Refraction seismic for mapping of limestone surface in a tunnel project in Copenhagen

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ABSTRACT
The Damhusledningen (Damhus pipeline) project in Copenhagen will improve water quality in and around the Damhus river and secure the area from flooding at downpour. The tunnel is constructed with "Pipe Jacking" in the top of the limestone. In the summer of 2014 the tunnel front reached an area where it unexpectedly broke through the top of the limestone into a permeable gravel layer. This led to loss of air pressure and inability to keep stability in the tunnel front. Drillings in the area indicated the possibility of a dramatic topography of the limestone surface, but none had indicated depressions into the tunnel alignment. To map the extent of the depression with sufficient lateral resolution it was decided to use refraction seismic tomography in combination with drillings. The seismic results showed very good correlation with available drillings and with the level of the limestone surface as found in the tunnel front. After grouting of the permeable layer the construction could continue successfully. Based on these encouraging results it was decided to use refraction seismic also at a crossing of a large railway embankment where it had been difficult to place enough drillings. The Danish Railway Administration's strict requirements on vertical displacement of the tracks required further knowledge on whether there exist any depressions in the limestone surface under the embankment. The embankment and the railway constituted a serious challenge to the refraction seismic method and great care was taken to ensure good results. It was finally concluded that the limestone surface under the embankment did not show any dramatic drops. With this information the project could go on with acquiring permission for the construction from the Danish Railway Administration.

Keywords: Site investigation; Refraction seismic; Pipe jacking; Limestone; Risk management

1 INTRODUCTION

HOFOR is establishing a new sewer pipe in Copenhagen (Damhusledningen København) with Niras as consulting engineers. The pipe has a diameter of three meters and was to begin with installed using pipe jacking, but is now driven with an EPB micro-tunnelling machine. In the Copenhagen area tunnelling has historically been preferred at some depth into the limestone. This is due to the characteristics of the limestone, which normally gives a safe and stable tunnelling process with little risk for settlements. The Damhusledningen has been placed in the very top of the limestone to minimize the depth of the shafts and pipe connections. However, in the top of the limestone there is a risk that the tunnel at some point come out of the limestone, due to the considerable variations in the limestone topography that can occur. When the tunnel comes out of the limestone and enters soil materials the risk for settlements becomes much higher. In an urban environment this can be a problem in many places, even if the tunnel, as in this case, is placed mainly along a recreational area as the Vigerslev Park that run along the Damhus River. This paper will demonstrate the use of the refraction seismic method as a tool, together with drilling, in mapping the top of the Copenhagen limestone. Two cases are presented, one where a breakout of the tunnel into the soil caused washout of sediments and settlements, and one where the tunnel is to cross a railway embankment and where settlements cannot be allowed.

1.1 Geology

The geological sequence in the study area comprises the following main layers, from the surface and downwards:

1. Fill layers mainly composed of sand, peat, mull, clay and gravel with various artefacts;
2. Postglacial freshwater deposits, mainly peat, sand and gravel;
3. Late glacial and glacial deposits, generally composed of meltwater deposits (mainly sand and gravel, occasionally with large boulders), but occasionally with sections of glacial till;
4. Glacially disturbed limestone, soft, with clayey zones. This zone may be up to around 2 m thick; and
5. Undisturbed and generally hardened limestone of Danien age.

Depth to the top of the undisturbed limestone is 4 – 14.5 m in the study area, and it varies considerably, sometimes within short distances.

In the Copenhagen area, the morphology of the limestone surface is to a large extent controlled by structures in the limestone, i.e. faults, fractures and folds. The two main orientations of these structures are NW/SE and NNW/SSE (Jakobsen et al., 2002). The orientation of the valley with the Damhus River more or less follows these orientations, a fact which may indicate that the valley is structurally controlled. This would be a plausible explanation of the observed strong gradients of the limestone surface.

