks in the clay till matrix control the hydraulic conductivity, rather than the matrix type of conductivity found in the laboratory tests.

Based on the initial tilt measurements (maximum 0.1%), it was concluded, that for large foundation areas, as applied for the West Bridge piers, the maximum corner to corner differential settlement is of the order 30 to 35% of the average foundation settlement (according to Kristensen et al., 1995).

4.3. Monitoring results

An evaluation and status of the monitoring results for the West Bridge piers was carried out by COWI in 2013 based on monitoring results:

- January 1994, (ESG's hand-over document)
- June 1994, DRD measurements
- July 1996, DRD measurements
- July 1997, DRD measurements
- October 2002, DRD measurements
- October 2010, LE34 measurements
- February 2014, DRD inclinometer measurements pier shafts

The recorded settlements for Piers 1 to 64 in 1994 and 2010, together with COWI's extrapolated values for year 2100, are shown in Figure 6. The 1994 settlements were calculated by the Contractor ESG (based on the soil parameters defined by the designer CCL).

These were then extrapolated to 2010. i.e. taking creep into consideration, and compared to the actual, recorded settlements in Figure 7.

Please note, that in this paper the settlements are shown as negative values and heave as positive values.

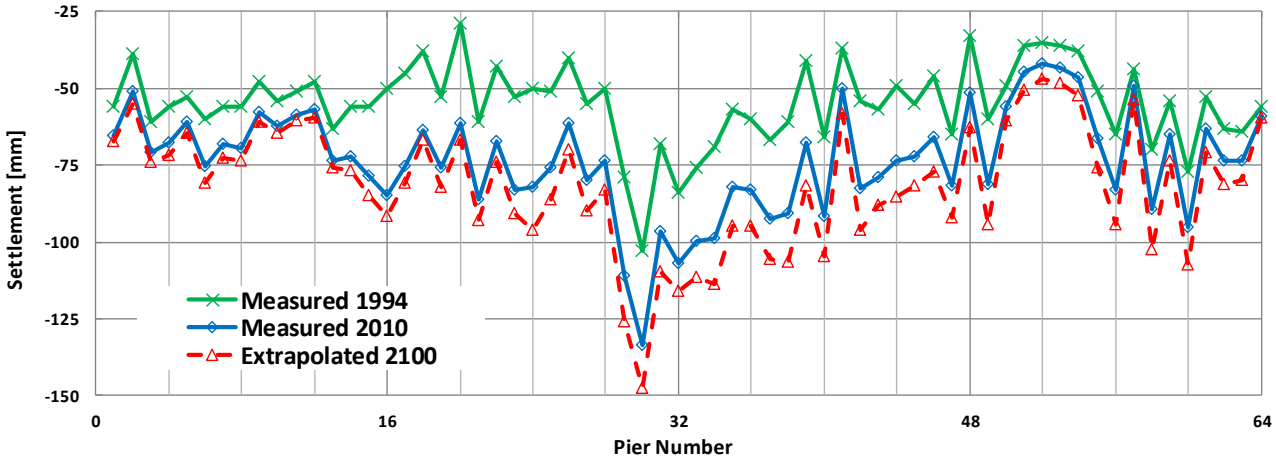

Figure 6. Recorded settlements in 1994 and 2010 compared with extrapolated values for 2100 for Piers 2 to 63 and abutments of the West Bridge

