Underwater resonance compaction of sand fill

Compactage à résonance d'un remblai de sable sous-marin

K. Rainer Massarsch
Geo Risk & Vibration Scandinavia AB, Sweden. <rainer.massarsch@georisk.se>

Peter Zackrisson
Swedish Transportation Administration (Trafikverket), Sweden

Bengt H. Fellenius
Consultant, Sidney, Canada

ABSTRACT: Underwater compaction of sand fill was required for the stabilization of bridge piers to mitigate the effects of ship impact. Steel caissons were installed to great depth and loose soil layers were excavated and replaced by sand fill. The resonance compaction method was used to increase the stiffness and strength of the sand fill. Vibratory compaction was performed using a variable frequency vibrator, attached to a flexible compaction probe. Compaction was monitored and optimized using an advanced electronic process control system. The compaction effect was controlled using cone penetration testing.

RÉSUMÉ: Le compactage sous-marin d'un remblai de sable fut requis pour stabiliser les fondations d'un pont et pour atténuer les impacts causés par les navires. Des caissons en acier furent installés à de grandes profondeurs et des couches de sol meuble ont été excavées et remplacées par du sable. Le procédé de compactage de résonance fut utilisé pour augmenter la rigidité et la résistance du remblai de sable. Le compactage par vibration fut effectué à l'aide d'un vibreur à fréquence variable branché à une sonde flexible de compactage. Ce compactage a été contrôlé et optimisé à l'aide d'un système de contrôle électronique avancé. L'effet de compactage fut contrôlé en utilisant le pénétromètre à cône.

KEYWORDS: caisson, compaction hydraulic CPT, fill, resonance, off-shore, sand, vibration.

1 INTRODUCTION

The bridge across the bay of Sundsvall was built from 2011 to 2015 and is the longest (2,109 m) motorway bridge in Sweden. A novel foundation solution was developed to support the eight bridge piers. Instead of conventional pile foundations, coffer dams consisting of steel sheet piles, filled with compacted sand, were chosen. This solution has major advantages in the case of ship impact as the sand-filled steel caissons can absorb high horizontal forces. For the densification of the sand inside the coffer dams, the resonance compaction method was used under difficult construction conditions.

2 BRIDGE PIER FOUNDATION

The foundation of the bridge piers was a highly challenging task, as compaction had to be carried out at water depths of up to 14 m. Figure 1 shows the coffer dam, consisting of vibrated sheet piles and the barge used for vibratory driving of sheet piles and sand compaction.

Figure 1. Steel caisson in foreground and barge with pile driving and compaction equipment in background.

Extensive geotechnical investigations, comprising cone penetration tests with pore water pressure measurements, heavy dynamic probing, field vane tests and Swedish weight sounding, were performed to investigate the complex geotechnical conditions. At the sea bed, very soft organic soil (gyttja) and soft silty clay were encountered. Below followed 1 through 10 m thick silt that progressively changed into sand with a thickness of about 8 m. Till (moraine) of varying thickness rested on rock, which occurred at depths ranging from 5 m through 44 m below the sea bed, Figure 2.

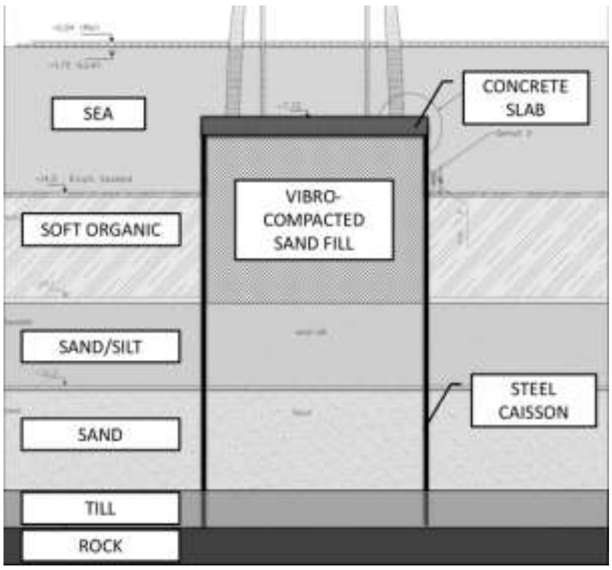

Figure 2. Foundation conditions of bridge pier with vibratory-compacted sand inside steel caisson.