1.2 Case One

In the summer 2014, the tunnel front unexpectedly broke through the top of the limestone into a permeable gravel layer. This led to loss of air pressure and inability to keep stability in the tunnel front. A refraction seismic survey was done by Rambøll in order to get a better understanding of the local geology through mapping of the limestone surface. This helped delineate the volume of gravel that the tunnelling machine needed to pass before entering into limestone again. It was decided to use grouting to increase stability and decrease permeability. After grouting, the drilling could continue without further stability problems. The survey is described as Case One below.

1.3 Case Two

At a later stage of the works, the sewer pipe is planned to cross under a large and old railway embankment, which holds six tracks. If a similar depression in the limestone surface is encountered here unexpectedly, it can have a large negative effect on both the project economy and time schedule. Furthermore, the Danish Railway Administration allows only very small displacements of the railway tracks during the tunnel construction. The embankment holds the main tracks into Copenhagen and a settlement of the tracks would have large consequences, not only for the local, but also for the national traffic.

Drilling a set of boreholes across the embankment to get the geological profile is very costly due to the need for rail safety measures and short time windows at night, in which the work must be done. An alternative could be a horizontal drilling under the embankment, but also this is very costly. Refraction seismic is a comparably cheaper solution and with the good results from Case One in mind, it was decided to use refraction seismic to map the top of the limestone. This is described as Case Two in this paper.

2 SEISMIC REFRACTION METHOD

Sound travels at different speeds depending on the stiffness of the material it travels through. Following Snell's law on reflection, there will be a refracted wave travelling along the interface between a low-velocity and high-velocity layer (Figure 1).

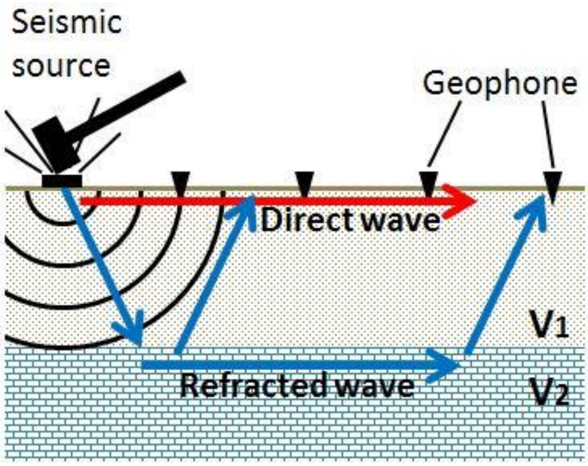

Figure 1 Physical principle in seismic refraction surveys. The top layer has a lower velocity than the bottom layer ($V_1<V_2$).

In simple terms, measuring the travel times of the direct and the refracted wave along a line, where the sensors (called geophones) are kept at constant locations and the seismic source (e.g. a sledgehammer) is moved along the line, you can calculate the sound velocity in the two layers and the depth to the layer interface (see e.g. Keary et al., 2002). The result is a velocity model for the subsurface. There are various methods for this calculation. Traditional methods like the plus-minus method (Hagedoorn, 1959) or the generalized reciprocal method (Palmer, 1981) are computationally simple, but do not handle topography well and only provide a crude one-dimensional model of the subsurface. Here we have used tomographic inversion, which handles topography variations better and provide a two-dimensional model of the subsurface. The processing was done in the software Rayfract, from Intelligent Resources Inc., that utilizes a wavepath eikonal traveltime tomography (Schuster and Quintus-Bosz, 1993).

3 CASE ONE – ENCOUNTERED LIMESTONE DEPRESSION

As described earlier the seismic data for Case One was collected after the tunnelling had to be temporarily stopped when a gravel layer in an unexpected limestone depression had been encountered.

3.1 Survey setup

The survey area was in the Vigerslev Park in the southeast part of Copenhagen. To map the top of the limestone, seven seismic profiles where recorded (see **Error! Reference source not found.**). The geophone distance was 2-2.5 meters. Often refraction seismic surveys use a geophone distance of five meters, but here a higher resolution was desired. The source was a 40 kg accelerated weight drop. A test was made with a seven kg sledgehammer that showed data that was possible to interpret, however the signal to noise ratio was on the border to what can be allowed and so it was decided to use a slightly more powerful source. The data was collected in day-time and in a city like Copenhagen there will always be a significant amount of seismic background noise during the day.