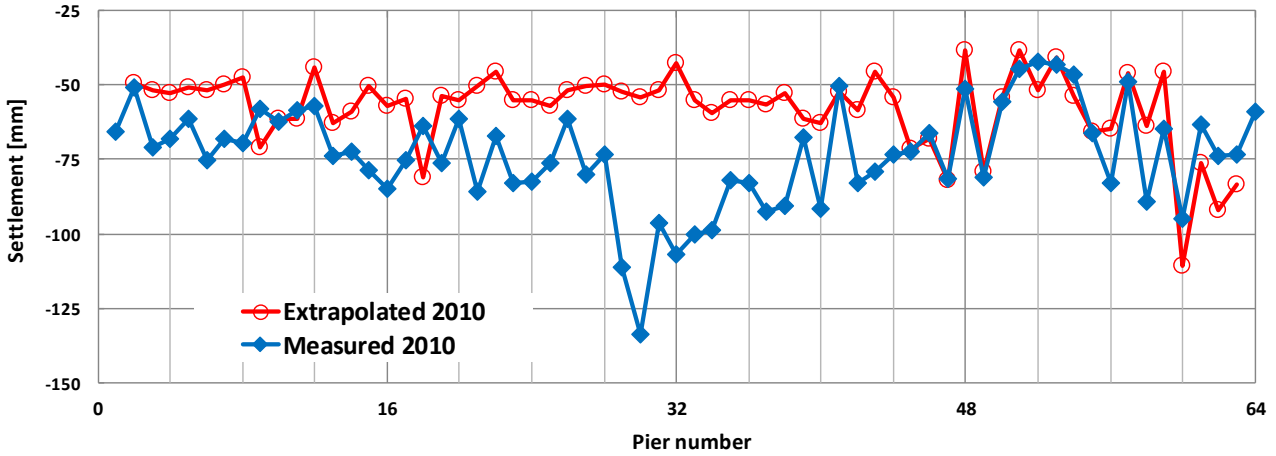

Figure 7. Calculated and measured settlements in 2010 for the West Bridge piers and abutments

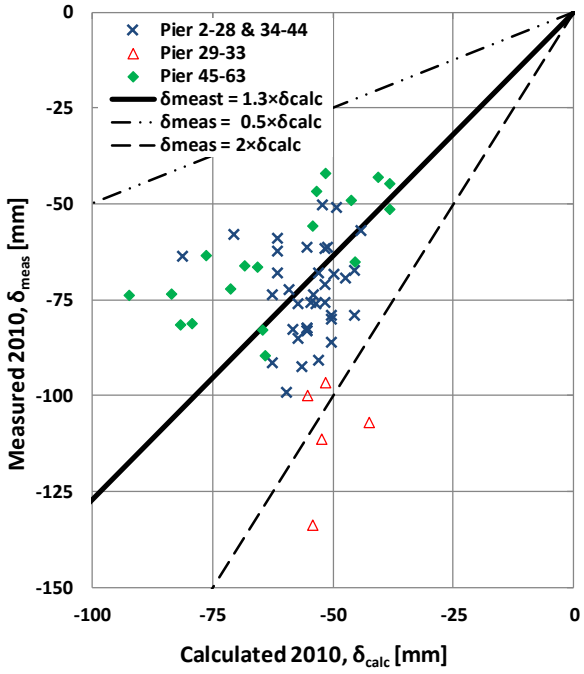

Figure 8. Measured versus calculated settlements in 2010 for the West Bridge piers and abutments

As seen in Figure 8, there is generally fair agreement between predicted and recorded settlement, except for piers 29-34. This discrepancy was realized and given particular attention during the construction of the bridge. The only rational explanation is thought to be a particularly high stress relaxation by upward gradients immediately in front of the retracting glacier towards the end of the ice age (see e.g. Foged and Steenfelt, 1992).

For all other piers, the settlements are within the assumed minimum (0.5 $\delta_{estimate}$) and maximum (2.0 $\delta_{estimate}$) limit values anticipated in accordance with general experience for pre-consolidated soils. However, it would appear that the stiffness of the clay tills was slightly overestimated as the ratio $\delta_{meas}/\ \delta_{calc} \sim 1.3$.

The total settlements are not decisive for the superstructure or the train runability, considering the distance of 110 m between piers. The maximum double differential settlement for Pier No. i, δ_i, allowed for in the design was:

$$-50 \text{ mm} \leq \delta_i - \frac{\delta_{i+1}+\delta_{i-1}}{2} \leq 25 \text{ mm} \qquad (2)$$

where δ_{i-1} and δ_{i+1} are the neighbouring piers.

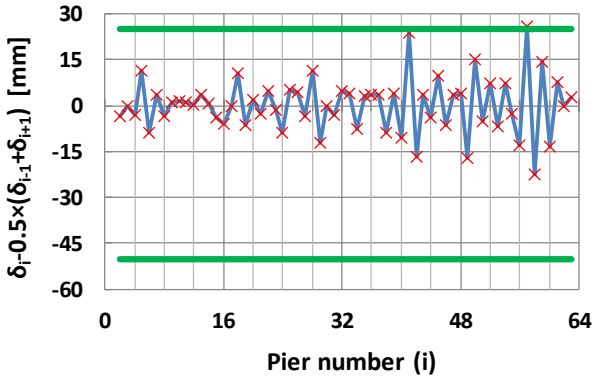

Figure 9. Double differential settlements extrapolated to year 2100

A seen in Figure 9, this criterion (shown in solid green lines) is still not exceeded, and thus the monitoring intervals will be maintained.