An important design aspect was the selection of sand fill. The required geotechnical properties were: mean particle size

d_{50} = 0.45 mm and coefficient of uniformity, C_u = 3.8. The fines content (d < 0.063 mm) was 6% and the dry density of the placed but uncompacted material ρ = 1,560 kg/m^3 and a friction angle of the uncompacted material, as determined from direct shear tests, ϕ = 37°. The geotechnical parameters of the sand fill to be achieved after compaction are given in Table 1.

Table 1. Geotechnical design requirements for compacted sand fill.

Parameter	*Value*	*Units*
Density, ρ	1,800	kg/m^3
Friction angle, ϕ'	35	degrees
Oedometer modulus, E_{oed}	40	MPa
Elastic modulus, E_{50}	30	MPa
Poisson's number, ν	0.3	-

The bridge foundations were constructed in stages: first, coffer dams consisting of rectangular 13 m x 26 m, large, water-filled steel caissons were built up by interlocking steel sheet piles driven through the soft soil layers and into the till or down to firm rock, using a hydraulic vibrator unit operating with variable frequency. To ensure satisfactory bearing, each sheet pile was re-struck with a 120 kN hydraulic impact hammer. Thereafter, the soft soil with a thickness of approximately 8 m was removed from the inside and replaced by sand. The total volume of sand in each coffer dam was 2,400 m^3. Vibro-compaction of the on average 10 m thick sand layer was carried out at water depth of approximately 14 m until the required strength and stiffness had been achieved. Then, the caisson was emptied from water down to the upper surface of the sand layer and a concrete slab cast between the sand and the top of the steel caisson. Finally, the concrete bridge pier was cast, cf. Figure 2.

3. RESONANCE COMPACTION

Vibratory compaction has a long tradition in Sweden and different innovative methods have been developed. The most common compaction method is by vibrating surface rollers for the stabilization of embankments or earth fill dams. For treatment of deep soil layers, different compaction probes have been developed, such as the VibroWing (Massarsch and Broms, 1983) or the TriStar (Neely and Leroy, 1991). Compaction probes are inserted into the soil layer to be treated and then extracted in steps.

In both applications of vibratory treatment, an important—often neglected factor—is the effect of vibrator operating frequency (Massarsch 1991, Wersäll and Larsson 2013). When the vibrator operates at the resonance frequency of the vibrator-probe-soil system, maximum densification (compaction) is achieved, which is what the resonance compaction method takes advantage of. Details of the method have been described by Massarsch and Fellenius (2005). Its practical application for the compaction of a sand fill will be described below. The principal elements of resonance compaction are shown in Figure 3.

A hydraulic vibrator with variable frequency and amplitude control is connected to the top of the light-weight compaction probe, which is guided by a lead to assure vertical insertion. The probe has a double Y-shape, which achieves the optimal transfer of vibration energy from the vertically oscillating probe to the surrounding soil. The weight (and impedance) of the probe is reduced by circular openings in the compaction probe walls. In addition, wings can be attached to increase the influence radius. The performance of the vibrator, the probe and the response of the ground are measured by sensors, cf. Figure 3. All data are stored in the on-board computer and also displayed to the machine operator.

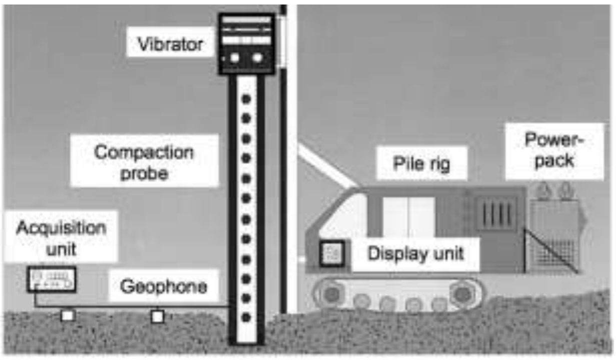

Figure 3. Electronic monitoring and control system for resonance compaction.