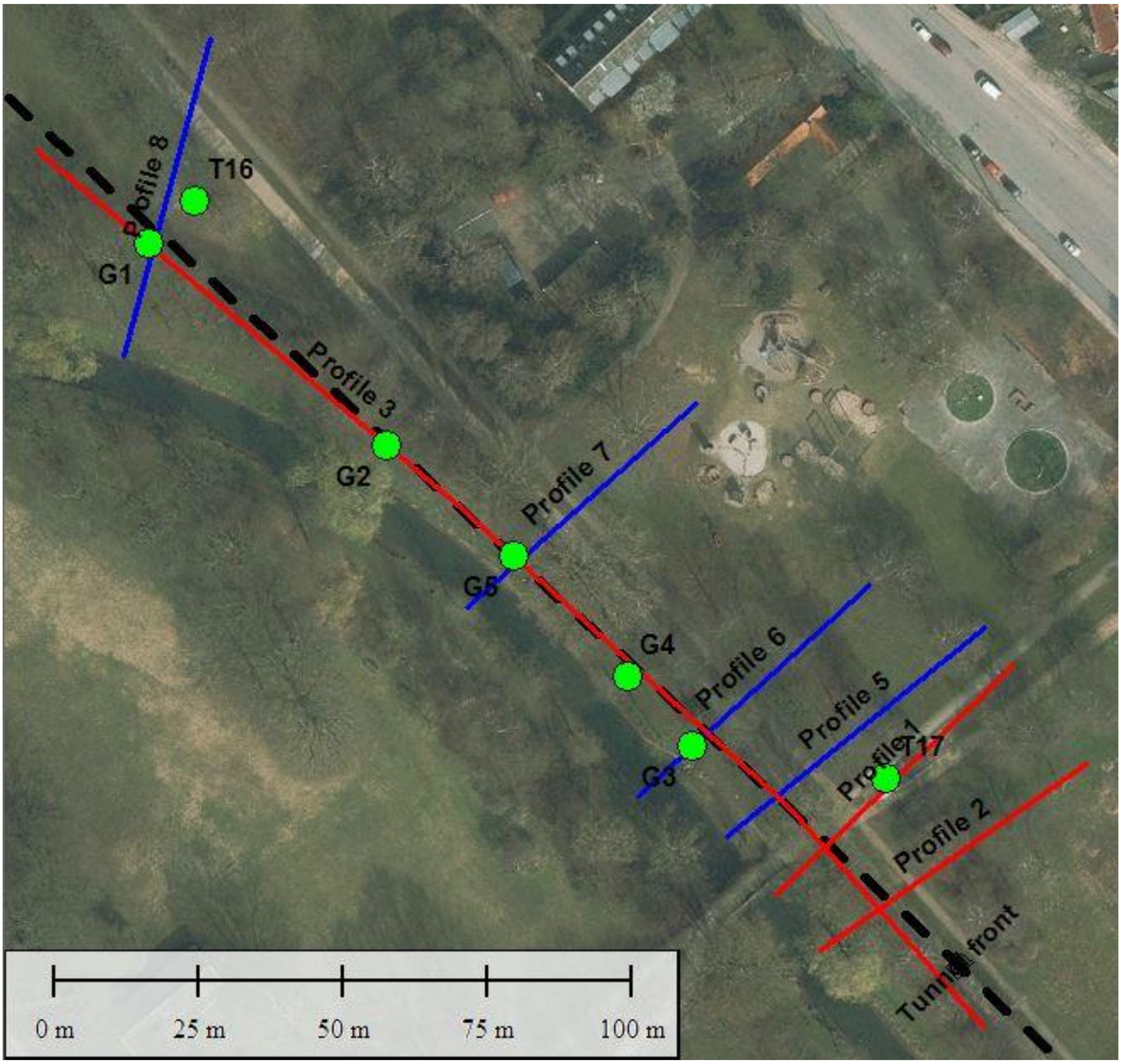

Figure 2 Line placements. Dashed black line is the projected tunnel path. Red lines show profiles part of this paper, blue lines profiles not treated here. Green dots are drillings.