The next full scale measurements is scheduled for 2026, i.e. 32 years after hand-over, but in addition an automated monitoring system using inclinometers on selected piers has recently been made available on-line.

The tilts have been recorded by inclinometer measurements in 1997, 2002 and 2014. The inferred horizontal displacements at the pier tops are shown in Figure 10a and Figure 11 for displacements along the alignment and perpendicular to the alignment, respectively.

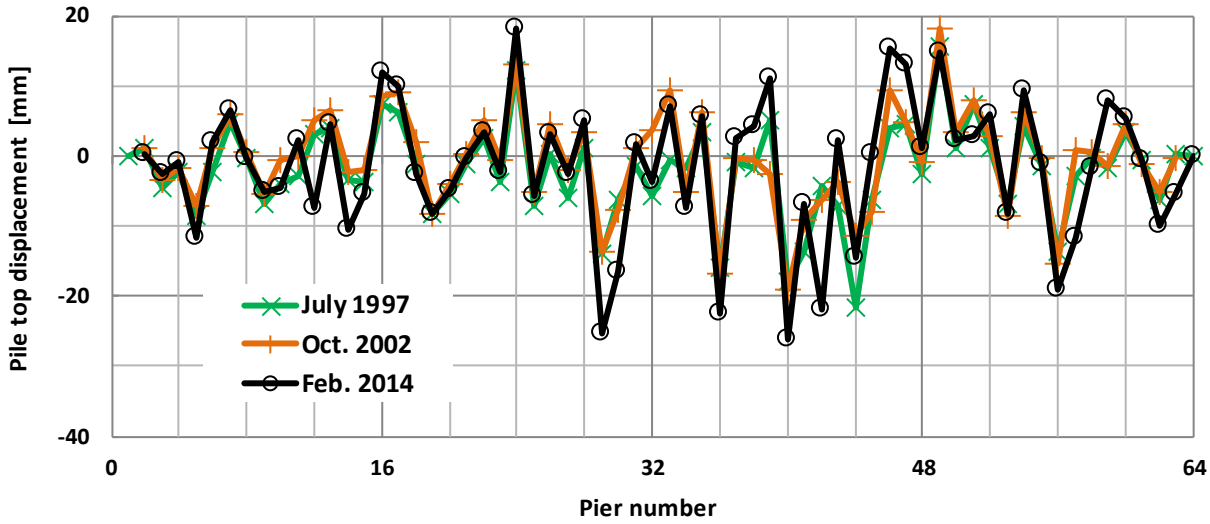

Figure 10. Horizontal displacements at pier top "along the alignment" for West Bridge piers (positive towards east)

