Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Correlation between shear wave velocity from borehole seismic and CPT data for the application of numerical analysis

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ABSTRACT

The Federal Waterways and Shipping Administration of Germany is currently planning the construction of a lock next to the existing Lueneburg twin ship lift on the Elbe Lateral Canal. The vertical lift of both the ship lift and the new lock is 38 m. The lock will be the biggest of its kind worldwide and will require an excavation pit of about 260 m length, 60 m width and 26 m depth. The adjacent ship lift is a major constraining factor for the project, as it must remain in operation throughout construction and thereafter. As part of an extensive site investigation, geophysical crosshole measurements were carried out up to a depth of 70 m to obtain dynamic soil properties necessary for the numerical analyses. This paper shows the results of the geophysical survey as well as a comparison of the in-situ measurements with well-established CPT correlations. The comparison shows a moderate to good match for the dynamic soil parameters such as the small-strain shear modulus G_{max} or the shear wave velocity V_s respectively, providing confidence in the derived soil parameters across the site.

Keywords: crosshole seismic; dynamic shear modulus; CPT correlations; soil-structure interaction.

1. Introduction

The Lueneburg twin ship lift was built between 1969 and 1975 and is situated on the Elbe Lateral Canal (Elbe-Seitenkanal) which connects the port of Hamburg to the entire waterway network of Germany and Europe. The ship lift provides a vertical lift of 38 m and the troughs are 100 x 12 x 3.4 metres. Due to these trough dimensions the ship lift nowadays represents a bottleneck on this major waterway. In order to improve the traffic situation, the construction of a new lock with a chamber size of 225 by 12.5 m next to the existing twin ship lift is currently being planned by the Federal Waterways and Shipping Administration of Germany (WSV) (Fig. 1).

The design of the scheduled lock is a reinforced concrete frame structure with water saving basins within the chamber walls. Throughout construction of the new lock and thereafter the adjacent ship lift is to remain in operation. Due to the small allowable deformations of the ship lift and its lift system, particular focus had to be put on both the exact location of the lock as well as the geotechnical design of the required excavation pit.

Preliminary numerical analyses have shown that strain levels of the soil in the vicinity of the ship lift caused by the construction of the lock are relatively small (Fig. 1). Thus, the small-strain shear modulus G_{max} of the subsoil is a key parameter. Small-strain stiffness is usually found to be a multiple of the stiffness obtained in classical laboratory testing. Therefore, considering the small-strain stiffness considerably increases the overall reliability of numerical displacement analysis (Benz 2007). Given the size and the importance of this project, G_{max} was to be determined from geophysical in-situ measurements using geophysical crosshole testing.

In this work the results of the in-situ geophysical and geotechnical site investigations are presented and the use of empirical relationships for deriving G_{max} based on CPT data are evaluated.

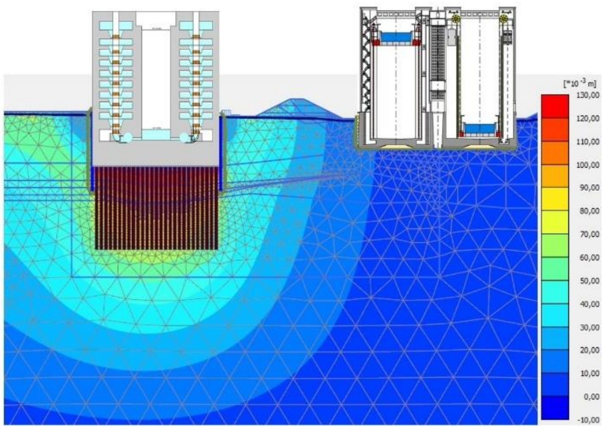

Figure 1. Preliminary 2D FEM analysis (max. deformation due to lock construction) showing a cross-section of the proposed new lock (left) and the existing twin ship lift (right)

2. Site investigation

An extensive ground investigation was carried out in two stages including cone penetration tests (CPT) and boreholes with continuous sampling of up to 80 m depth followed by extensive laboratory testing. Additionally, geophysical crosshole testing was carried out at three locations across the site to derive the dynamic soil properties required for the intended numerical analyses.