3.2 Results for Case One

The first two profiles that were collected, Profile 1 (Figure 4) and Profile 2 (Figure 5), showed good correlation with the available reference data from boreholes. The level of the limestone surface in drilling T17 was used to verify and calibrate the interpretation of the limestone surface, and the level of the limestone surface as seen in the tunnel front fit very well with what was seen in the refraction seismic in Profile 2. Even though it was known that the level of the limestone surface could vary considerably, it was surprising that it was encountered at tunnel level so close to a geotechnical boring that had indicated that it should be placed several meters higher. The seismic results showed that there clearly is a local depression of the limestone here, and it is the eastern flank of this that can be seen in Profile 1 and 2.

The available drilling information, some of it available from the original site investigation and some acquired as new drillings in the same time as the seismic survey, showed very good correlation with the seismic results. The top of the limestone as interpreted in the drillings correlates with a velocity of 1500 m/s in the refraction seismic. This velocity is slightly lower than you would expect from a hard limestone and this indicates that the top of the limestone is fissured and fractured. As described in the geology section it is expected to find up to two meters of disturbed limestone. A few drillings, such as G4 on Profile 3 (Figure 3), which does not correlate, is explained by the fact that they are placed at some distance from the line. Another reason for not having perfect correlation is that the interpretation of top of limestone in drillings is made by a geologist based on the materials present in the drilling, while the seismic method do not see different geological materials but rather the stiffness of the ground. Due to this it is often necessary to take the condition of the top of the limestone into account when comparing it to the seismic result. However, this was not a big problem for Case One.

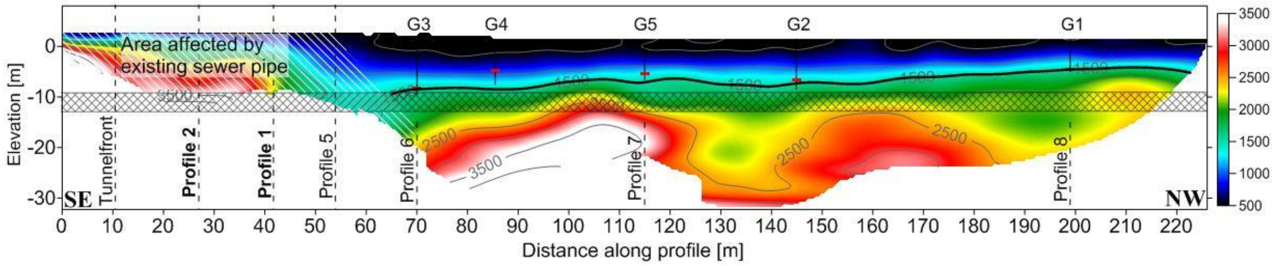

Figure 3 Profile 3. Cross-lines are shown as dashed lines. Bold names indicate the two other profiles shown in this paper, Profile 1 and 2. The tunnel is drilled from SE to NW with the projected position shown as a crosshatched area. Letter G indicates position of borehole and red marking the top of the limestone from the borehole log. Black line along the 1500 m/s isoline shows the top of limestone as interpreted from the seismic profile.

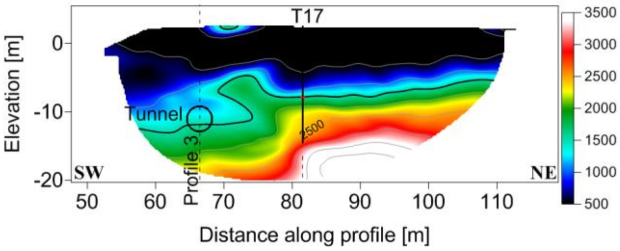

Figure 4 Profile 1. Cross-line is shown as a dashed line. Projected tunnel is shown as a circle. The strange extreme shape of the limestone, as interpreted along the 1500 m/s isoline, is probably an artefact of the inverse modelling. However, it can be expected that there is a very sudden drop in the limestone level towards SW.