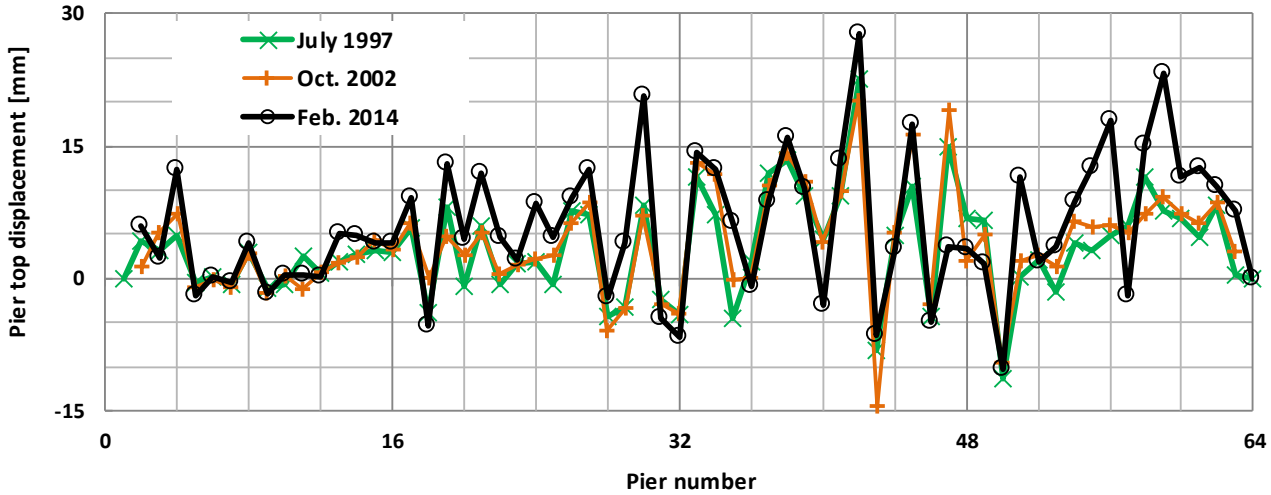

Figure 11. Horizontal displacements at pier top "perpendicular to the alignment" for West Bridge piers (positive towards north)

It is apparent from the graphs that the horizontal displacements are "randomly" distributed but tending to slightly increase with time. The relative displacement was initially towards south due to "geotechnical and loading conditions", as the road girder was placed ahead of the railway girder. The subsequent tendency for displacement towards north is a combination of the continuity created in the interface between sub- and superstructure and the effect of the bearings.

The maximum displacements are of the order 25 mm. For a maximum "pier height" of ~50 m this corresponds to a maximum pier tilt of 0.1%. This is of no significance aesthetically or statically.

Thus, the seeming variability based on single CPTs and boreholes across the foundation footprint could not be rationally used to predict tilts and differential settlements of individual foundations.

Another complication in using the monitoring data is the time delay in creating continuity of the bridge girders across individual piers. This varied from 11 to 677 days compared to the January 1994 hand-over measurements, complicating assessment of the creep behaviour.

The settlement of selected piers are shown in Figure 12 versus the time after creating continuity. Despite the inherent uncertainty in the measurements, it is clear that all piers show a linear creep behviour in logarithmic time scale.

The rate of creep in relation to the settlement at the end of primary consolidation can not reliably be determined based on the sets of monitoring data now available, but indications are, that the ratio is higher than the value of 10% originally anticipated. The graph indicates a range of creep rates of 6 to 20 mm/lct for the total range of piers.

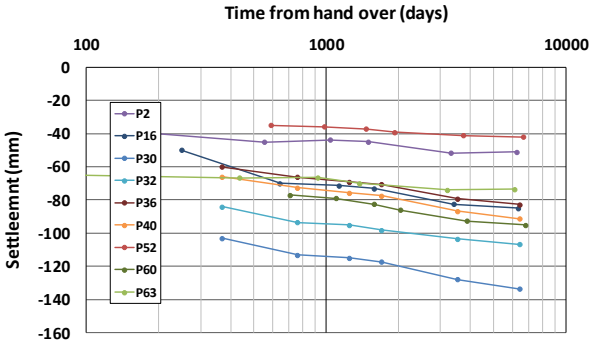

Figure 12. Creep settlements for selected West bridge piers versus time after hand-over

5. Application of West Bridge experience to the Storstrøm Bridge

Based on the predictions and measured settlements and tilts of the West Bridge piers, with comparable soil conditions and foundation principles, COWI concluded that the design calculation of settlements and tilts could be carried out in the same way for the Storstrøm Bridge. That bridge is approximately 4 km from abutment to abutment with 80 m viaduct spans and two cable stayed spans of 160 m. The bridge carries a two-lane motorway and a double track railway.

The Storstrøm Bridge project was tendered based on comprehensive site characterization by geotechnical boreholes with sampling and SPT testing, CPTu tests and a suite of classification and advanced laboratory tests together with a very detailed geological soil model.

For geotechnical design purposes, a "Reader's Guide to Geotechnical Interpretive Report" was prepared along with an "Illustrative Design". A "Baseline 1" using a versatile, simplified geotechnical soil model (condensing the very detailed geological model) outlined the Client's (Danish Road Directorate) principles for the Tender design based on the data available in the Geotechnical Interpretive Report.

At the award of contract in 2018 to SBJV, detailed design investigations were carried out for all the pier foundations and the pylon, to meet the accumulated minimum requirements of one geotechnical borehole, five CPTUs for each of the approach piers (a total 44 piers) and a minimum of two boreholes and eight CPTu tests for the Pylon foundation.

As seen in Figure 13, the plasticity index and the water content from the pier investigations are in line with the parameters found at Storebælt.

Based on the combined tender and detailed design ground investigations, a Baseline 2 was prepared by COWI, constituting mandatory correlations and a specific detailed design basis for each pier foundation, to be applied by the Contractor SBJV.

