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Obtaining a clear image of the subsurface in front of the Tunnel Boring Machine (TBM) is one of the main objectives to increase safety during tunnel drilling in soft soil. Before construction, geotechnical and geophysical surveys from the surface give a good impression of the soil structure and heterogeneities. During construction, more information can be obtained by installing a seismic system on the head of the TBM. Traditional data processing techniques do not lead to accurate images of the subsurface. The limited number of receivers causes artifacts. Special focusing techniques have been developed with a weighted least-squares optimization, to take this problem into account and improve the image of the area of interest.

1 INTRODUCTION

One of the problems while boring a tunnel in the soft soils of the Netherlands is lack of information about the subsurface. Before construction starts, geological sections of the area are made, based on CPT (cone penetration test) measurements. The information of these CPTs is very local. They measure the vertical changes at only one position and are discontinuous in the lateral sense. In heterogeneous areas, this method gives an insufficient accuracy. A more accurate picture of the subsurface could be made by performing a 3D seismic survey over the planned trajectory of the tunnel which will also show lateral variations. In combination with the CPTs, this would lead to a much more reliable impression of the area.

Seismics can also be used during the drilling process, to image the subsurface just in front of the TBM. The application of a seismic source and receivers will give more detailed information about the situation in the path of the machine. A characterization of the soils (e.g. sand, clay or peat) can be made. This is useful to allow timely adjustment of the drilling parameters, like the properties of the bentonite or foam that is used to keep the bore front stable. Also unexpected geological features or man-made obstacles in the path of the TBM can be detected and accurately localized to indicate if they will disturb the boring process. These can be large rocks, pieces of metal, but also foundations. Contact with the head of the machine can cause great damage to the TBM which causes delay, creates

safety problems and raises project costs. Increasing the knowledge about the subsurface in advance leads to a safer tunneling project.

2 SEISMICS

When installing seismic sources and receivers on the head of the TBM, the design of the cutter wheel constrains the possible configuration. It is not realistic to put an large number of transducers on the arms. The rotation of the wheel brings an advantage here. In the time lapse of one complete rotation, the TBM has only moved a few centimeters. If during that time several measurements are made with receivers on the cutter wheel, it can be considered as if they were all taken at the same TBM position. Therefore a large set of measurements can be made with only a limited number of receivers which are all positioned at a different distance from the axis. This configuration can be seen in Figure 1 where the star represents the source of seismic signals and the receivers are indicated by triangles. The emitted wave fields are reflected on obstacles and ground layers and registered by the receivers. Since measurements are made during excavation, they cause no delays for the tunneling activities.

One of the main differences with traditional seismic surveys for oil and gas exploration, is the limited aperture of the measurements. On land, geophone lines of several hundreds of meters are installed and on sea, areas of even several square kilometers

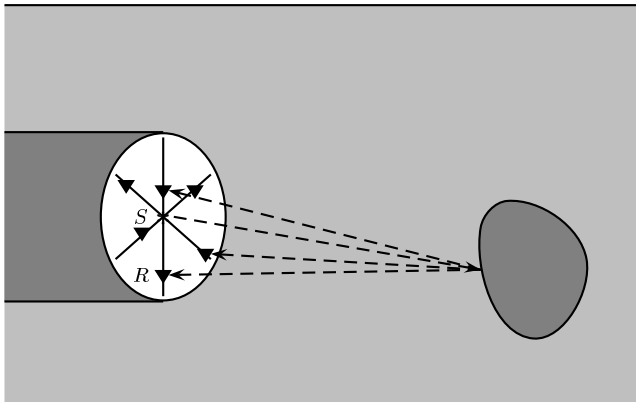


Figure 1: TBM configuration with source and receivers on the cutter wheel

are investigated with thousands of receivers. They all register seismic signals in time. In oil and gas exploration, focusing techniques will transform the time data which is measured at the surface into depth data where the reflectors are shown in their correct position. Traditional data processing techniques (Gazdag 1978) are all attuned to this kind of circumstances. For tunneling applications, receivers are installed in a vertical plane on the head of the TBM and time measurements have to be transformed to distance plots horizontally away from the receivers on the TBM. The configuration, where receivers are spread over a circle with a diameter of an average 10 m, requires special imaging techniques as standard data processing will become unstable and introduce strong artifacts in the data.