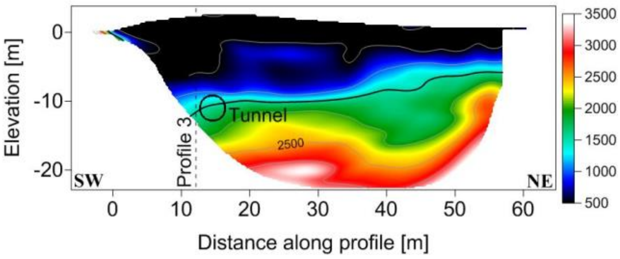

Figure 5 Profile 2. Cross-line is shown as a dashed line. Projected tunnel is shown as a circle. Black line along the 1500 m/s isoline shows the top of limestone as interpreted from the seismic profile.

4 CASE TWO – RAILWAY EMBANKMENT

At one location it is planned that the tunnel cross under a 6 track wide and 10 meter high railway embankment that was constructed over several stages during the past more than 100 years. Due to the age of the embankment there is not sufficient documentation on how it is constructed and therefore it must be treated with care. As described before the allowed settlements for the railway tracks are very small and therefore it becomes important to map the limestone under the embankment to reduce the risk of unexpected geological conditions. Two drillings where made as close to the embankment as possible on each side, still leaving an un-investigated stretch of 95 m under the embankment. After the successful survey described in Case One it was decided to perform a refraction seismic survey over the embankment. Even if a seismic survey in a place like this is complicated and costly compared to the survey in Case One, the alternatives would be to perform complicated and very expensive drilling on the embankment or horizontally under the embankment with budgets far exceeding the one for seismic.

4.1 Survey setup

To map the top of the limestone, three seismic profiles where recorded (see Figure 6). The geophone distance was 2.5 meters. The measurements where conducted at night to avoid train traffic. As a consequence the seismic background noise was very low. The source was a seven kg sledgehammer since this was the only source that was possible to bring on to the embankment without special arrangements.

For practical reasons the measurements where divided into stages. The first stage was to instrument the area outside of the tracks with geophones. A full dataset was collected along the instrumented line, and in addition a few source points where placed on the tracks. These points made it possible to test the signal to noise ratio of the source without time consuming instrumentation on the tracks. For this first stage all measurements on the Profile 10 (purple line in Figure 6), except the part over the tracks, where performed. A preliminary processing of stage one was made that showed encouraging results and so the second stage with geophones on the tracks was performed. This required three nights of work where the first night was used to get the cables in place under the rails and to mount geophones. The second night was used to shoot the line, and the last night used to remove the instrumentation on the tracks. In a third stage a Profile 10 parallel to the tracks was performed (yellow line in Figure 6). Furthermore, a profile was made north of the embankment (blue line in Figure 6) to get results closer to the planned tunnel alinement. Results from that profile were poor due to effects two from major sewer pipes crossing the line at an acute angle and are not treated here.

For this survey there were several things to take into account when planning, performing and interpreting the survey. The most obvious problem was the logistical needs to perform a survey over a busy six-track railway in a large city as Copenhagen. In addition it was essential to control the data quality and to make sure that the strong surface topography did not cause negative effects during modelling. As a further complication there are concrete structures in the embankment close to the planned tunnel. The positions of these are presented in Figure 8. The seismic lines had to be placed at sufficient distance away from these to make sure that these structures did not prevent mapping of the limestone. This is why the profiles where placed at a little distance from the planned tunnel, as can be seen in Figure 7. The structures where a combined bicycle/sewage water tunnel running parallel to the planned tunnel about 12 m to the side, and another sewage tunnel only 2 m to the side of the planned tunnel. From this there is also a shaft going to the surface of the embankment to a railway platform.

There were also technical matters with the instrumentation to consider, like how data is affected when railway sleepers have to be used as source points, when geophones are placed in materials that are far from natural, like macadam, or how other types of fill that creates a very heterogeneous structure effect the modelling of the data. In addition the railway use high power electricity to drive the majority of their trains and high enough currents will be picked up by the analog seismic cables through induction.