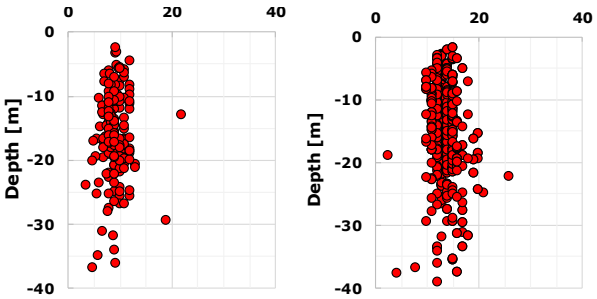

Figure 13. Plasticity index and water content from Storstrøm Bridge boreholes

An example of the compiled data for one of the approach piers is shown in Figure 14, demonstrating a variation recognizeable from the West Bridge piers.

The CPTUs in Figure 14 have neither been filtered nor smoothed. The solid red and broken gray lines indicate the parameters of Baseline 2 and Baseline 1, respectively.

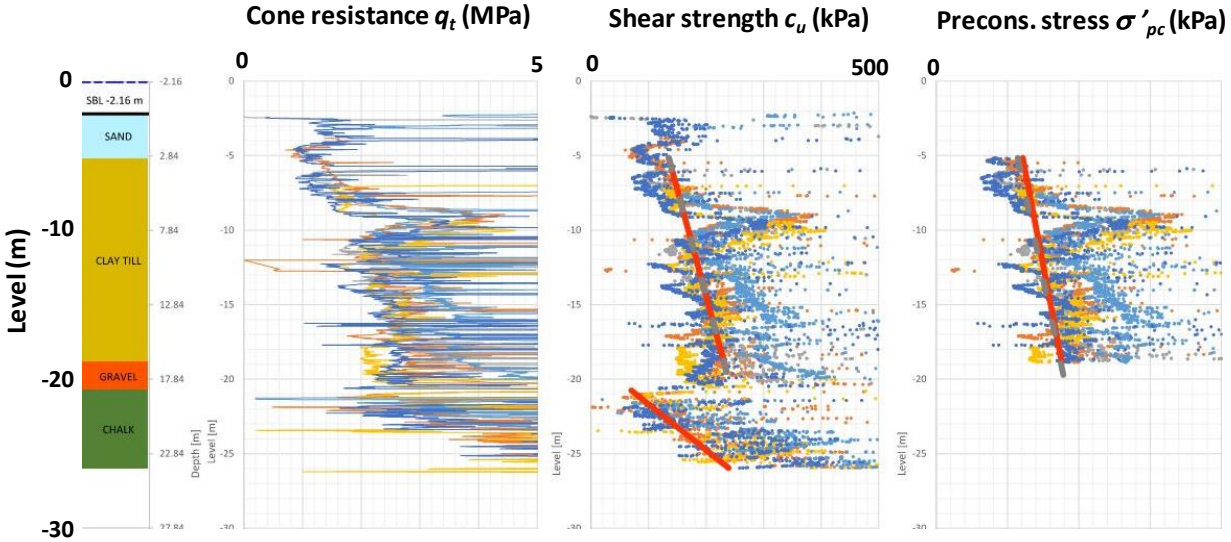

Figure 14. Example of simplified borehole log, composite q_t profiles and the interpreted variation of undrained shear strength and effective pre-consolidation stress (5 CPTUs). Solid and broken lines indicate the Baseline 1 and Baseline 2 parameters to be applied in design

The mandatory requirements were e.g. the application of a cone factor N_{kt} = 11 for the CPTUs in clay till and N_{kt} = 21 in Tertiary Chalk, together with assessment of the undrained shear strength and preconsolidation stress of the clay till based on the CPTU results as shown in Eq. (3) and (4).

$$c_u = \frac{(q_t - \sigma'_{v0})}{N_{kt}} \quad (3)$$

$$\sigma'_{pc} = 0.4(q_t - \sigma'_{v0}) \quad (4)$$

The visual appearance of the clay till deposits was likewise supporting the similarity of the conditions at the two sites as seen in Figure 15 and Figure 16. The figures show the trial pit excavation to be used for verification of the Contractor's (SBJV) ability to place, level and compact the gravel bed placed between the clay till and the precast pier foundation caissons.