Figure 4 shows the resonance compaction system used to compact the sand fill inside the water-filled steel caisson. A hydraulic vibrator with a maximum centrifugal force of 1,100 kN and variable frequency (0–38 Hz) oscillated the 12 m long compaction probe. The maximum eccentric moment could be varied between 0 and 190 Nm.

a) Vibrator and compaction probe b) Electronic monitoring unit

Figure 4. Resonance compaction of 10 m sand fill inside water-filled steel caisson.

The vibrator was operated below water, thereby reducing the required length of the compaction probe. The verticality of the compaction probe was controlled by a hanging lead. Extensive field trials were carried out to establish the optimal compaction procedure. All phases of the compaction process were continuously monitored by a computer-supported process control system. Important compaction parameters, such as vibration frequency, depth of probe, penetration speed, and particle velocity of the ground/sheet pile were displayed in the cabin to the machine operator, assisting in the execution of the compaction process.

Compaction requirements were given in terms of cone stress. To resist horizontal stress due to ship impact, a minimum cone resistance (q_t < 10 MPa) was required throughout the sand fill. Figure 5 shows the under-water compaction process, where the vibrator is lowered below the water surface where compaction was carried out. Therefore, it was important for the machine operator to control compaction parameters electronically, such as the operating frequency of the vibrator, the probe depth and the probe penetration speed.

The compaction process is shown in Figure 6. The probe was inserted at a low frequency (20 Hz) to full depth at which the operating frequency was adjusted to the system resonance frequency. Thereafter, the probe was extracted in three surging-mode steps (2 m). During extraction, the vibrator frequency was increased to the maximum value (38 Hz) while during re-penetration, the frequency was lowered to resonance, which was typically about 20 Hz at first and increased due to densification.

a) Vibrator lower into water   b) Compaction monitoring panel

Figure 5. Under-water resonance compaction which required electronic monitoring of compaction process.

Soil compaction is most efficient during the resonance phase, see Figure 7, when the probe and the surrounding soil oscillate in phase. The total duration of compaction in each point was approximately 12 minutes.

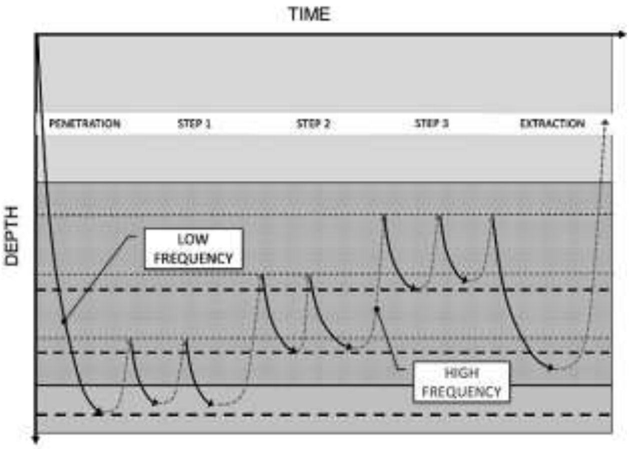

Figure 6. Resonance compaction process, showing probe penetration and extraction as function of time. Note the change in compaction frequency during penetration and extraction.

An important advantage of resonance compaction is that a direct relationship can be developed between cone stress and probe penetration speed. A typical record of measured compaction parameters during penetration (compaction) and extraction is shown in Figure 7. From the start at 7 m depth, the probe penetrated to 13 m at resonance frequency (20 Hz). The compaction duration was about 3 minutes. Thereafter, the probe was withdrawn to 8 m depth with the frequency raised to 38 Hz. Then followed the next surge when the probe was allowed to penetrate to 11.5 m at 20 Hz, terminating the compaction phase when the probe penetration speed became very slow (i.e. below 100 cm/min—the limiting value determined during the compaction trials). It is also interesting to note the increase in the probe movement amplitude at the resonance frequency. After moving the probe to the next compaction point (Figure 8), the procedure of extraction at high frequency and compaction at (lower) resonance frequency was repeated with until the entire soil layer has been compacted. Due to the stringent compaction requirements in the top layer of the steel caisson (ship collision), compaction effort was increased at shallow depth.