Special focusing operators have been developed, using a weighted least-squares optimization (Swinen 2002). These focusing operators take the small number of receivers into account and make optimal use of the limited information present in the measurements. This will lead to a more accurate image of the subsurface in front of the tunnel boring machine and will improve safety during tunneling.

3 EXAMPLES

The shown examples are 2D configurations where a vertical line of 21 receivers with a spacing of 0.5 m is assumed. The source coincides with the middle receiver. This configuration will rarely occur in reality, because of the rotation of the cutter wheel, but still this is a realistic example. If 11 receivers are placed on the arms of the wheel, at a different distance to the axis, they will all cross the implied positions at some point during one rotation. As mentioned before, the progress of the TBM during this rotation is negligible.

3.1 Example 1: Boulder

The configuration of a first example is sketched (not to scale) in Figure 2. The 21 receiver positions on the head of the TBM cover a total height of 10 m. A round obstacle like a boulder is considered in the trajectory of the TBM. The boulder is situated at a distance of 10 m from the head of the machine. It has a diameter of 2 m and its lowest point is located at the same depth as the lowest receiver position. The homogeneous background has a wave speed of 150 m/s, which is a realistic average for shear waves in soft sand, clay and peat. In the boulder, waves will travel with a velocity of 300 m/s.

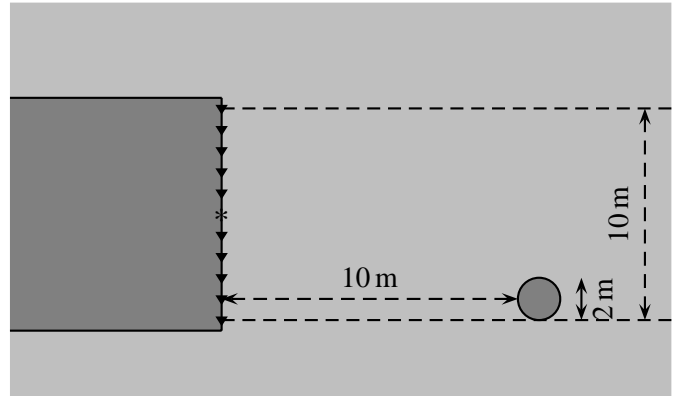


Figure 2: Example 1: boulder in trajectory of TBM

The source emits a single signal, a second derivative Gaussian wavelet with a maximum amplitude at 50 Hz and ranging up to 140 Hz. Simultaneously, the receivers record for 0.8 s. The direct waves that travel from the source straight to the receivers are not considered. Only reflections from the boulder are taken into account. The 0.8 s time data is then transformed into distance data, using standard data processing. The result for the first 20 m in front of the TBM is shown in Figure 3. The vertical axis coincides with the receiver positions, the source located at 0 m. On the horizontal axis, the distance to the head of the TBM is plotted.

Figure 3 indicates that some reflector is present in the area in front of the TBM, around 10 m from the head. In the model, the boulder is situated at a depth between the receiver positions at 3 and 5 m. It is very difficult to determine the position and the size of the boulder accurately from the distance plot. The limited number of receivers causes a lot of side effects in the data which have a negative influence on the image of the boulder. The energy of the artifacts is almost of the same order as that of the reflector. If more than one obstacle would be present in front of the TBM, the noise would dominate the image.

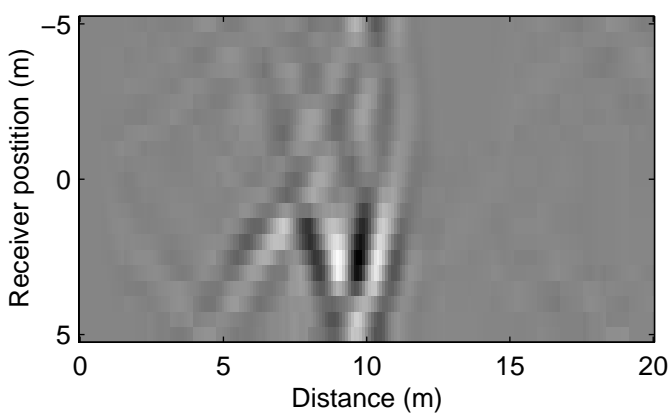


Figure 3: Distance data of boulder for 21 receivers, using traditional focussing techniques