Figure 15. Test pit for verification of compaction of gravel beds below the precast bridge pier caissons



Figure 16. Close-up of test pit excavation slope

Before placing the gravel (in the test pit) the lower level will be cleaned for the 5-10 cm remoulded layer resulting from heavy rainfalls and the trial pit will be flooded.

This will allow for conditions simulating the offshore conditions for most of the piers with sufficient water depth to allow offshore operations.

Figure 15 and Figure 16 demonstrate how the upper slightly dessicated brownish clay till changes to the blue-greenish clay till at depth. Likewise, the gravel and stone content in the clay till is apparent from the Figures.

The ground conditions at the trial pit are similar to the ground conditions at the nearby northern abutment, as shown in Figure 17. The Figure shows that for this position the combination of Tender and supplementary, detailed design ground investigations gave rise to a change from Baseline 1 to Baseline 2 parameters for the clay till.

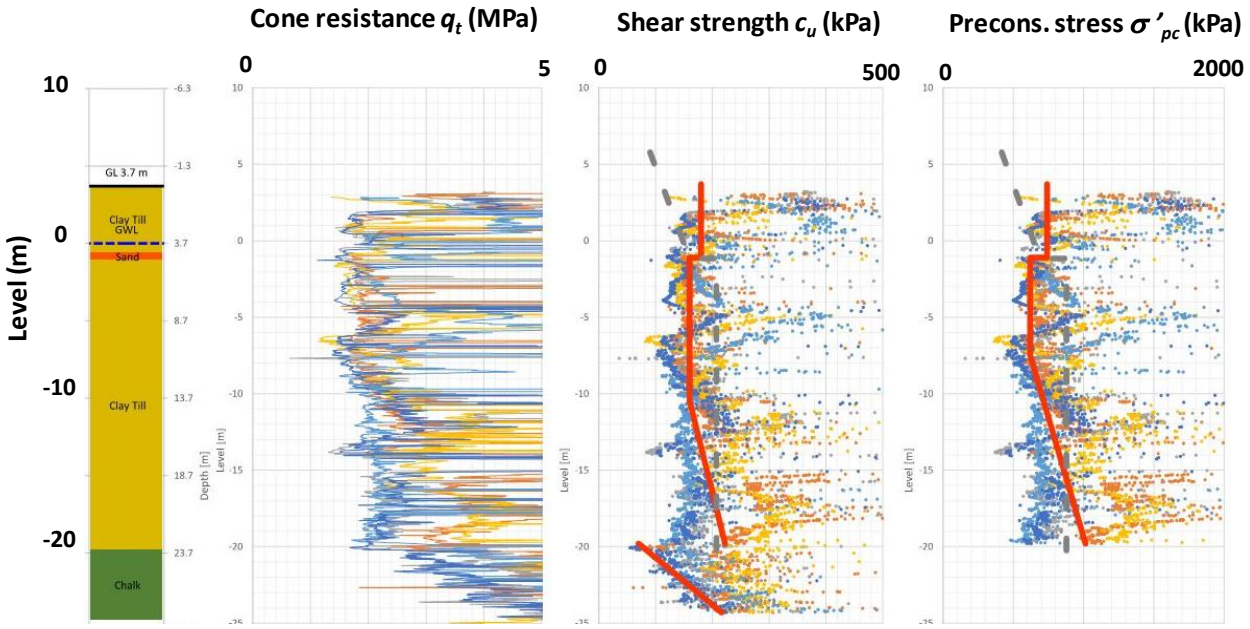

Figure 17. Ground conditions at the northern abutment close to the test pit position Baseline 2 in solid red line, Baseline 1 in broken grey line).

The (financial) implications of changes in parameters from Baseline 1 to Baseline 2 (covering unforeseen ground conditions) were outlined by the Client, The Danish Road Directorate (DRD), as part of the Tender documents and is part of the contract.

The Illustrative Design was prepared by COWI for DRD to support the Tenderers and to demonstrate the robustness and economic viability of a foundation solution based on direct foundation in clay till at shallow depth.

To allow for a unified precast caisson foundation principle, ground improvement by pile inclusions were considered, to reduce vertical settlements and to enhance vertical and in particular the horizontal resistance capacity (ice and ship impact).

In the illustrative design, it was concluded that ground improvement was only required for the pylon foundation. A cable stayed bridge is relatively „forgiving“ with regards to settlements, whereas the double differential settlements need to be limited in order to ensure train runnability.