2.1. Geology and ground water conditions

The local geology is composed of highly over-consolidated quaternary soils consisting mostly of dense to very dense sands and an interbedded cohesive silt layer of varying thickness. The geo-hydraulic conditions show two aquifers separated by the above-mentioned cohesive layer. The layer sequence is as follows:

- Dense to very dense fine to medium glaciofluvial sand
- Dense to very dense glaciofluvial sand & gravel
- glaciolacustrine silt
- Very dense, fine glaciolacustrine sand

2.2. Geophysical crosshole measurements

2.2.1. Theory - deriving G_{max}

Prior to the seismic testing, a borehole log was documented for all nine boreholes using the continuous core samples. Additionally, the inclination (deviation from true vertical) and azimuth (deviation orientation) of the boreholes was measured in order to consider the length of the wave paths when analysing the crosshole tests. Furthermore, gamma-gamma-density (GGD) logging was used to obtain the bulk density of the subsoil.

The measurement method is aimed at determining the propagation velocities of compression (P) and shear (S) waves in the ground and to provide vertical profiles of these velocities. P- and S-waves are seismic waves with different propagation characteristics and velocities. The propagation speed of the wave of the respective type is determined from the transit times. The elastic parameters of the subsoil are then calculated as follows using the measured propagation velocities.

The Poisson's ratio ν can be calculated directly using the propagation velocities of the compression wave V_p and the shear wave V_s:

$$\nu = \frac{(V_p/V_s)^2 - 2}{2[(V_p/V_s)^2 - 1]} \quad (1)$$

If the bulk density of the soil ρ is known, the dynamic shear modulus can be derived from the shear wave velocity V_s:

$$G_{max} = \rho V_s^{\,2} \quad (2)$$

From G_{max} and ν in turn the dynamic modulus of elasticity E_{max} can be calculated:

$$E_{max} = 2(1+\nu)G_{max} \quad (3)$$

2.2.2. Measurement setup & procedure

Geophysical crosshole tests were carried out on three cross sections comprising of three boreholes. The boreholes in each cross section were spaced approximately 5 m apart (Fig. 2). The sections were named BKF 02-10, BKF 14-10 and BKF 14-19.

For the wave excitation, a seismic borehole source (type BIS-SH) was placed in one borehole of a cross-section while borehole geophones (type BGK5) were positioned in the other two. Starting from the bottom, measurements were carried out at vertical intervals of 2 m for the full length of the boreholes of approx. 65 m. To allow the measurement of the horizontal pulse, the source and receivers were positioned at equal depths.

Due to the different positioning of the source and the geophones a total of three possible arrangements per borehole group were realised, i.e. 6 different source-geophone positions. Half of these are redundant, as seismic travel times should be the same when the source and receiver are swapped. However, this procedure was carried out for a consideration of the repeatability and accuracy of the measurements (Fig. 2).

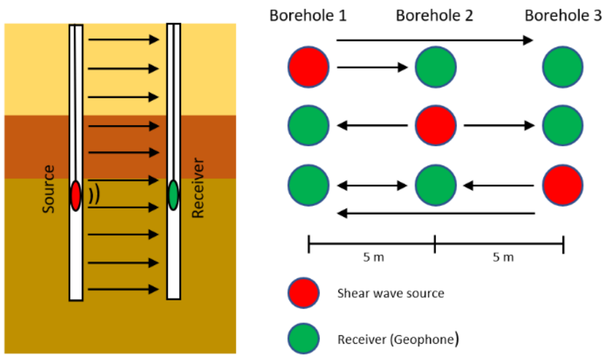

Figure 2. Principle of the crosshole test (left) and testing variants in a borehole group (right)

To determine the P-wave and S-wave velocities for each interval, the measured travel times must be correlated to the linear distance between the source and receiver, which was done using the aforementioned borehole logging data.