To show the effect of the small range of receivers more clearly, the same configuration is modelled using 101 receivers instead of 21. The same 0.5 m spacing is used to the receivers are spread over a 50 m long line, five times the length of the line on the TBM. The source is still located in the middle of the line. The boulder remains in the same position relatively to the source, 10 m in front of the TBM, at a depth between the receiver positions at 3 and 5 m. All other parameters are the same. The time recordings are processed with the traditional focusing techniques. For easy comparison with Figure 3, only the middle 21 receivers are plotted in Figure 4 so that both images have the same vertical axis.

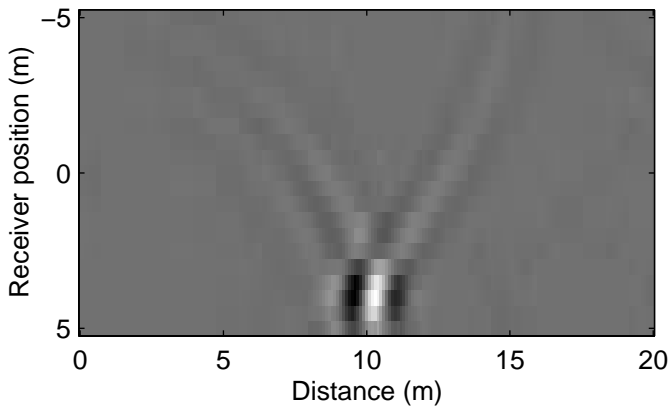


Figure 4: Distance data of boulder for 101 receivers (only 21 middle receivers plotted), using traditional focussing techniques

The difference between both images is clearly visible. In Figure 4, a distinct image of the boulder can be seen. Its position and height can be accurately determined from the distance plot. The negative side effects of the limited number of receivers have been decreased a lot. The more receivers are used, the stronger the side effects are suppressed.

In Figure 5, the special short focusing operators are used on the original time data with 21 receivers. A clear image of the boulder is visible in the distance plot, with a maximal energy at a depth between the receiver positions at 3 and 5 m. Figure 5 does still show some side-effects of the limited range of receivers, mainly at the most shallow receiver positions some energy is visible. In comparison with the result in Figure 3, a large improvement has been obtained.

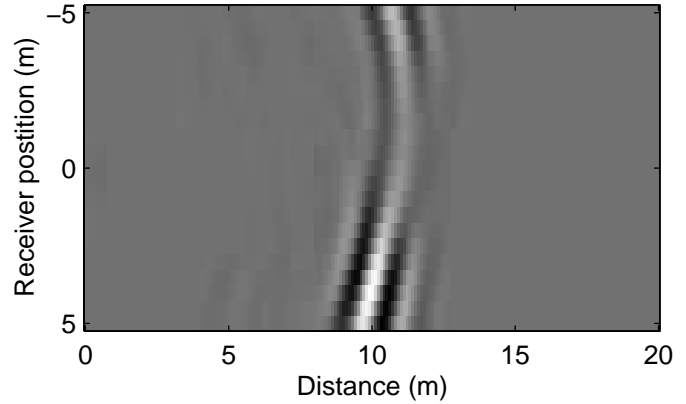


Figure 5: Distance data of boulder for 21 receivers, using optimised focussing operators

3.2 Example 2: Pipe

In a second example, a 20 cm thick pipe is located vertically in the homogeneous soil, at a distance of 5 m from the head of the TBM. The bottom of the pipe would cause disturbance during drilling as it goes 5 m down into the trajectory of the tunnel, to the depth of the axis. A sketch of the configuration is shown in Figure 6. The same line with 21 receivers is assumed on the head of the TBM. The source is situated on the axis of the machine, emitting the same source signal as in example 1. For the homogeneous background, a velocity of 150 m/s is set, waves inside the pipe have a velocity of 300 m/s.

After modelling the time recordings, the data is focussed with the traditional processing techniques. The first 20 m of the area in front of the TBM are plotted in Figure 7. There is a very local maximum around the receiver position of -1 m. At shallower depths, the reflector is damped. Although the image is less influenced by negative effects than the image of the boulder in Figure 3, there are still a lot of artifacts present in the data, mainly at the bottom of the pipe and at the outmost receiver positions.