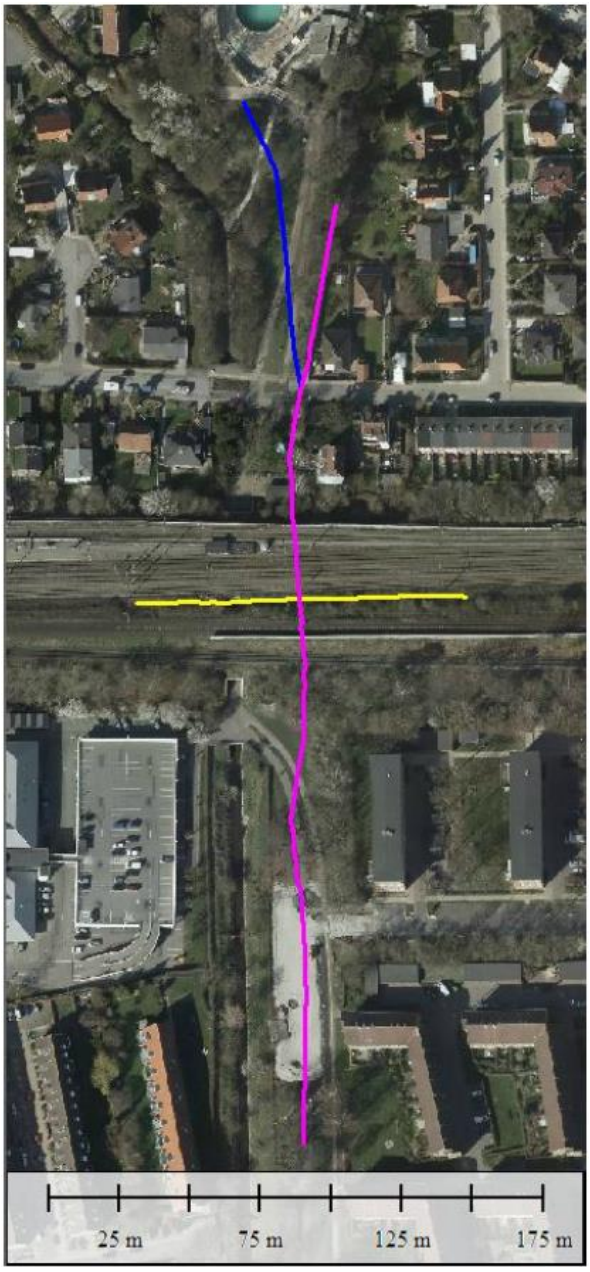

Figure 6 Profile 9 (Pink) and profile 10 (yellow). Profile 11 (blue) is not treated in this paper.

4.2 Results for Case Two

When all of these matters had been dealt with we could conclude that we had collected a high quality dataset on which it was possible to do a qualified interpretation of the limestone surface (Figure 7 and Figure 8). In the raw data there was clear evidence of the existing concrete structures, especially when crossing water culverts north of the embankment, but with good control of where the existing structures are placed the effect from this could be almost completely removed in processing. In the velocity profiles there is almost no evidence of these structures, as can be seen for example between 30-50 m in Figure 8.

The correlation with drillings on the north side of the embankment is very good (T57 and T02 in Figure 7), while on the south side it seems that the seismic find the limestone slightly lower than the drillings (S1 and T03 in Figure 7). To some extent this might be due to the distance between drillings and the seismic line but another reason might be that the limestone surface in the drillings are interpreted based on the geological material while the seismic method measures the stiffness of the ground. Drillings to the north show a sharp transition from the softer top-soil to a stiff limestone. To the south the drilling records show a gradual transition from top-soil over a very soft limestone to a stiff limestone.

After verification and calibration with drilling data it can be concluded that the interpretation of the limestone surface lies at safe distance above the planned tunnel, and does not show any irregular behaviour under the railway embankment. This can be clearly seen at 160-220 in Profile 9 (Figure 7) and at 40-60 in Profile 10 (Figure 8).

