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On the prediction of settlement from high-resolution shear-wave reflection seismic data: The Trondheim harbour case study, mid Norway

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ABSTRACT

This paper presents a novel approach to predict long-term settlement in the Trondheim harbour, mid Norway, from high-resolution shear-wave seismic reflection data, complemented with cone penetration test results (CPTU) and index soil properties from nearby boreholes in this reclaimed coastal area. The data enables sub-surface geo-characterisation in high-resolution, down to the basement at a depth of about 175 m. Correlations between shear-wave velocity and Janbu's classical 1D consolidation parameters (m, M_0, M_1, σ'_c and OCR) are used for settlement analysis. Both the magnitude and rate of time-settlement predictions compare well with the measured settlements from GPS levelling and PSInSAR data acquired since the late 1980s and the early 1990s in the area, respectively. The shear-wave reflection data further provide important input to understand the spatial patterns of land-subsidence in the Trondheim harbour. The highest settlement rates occur in areas where depth to bedrock is greatest and where thicker deposits with low stiffness are found. In summary, the data and workflow presented here are useful tools for predicting settlements based on correlations with shear-wave velocity measurements.

1. Introduction

The construction of large embankments on thick deposits of soft and sensitive soils is a major challenge in geotechnical engineering. Conventional methods for estimating total settlements and settlement rates rely on a combination of ground investigations with drilling, sampling, in-situ tests as well as advanced laboratory testing. The results from these tests are often compromised due to sample disturbance and the presence of soil heterogeneities. These methods are also time-consuming and costly, as a large number of tests are needed to characterise the sub-surface conditions at a given site in sufficient detail.

Over the years, researchers are gradually moving towards a better integration of geophysical and geotechnical methods. Particularly, the potential of shear wave seismic data for predicting soil stiffness, static deformation analyses and long-term settlement predictions is recognised (e.g. Abbiss, 1983; Campenalla and Robertson, 1984; Tezcan et al., 2006; Omar et al., 2011). Proper multi-channel shear wave reflection profiling in the field can be used to map shear wave velocities and their lateral and spatial variations in the sub-surface. As a consequence, the small strain or dynamic shear stiffness (i.e. G_{max}) of the geo-material can be assessed over larger areas. Presently, the established techniques for shear wave velocity with depth analyses are based on the geometrical dispersion of surface waves [e.g., spectral analysis of surface waves (SASW), continuous surface wave (CSW), multichannel analysis of surface waves (MASW)] mainly applied onshore (e.g. Xia et al., 1999; Stokoe and Santamarina, 2000; Socco and Strobbia, 2004; Long and Donohue, 2007; Omar et al., 2011) but also offshore (Socco et al., 2011; Vanneste et al., 2011). Whereas surface waves provide high-resolution S-wave velocity information, the depth range is typically limited. More recently, specially-designed land-streamers as well as shear wave vibrators are designed for near-surface seismic reflection acquisition, making them a great asset for regional, multi-channel seismic profiling, particularly in urban areas (e.g. Pugin et al., 2004; Polom et al., 2010).

This paper explores the use of the shear-wave seismic reflection method using a land-streamer and shear wave vibrator source to predict long-term settlement in the Trondheim harbour, mid Norway (Figure 1). During the last century, most of the urban development took place along the coast where large near-shore areas have been reclaimed from the