3. Measurement results

Fig. 3 shows the dynamic shear modulus G_{max} determined by the in-situ crosshole testing over the borehole depth for the aforementioned locations. For visualisation purposes, the respective strata derived by the borehole logging as well as the groundwater levels are shown in the figures.

The lowest values of G_{max} are found above the groundwater table at all three locations. Below the groundwater table, the dynamic shear modulus within the glaciofluvial sand tends to increase with depth at all three locations. The shear moduli G_{max} at locations BKF 02-10 (70-126 MPa, av. 92 MPa) and BKF 14-10 (87-114 MPa, av. 101 MPa) are of comparable magnitude. At location BKF 14-19 lower values of G_{max} are measured with values ranging from 39 MPa to 87 MPa (av. 55 MPa).

The underlying layer of coarse grained glaciofluvial sand & gravel shows higher G_{max} values for all three locations, ranging from 99 MPa to 167 MPa (av. 124 MPa) at location BKF 02-10, 81 MPa to 173 MPa (av. 136 MPa) at location BKF 14-10 and 75 MPa to 125 MPa (av. 101 MPa) at location BKF 14-19.

In the glaciolacustrine silt the dynamic shear modulus continues to increase, ranging between 193 MPa and 219 MPa (av. 206 MPa) at location BKF 02-10, between 142

MPa and 208 MPa (av. 175 MPa) at location BKF 14-10 and 98 MPa and 149 MPa (av. 123 MPa) at location BKF 14-19.

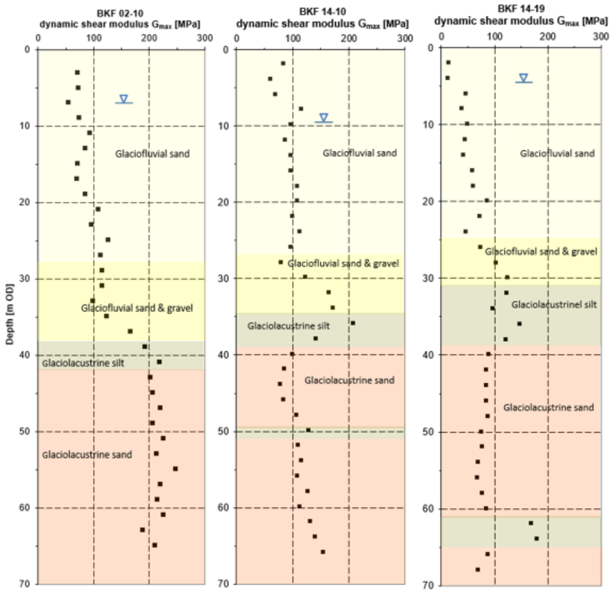

Figure 3. In-situ measurements of G_{max} using crosshole seismic testing at the three locations

In the bottom soil layer, the glaciolacustrine sand, the dynamic shear modulus differs the most between the three locations. At location BKF 02-10, G_{max} shows the highest values in this soil layer with an average of 215 MPa. At locations BKF 14-10 and BKF 14-19, the average values of G_{max} range between 113 MPa and 80 MPa respectively, showing less than half the soil stiffness compared to the first location.