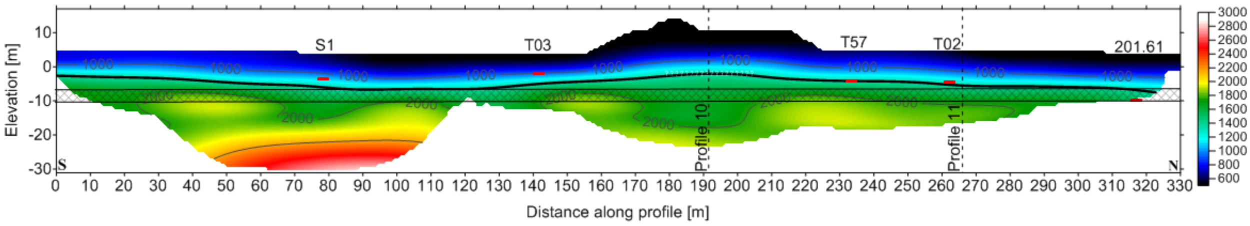

Figure 7 Profile 9 from Hvidovre Station. Cross-lines are shown as dashed lines. The tunnel is drilled from SE to NW with the projected position shown as a crosshatched area. S1, T03, etc. indicates position of borehole and red marking the top of the limestone from the borehole log. Black line along 1500 m/s isoline shows top of limestone as interpreted from seismic profile. Drilling 201.61 is more than 100 years old and the location is highly uncertain.

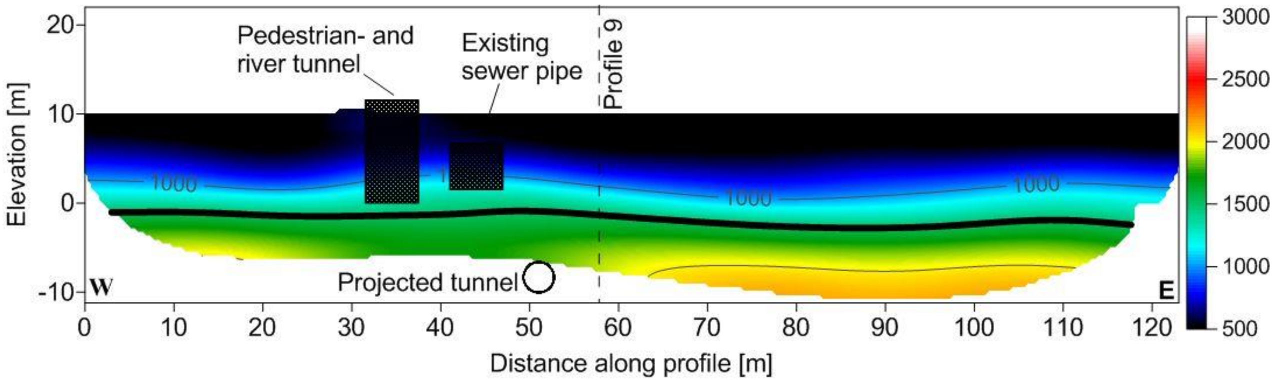

Figure 8 Profile 10 from Hvidovre Station. Cross-line is shown as a dashed line. Approximate dimensions of concrete constructions in the embankment are shown.

5 DISCUSSION AND CONCLUSION

In Case One, refraction seismic in combination with drilling proved to be a robust method to map the limestone surface. Through this an unexpected situation that had temporarily stopped tunnelling was cleared out. A gravel layer in a limestone depression could be assessed and grouted, where after tunnelling commenced.

In Case Two, the refractions seismic was used together with drilling in a technically very challenging environment. Despite this, the refraction seismic method provided good and useful results. They are used to document the geology and lower the expected risk when drilling under the embankment. This is crucial in the documentation towards the Danish Railway Administration prior to obtaining permission for the construction work.

Even though the seismic method has larger local uncertainty than drilling it has to be considered that drilling can’t be used to achieve continuous information along a tunnel alignment, the effect of this being clearly seen in Case One. Based on the two cases presented here we conclude that the combination of refraction seismic and drilling is a powerful tool, even in a challenging urban environment.

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