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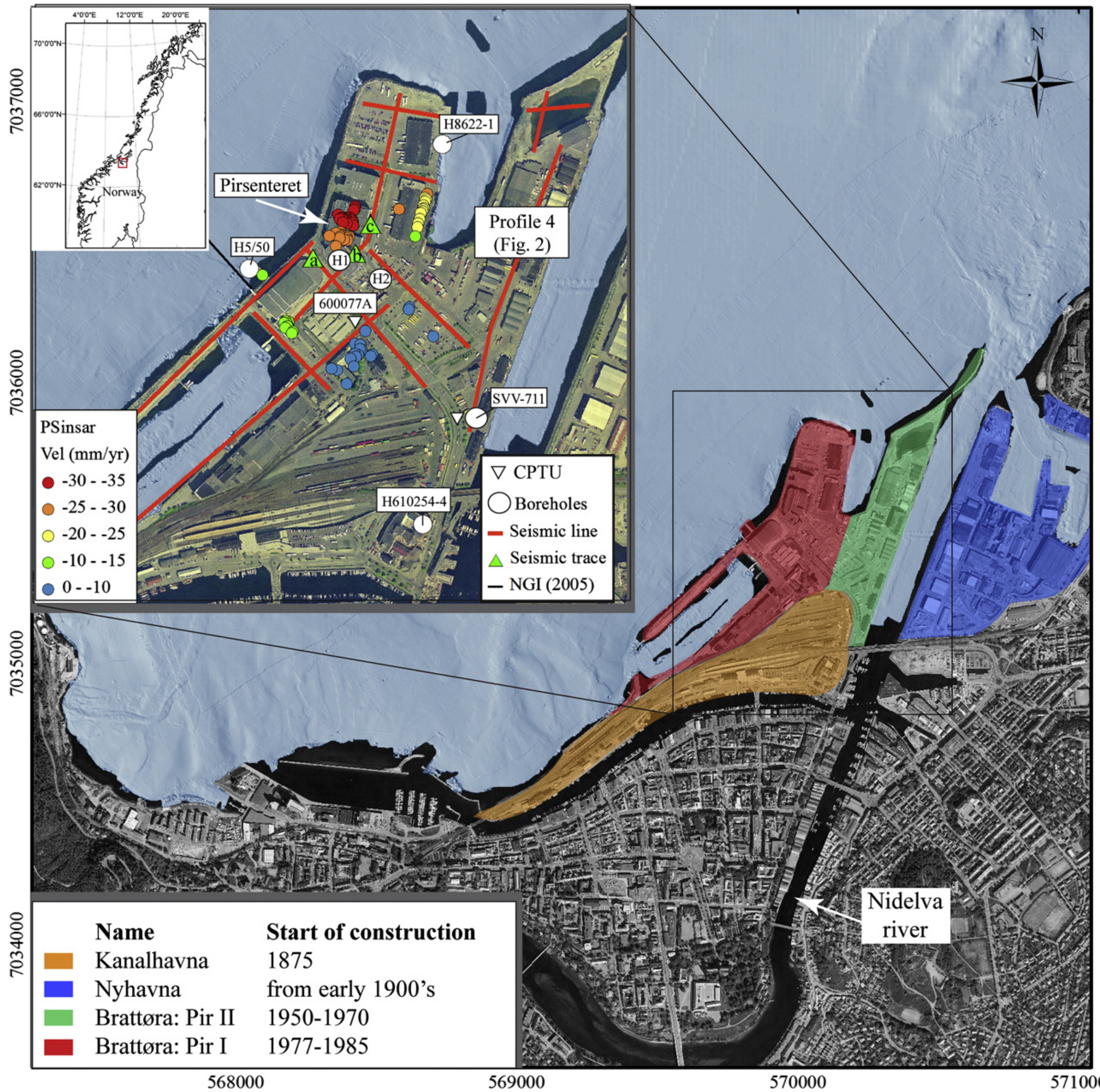

Fig. 1. Overview of the study area with land reclamation work in front of the city of Trondheim. The high resolution shear-wave reflection profiles are shown in the top-left panel together with geotechnical soundings and settlement velocities (average 1992–2003 from PSInSAR).

fjord. Interestingly, Synthetic Aperture Radar (SAR) interferometry data with GPS monitoring reveals significant land subsidence up to 35 mm/year (Dehls, 2005), implying that specific attention must be paid to the further development of the area. Prior to the acquisition of the high-resolution shear-wave data, sub-surface information onshore in the Trondheim harbour was limited to sparse boreholes and a few piezocone tests. Previous settlement predictions relied therefore mostly on settlement observations which started in 1988 (Janbu, 1997).

Following a brief historical and geological description of the site, the subsurface below the Trondheim harbour is described using a combination of geotechnical data and shear-wave seismic profiles. Based on data available in the literature, correlations between shear-wave velocity and 1D settlement parameters are used in combination with the sub-surface geo-model to predict future settlements in the Trondheim harbour. The results are finally compared with recorded settlements rates since 1988.

2. Site description

2.1. Geology

The city of Trondheim lies at the mouth of the Nidelva river at the border of Trondheimsfjorden, mid Norway. The soil below the Trondheim harbour consists of deltaic deposits of silt and sand overlying thick sequences of soft and compressible marine and glacio-marine clays (L'Heureux et al., 2009, 2010). The stratigraphic model consists of five main sedimentary units with total thickness between 100 and 185 m deposited on top of the bedrock (Polom et al., 2010; Hansen et al., 2013) (Figure 2). At the top, the embankment fills are up to 15 m thick. Below the embankment, a delta unit consisting of stratified silty and sandy deltaic deposits with thin clay layers is present. This unit is underlain by predominantly clays of prodeltaic and marine origin (herein called