The Design Basis had no requirements for total settlements, but the double differential settlements were limited to

$$\left|\delta_i - \frac{\delta_{i+1}-\delta_{i-1}}{2}\right| \leq 60 \text{ mm} \qquad (4)$$

where δ_{i-1}, δ_i and δ_{i+1} are the settlements of three consequtive piers.

The train runnability modelling showed that the demand regarding the double differentail settlements could be relaxed compared to the West Bridge (cf. Sec. 4.2).

In the Illustrative Design, the tilt has generally been neglected, as it was deemed insignificant based on the West Bridge monitoring experience. However, for the Storstrøm Bridge a combined girder is in contrast to the West Bridge, where girders for road and railway were placed separately, resulting in asymetric loading (causing tilts perpendicular to the bridge).

The settlements and double differential settlements extrapolated to year 2140 (120 years life time) resulting from the illustrative Design are shown in Figure 18. For simplicity square foundation footprints were assumed in the Illustrative Design, ranging from 12 × 12 m^2 to 23 × 23 m^2 for the viaduct piers to 34 × 34 m^2 for the pylon (with pile inclusions).

The range of double differential settlements is similar to the values for the West Bridge (Figure 9), but without the „outliers“.

As mentioned in Sec. 1, the Illustrative Design was carried out with the caveat that the final effective stresses after completion of the bridge should not exceed 0.75 σ'_{pc}. This explains the reduced values of double differential settlements.

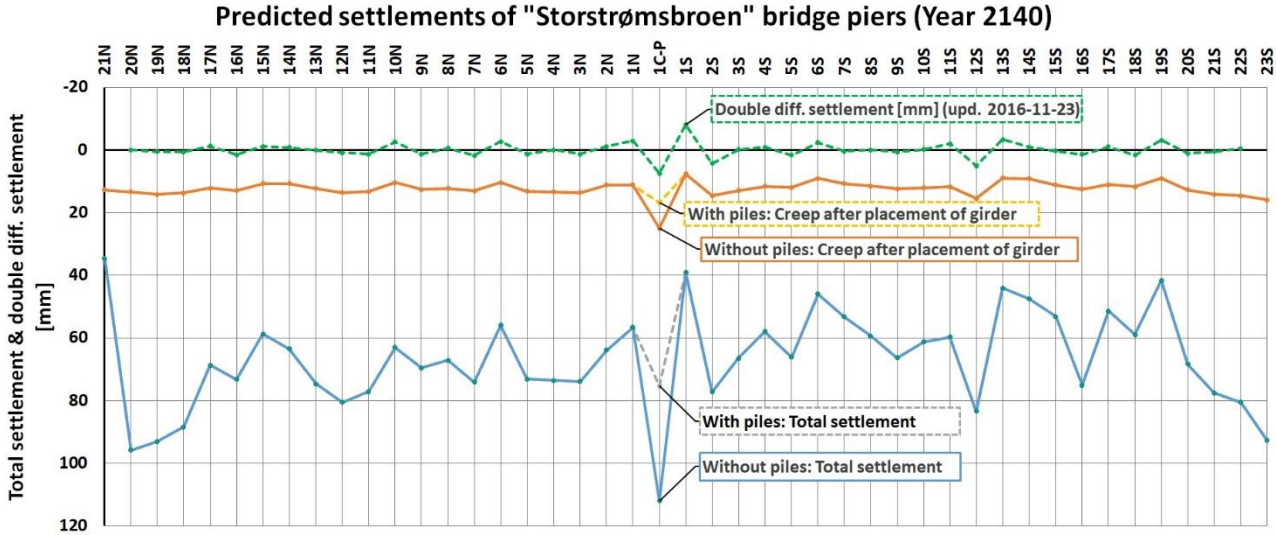

Figure 18. Settlements and double differential settlements corresponding to Illustrative Design

This caveat was introduced to provide robustness and to avoid the relatively high settlement values seen in some the West Brige piers, where the final load corrresponded to stresses near or above the pre-consolidation stress, σ'_{pc}.

Furthermore, the creep calculations were here based directly on assessed values of the modified secondary compression index, $C_{\alpha\epsilon} = \partial\varepsilon/\partial \log t$, as a function of stress level (rather than using a percentage of the sum of initial and consolidation settlements for creep per log cycle of time as initially done for the West Bridge).