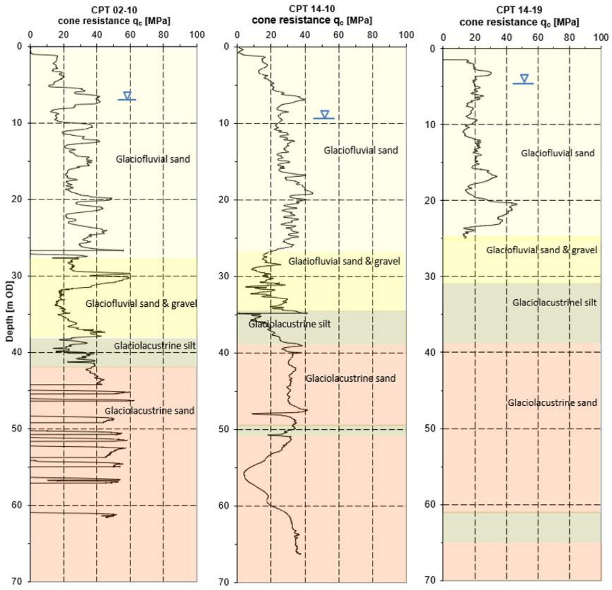

Figure 4. CPT cone resistance qc at the three locations

Fig. 4 shows the cone resistance q_c of the CPT tests adjacent to the above discussed borehole locations. The plots show the homogenous ground conditions and soil strengths, which have been confirmed across the investigated area as well as an increase in soil strength with depth. At location CPT 14-10 a section within the glaciolacustrine sand shows a decrease in q_c at 55 m depth, which represents an exception across the investigated area. It is assumed that this anomaly is due to a disturbance of the soil from the drilling of the adjacent boreholes.

4. Comparison to CPT correlations

Only the non-cohesive layers were considered for this evaluation as these are the dominant soil types. For cohesive layers different correlations would apply.

The above shown in-situ measurements of G_{max} using crosshole seismic data were compared with well-established CPT correlations for deriving either the dynamic shear modulus G_{max} or the shear wave velocity V_s using the adjacent CPT results at each of the three borehole locations. The CPT-V_s or CPT-G_{max} relationships used here are by Hegazy and Mayne (1995) (4), Baldi et al. (1989) (5) as well as Rix and Stokoe (1991) (6) proposed for sands.

$$V_s = 13.18 q_c^{0.192} {\sigma'_v}^{0.179} \tag{4}$$

where q_c and σ'_v are in kPa.

$$V_s = 277 q_c^{0.13} {\sigma'_v}^{0.27} \tag{5}$$

where q_c and σ'_v are in MPa.

$$G_{max} = q_c 1634[q_c/(\sigma'_v)^{0.5}]^{-0.75} \tag{6}$$

where G_{max}, q_c and σ'_v are in kPa.

The corresponding overburden stress σ'_v was calculated using the unit weight derived from the continuous soil samples. For the correlations of Hegazy and Mayne (1995) (4) and Baldi et al. (1989) (5) the derived shear wave velocity V_s was converted to G_{max} using the bulk densities derived from the borehole GGD-logging using Eq. (2).

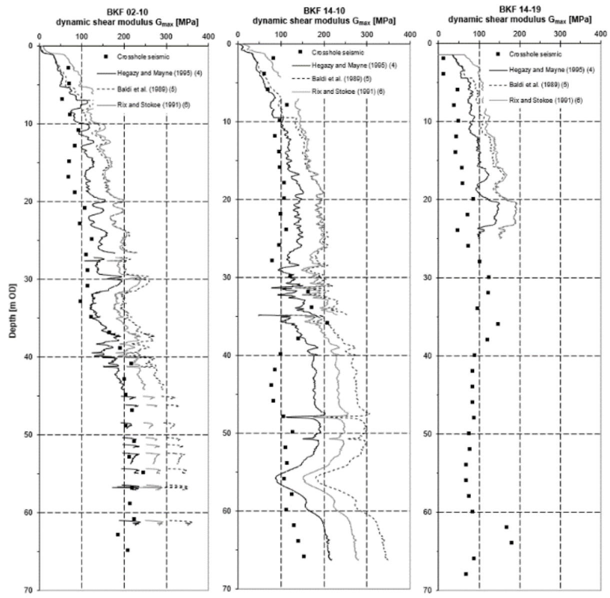

Figure 5. Comparison between measured (crosshole seismic) and correlated G_{max} using CPT results at locations BKF 02-10, BKF 14-10 and BKF 14-19

Fig. 5 shows the comparison between measured (crosshole seismic) and correlated values for the dynamic shear modulus G_{max} using the CPT. Unfortunately, the CPT at location BKF 14-19 wasn't carried out to full depth, therefore the correlations end at a depth of 25 m.