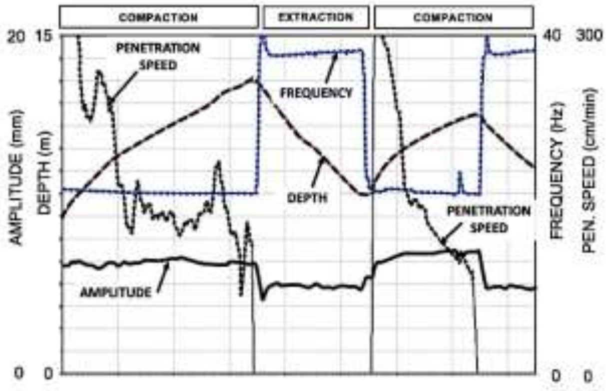

Figure 7. Compaction record showing the variation of different compaction parameters as a function of time. (Note, depth is shown in inverse scale).

Figure 8 shows the layout of compaction points inside the steel casing. Compaction was carried out from the perimeter of the caisson walls toward the center, thereby reducing the risk of local high lateral stresses acting against the sheet piles interlocks during the compaction work. The vertical and horizontal movements of the sheet piles were monitored at critical sections by inclinometers to verify that compaction did not negatively affect the interlocking of the steel caissons.

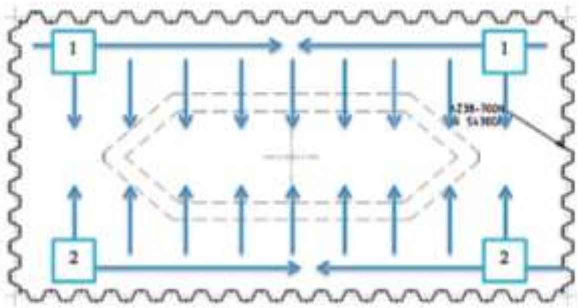

Figure 8. Compaction inside steel caisson (13 m x 26 m) from the perimeter towards the center.

Compaction was carried out in three phases. Phase 1: compaction was carried out at points placed in a 4.2 m x 4.0 m grid. Phase 2: compaction at points placed in the diagonal locations between Phase 1 compaction points. Phase 3: compaction at points placed in-between the Phase 2 compaction points. Figure 9 shows the vertical particle velocity measured at the top of the sand fill inside the caisson. During insertion and extraction of the compaction probe at high frequency (38 Hz), the vibration amplitude was generally smaller than 3 mm/s. At resonance, the vibration velocity became about five times larger.

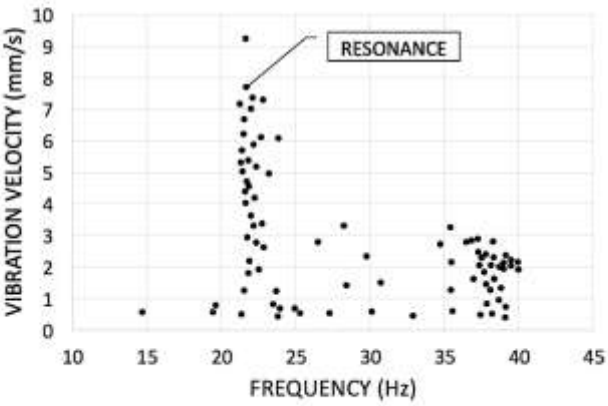

Figure 9. Variation of vertical particle velocity measured at the top of the sand fill during compaction.

4. CONE PENETRATION TESTS (CPT)

The required degree of compaction was specified in terms of cone stress, q_t. Figure 10 shows the cone stress and sleeve friction prior to and after three compaction passes. In the uncompacted fill, placed by dumping sand into the water-filled caisson, the cone stress was very low, typically 2 MPa at the surface increasing to 5 MPa at 7 m depth. Also the sleeve friction was low, generally lower than 5 kPa. As a result of the first and second compaction pass (cf. Figure 8), the cone stress increased to about 7 and 12 MPa, respectively. Also the sleeve friction increased following the first and second compaction pass, to about 10 and 20 kPa, respectively. After Phase 3, close to the wall, cone stress and sleeve friction increased significantly; the initial indication of loose state increased to dense after Phase 2 and became very dense after Phase 3 with values reaching 25 MPa. The sleeve friction values after Phase 3 exceeded 80 kPa. An often neglected effect of vibratory compaction is the increase in horizontal stress, which is reflected by the increase in sleeve friction. This fact is important for static, dynamic and cyclic analyses (liquefaction), as has been pointed out by Massarsch and Fellenius (2014).