It was rewarding for DRD and COWI to receive the original tenders, which closely resemble the Illustrative Design in terms of the foundation solutions.

In the final design by SBJV, considerations of ship and ice impact, together with constructability optimization, may warrant a reduced number of precast caisson types, and addition of inclusion piles in some of the viaduct piers.

Conclusion

The Danish Road Directorate is commended for the long-term monitoring of the Storebælt Link Project and in particular the monitoring of all bridge pier for the West Bridge. This should be a natural squel to important infrastructure project, but unfortunately, this is not normally the case.

The monitoring has allowed insight into the behaviour of large scale bridge piers with direct foundation in Danish clay till, at shallow depth. The data are very valuable and allow knowledge transfer to both small and large scale projects. Based on this experience, it was possible to carry out a robust and economically feasible design for the Storstrøm Bridge, having similar foundation conditions.

For both projects it was concluded that there is no merit in applying a detailed differentiation of parameters across a foundation foot print. This is due to the inherent

variability of the soil strata, and the relatively few investigation points, meriting the application of overall parameters representative of the entire pier footprint area.

The relatively high number of investigation points for the Storebælt West Bridge piers (up to 15 for each pier) has demonstrated, that the ability to make a detailed prediction, accounting for variation in soil parameters across the foundation foot print, was not merited. The ratio of measured to predicted settlements was between 0.5 and 2.0, and the resulting tilts were insignificant.

Acknowledgement

The in-depth analyses of the West Bridge data were prepared by the second author, who sadly passed away in February 2019. It is a small comfort, that the work on his pet project may now be published as his legacy.

The permission by COWI to publish the paper is gratefully acknowledged.

References

[1] Baumann, J. (1997). Panel discussion: Contamination and remediation of fractured clay till. *Proceedings XIV International Conference on Soil Mechanics and Foundation Engineering, Hamburg*, pp 2549-2550.

[2] Christensen, J.D., Frederiksen, J.K., Haahr, F., Lyse, C. (2015). Moræneaflejringer (Till deposits; in Danish). Draft version 2015-01-04 of Chapter in Bulletin 16 (under preparation) from the Danish Geotechnical Society.

[3] Ernstsen, V. (1998). Clay minerals of clayey subsoils of Weichselian Age in the Zealand-Funen area, Denmark. *Bulletin of the Geological Society of Denmark,* Vol. 45, pp 39-51.

[4] Foged, N., Larsen, G., Larsen, B., Thomsen, E. (1995). An overview on engineering geological conditions at Storebælt. Proc. XI European Conference on Soil Mechanics and Foundation Engineering, Copenhagen, Danish Geotechnical Society, dgf-Bulletin 11, Vol 5, pp 5.7 – 5.30.

[5] Foged, N, Steenfelt, J.S. (1992). An Engineering Geological Approach to Preloaded Clay Till Properties. *Proceedings 11. Nordic Geotechnical Meeting NGM-92*, Aalborg, Danish Geotechnical Society, dgf-Bulletin 9, Vol. 1, pp 75-80.

[6] Kristensen, P.S., Regtorp, J., Balstrup, T. (1995). Predicted and observed settlements and tilts of offshore bridge piers. *Proc. XI European Conference on Soil Mechanics and Foundation Engineering,* Copenhagen, Danish Geotechnical Society, dgf-Bulletin 11*,* Vol 5, pp 5.43 – 5.52.

[7] POS Report 157 (1992). *Approach Piers Geotechnical Investigations, Summary Report.* Prepared by Larsen, G., Galsgaard, J., Steenfelt, J.S., Danish Geotechnical Institute.

[8] Steenfelt, J.S., Hansen, K.H. (1995). Keynote address: The Storebælt Link – a geotechnical view. *Proceedings XI European Conference on Soil Mechanics and Foundation Engineering,* Copenhagen. Danish Geotechnical Society Bulletin 11, Vol 10, pp 10.11 -10.40.

[9] Steenfelt, J.S, Sørensen, C.S. (2019). *Fundering, kapitel 10, Teknisk Ståbi,* 25. udgave (Section 10, Foundation engineering, *Civil Engineering Handbook, 25. ed.,* in Danish*),* pp. 369-396.

[10] Sørensen, C.S., Steenfelt, J.S., Mortensen J.K. (1998). Foundation of the East Bridge. In *East Bridge,* A/S Storebælt, pp 97-110.