The profile at location BKF 02-10 (Fig. 5 left) shows a similar progression with depth of the dynamic shear modulus G_{max} between the measured and the estimated values using CPT correlations. All three CPT correlations, however, tend to overestimate the dynamic shear modulus. The relationship by Hegazy and Mayne (1995) (4) shows the lowest estimated values and therefore a moderate to good match with the in-situ measurements, especially in the bottom soil layer, the glaciolacustrine sand.

The second profile BKF 14-10 (Fig. 5 middle) initially shows a similar matching of the results between measured and estimated dynamic shear modulus in the upper soil layers. However, towards the bottom of the profile, in the glaciolacustrine sand, the crosshole measurements decrease significantly, as discussed before, while G_{max} values correlated from the CPT data tend to increase, resulting in a bigger discrepancy between correlated and measured values for G_{max}.

At the third location BKF 14-19 (Fig. 5 right) the CPT correlations could only be plotted to a depth of 25 m. The correlations significantly overestimate the dynamic shear modulus compared to the in-situ measurements. As discussed before, the in-situ measurements at this location showed the lowest results for the dynamic shear modulus for all soil layers.

4.1. Discussion

It can be seen that the CPT correlations at the three locations under consideration show fairly similar results across the site. This is due to the uniform CPT results and homogenous ground conditions across the investigated area. However, the seismic crosshole data obtained at the same locations shows significant differences in the measured small-strain shear modulus G_{max} across the three locations. While the measurement data on the small-strain modulus corresponds well with the identified increasing soil strength with depth for location BKF 02-10, G_{max} values decrease for the deeper sands at locations BKF 14-10 and BKF14-19. The reason for the decreasing G_{max} values obtained by the crosshole seismic at those locations, especially with regard to the glaciolacustrine sand, cannot be readily explained.

Given that the CPT data reflects the increasing soil strength with depth, the tested CPT-correlations show a good estimation of G_{max} values for location BKF 02-10. Applying the same correlations to the CPT data of locations BKF 14-10 and BKF 14-19 provided no good fit to the G_{max} data measured by the seismic crosshole setup at these locations.

Based on the data obtained for location BKF 02-10, the correlation derived by Hegazy and Mayne (1995) (4) results in the lowest values of G_{max} and best approximation of the measured in-situ G_{max} values, while correlations (5) and (6) significantly overestimate the soil stiffness. Hegazy and Mayne (1995) developed their relationship using data from 24 sand sites. The V_S measurements were determined by different in-situ measurement techniques, such as seismic cone-, crosshole-, downhole-measurements as well as spectral analysis of surface waves. Baldi et al. (1989) as well as Rix and Stokoe (1991) on the other hand used CPT calibration chamber and V_S resonant column measurements on silica sand and washed mortar sand respectively to develop their relationship. This suggests that - in this case - correlations derived from laboratory testing conditions do not account for all the variability associated with natural soil deposits.

5. Conclusions

The small-strain shear modulus G_{max} was obtained from in-situ measurements using geophysical crosshole seismic at three different locations across the proposed site of a new lock on the Elbe Lateral Canal. Despite homogenous soil conditions established by an extensive ground investigation, the results from the geophysical testing differed amongst the testing locations. At the same locations, CPT data shows – in general – homogenous and uniform conditions. This mismatch cannot be readily explained. Given the different measurement techniques, i.e. point data (CPT) vs. volume integrated data (crosshole seismic), effects of spatially small-scale heterogeneities in the soil properties cannot be ruled out and should be considered.

Using the CPT data to correlate small-strain moduli G_{max} seems to provide reasonable estimates if the correlation by Hegazy and Mayne (1995) (4) is used for the given site. However, it must be stressed that additional seismic campaigns would be required to confirm this.

An average lower bound G_{max} was selected for each soil layer for the numerical analyses, the results of which have been published in Matthiesen et al. (2017). Not accounting for the small-strain stiffness in the numerical analyses would have resulted in an increased spacing between the existing ship lift and the proposed lock, which may have rendered the project uneconomical.

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