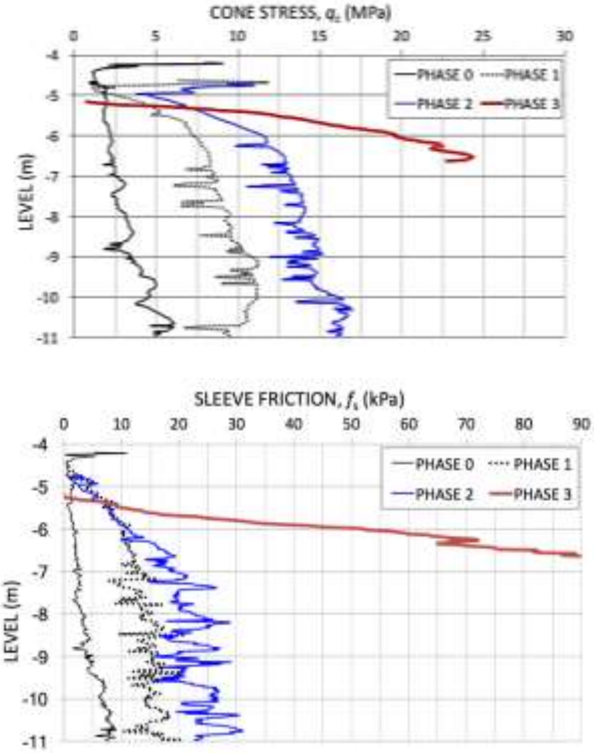

Figure 10. Variation of cone stress and sleeve friction prior to compaction, and after compaction phase 1, 2 and 3.

During the third compaction pass, the fill became so dense that the probe could penetrate only a few meters into the sand fill. As mentioned above, lateral displacements of the steel sheet piles were monitored using inclinometers. As a result of vibratory compaction, the sheet piles moved inward and toward the center of compaction, reflecting the volume decrease of the compacted sand fill. From Figure 10, it can be seen that the surface of the compacted fill settled by almost 1 m after compaction pass 3, cf. Figure 11. Settlements corresponded to about 8 % of the layer thickness, indicating a high degree of densification

5. CONCLUSIONS

A novel design concept was chosen for the foundation of the Sundsvall bridge. The bridge piers are supported by sand-filled steel caissons, which provide high lateral resistance and damping in the case of ship impact. Steel sheet piles were installed to great depth. Thereafter, loose soil was excavated inside the sheet piles and replaced by sand fill, which had to be compacted at 14 m water depth to a cone stress of 10 MPa.

The resonance compaction system uses a flexible compaction probe which is oscillated vertically by a hydraulic vibrator with variable frequency and eccentric moment. Compaction can be carried out with the vibrator submerged below the water surface. The operating frequency of the vibrator is varied to approach the resonance frequency of the vibrator-probe-soil system, which in the present case was about 20 Hz.

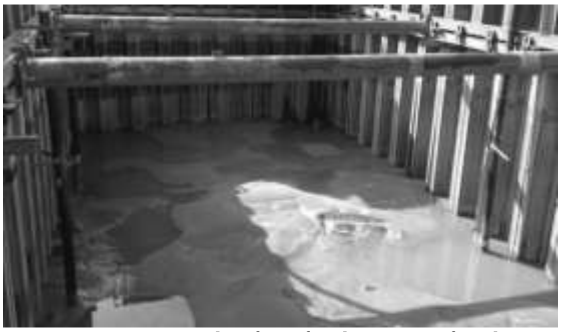

Figure 11. Compacted surface after dewatering of steel caisson. The probe insertion points can be detected.

An important compaction parameter is the probe penetration speed during compaction, which can be correlated to the cone stress from CPT results. Different compaction parameters, such as vibration frequency, vertical particle velocity, hydraulic pressure, depth of probe, and probe penetration speed, are displayed to the machine operator, who is instrumental in optimizing the compaction process. An excellent degree of compaction could be achieved, which is reflected by the high cone stress and sleeve friction values.

6. ACKNOWLEDGEMENTS

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