In Figure 8 it can be seen that the result has improved by applying the optimized focusing operators to process the data. The image of the pipe is more

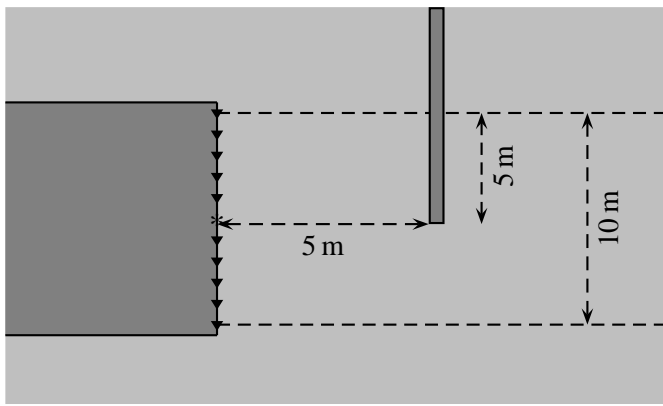


Figure 6: Example 2: vertical pipe in trajectory of TBM

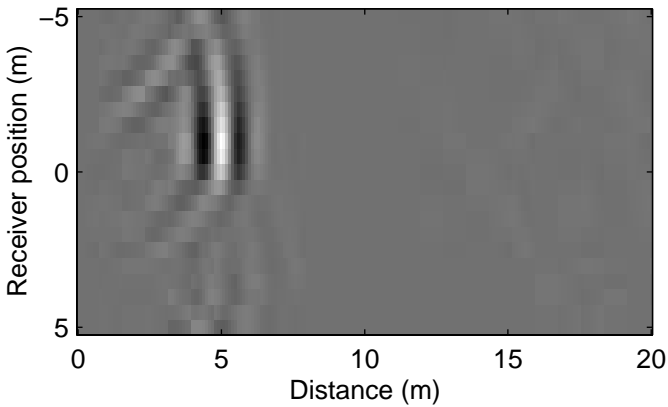


Figure 7: Distance data of vertical pipe for 21 receivers, using traditional focussing techniques

distinct up to higher receiver positions than the result obtained with traditional processing. At lower depths, side effects of the small range of receivers are present in the data but these have become weaker in comparison to the energy of the main reflector.

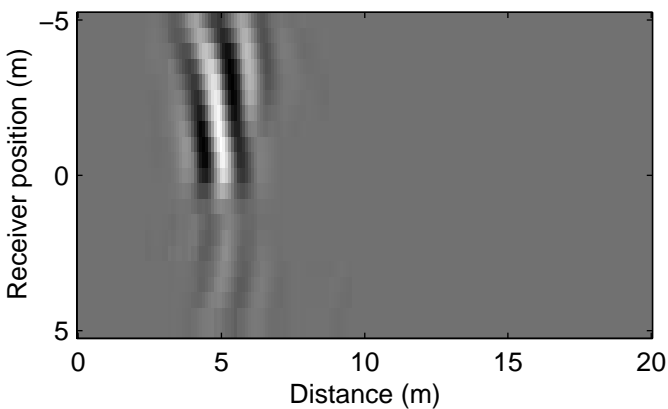


Figure 8: Distance data of vertical pipe for 21 receivers, using optimised focussing operators

It remains difficult to suppress all the side effects of the small number of receivers. During interpretation of that data, special attention is still required. Avoiding these little artifacts is one of

the main points of consideration in the further research of the new focusing operators. It is expected that 3D implementation will also improve that results.

4 CONCLUSIONS

When seismic data are recorded by only a small number of receivers, traditional data processing techniques will fail to make an accurate image of the investigated area. Artifacts will be introduced into the data and highly interfere with the reflectors. This makes exact localization and size determination of the reflector difficult. New focusing techniques take the small number of receivers into account and make optimal use of the limited information that is present in the data. Applying these optimized focusing operators decreases the side effects and makes a more accurate image of the subsurface possible. This will increase safety during the construction of tunnels in soft soil.

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