Voids and cavities in tunnelling: why do they occur and how to detect them using non-destructive methods?

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Abstract— ***Tunnelling by a Tunnel Boring Machine (TBM) encounters a range of ground conditions ranging from hard rock to soft ground. To maintain the stability of routed ground, treatment is required both before and during the advance of the machine. Due to difficult geological conditions and incomplete grouting, cavities and voids can be created around the tunnel excavation. These can cause unpredictable settlements of the ground and peak stresses in the tunnel lining. So far, these hollow or water-filled spaces have only been detected manually by boreholes driven through the crown of the tunnel lining. Non-destructive methods can be used as an alternative method to detect these spaces.***

Keywords; TBM, ground stresses, voids, non-destructive methods, FDTD.

I. INTRODUCTION

Tunnelling technology has significantly advanced in the past few decades. Meguid and Saada recently wrote [1] that due to the increase in urbanization found all over the world, tunnelling has become a preferred construction method for transportation and underground utility systems.

When tunnelling with a boring machine (TBM) in soft ground, the face must be reliably supported during excavation and the surrounding ground behind the shield tail must be held in balance by grouting during the erection of the lining [2]. To control changes in stresses and resulting settlements, simultaneous backfill grouting was carried out in shield tunnelling for the first time in 1982 in the construction of the Osaka Subway, Japan. Since then, this method has been introduced and continuously applied in many regions of the world, therefore reducing settlements or predicting the range of it associated with shield tunnelling [3].

As is generally the case in soft ground, the main objective is to preserve the initial stresses and in particular to avoid unintentional over-excavation. Therefore, the body of ground surrounding the tunnel drive should not be too damaged by overbreak or loosening/relaxation. Settlements that appear at the surface are one of the indications of inadequate tunnelling. They show the extent to which the lining is embedded in the ground [2]. Based on ITA/AITES [4] there are four types of settlements which occur during the TBM tunnelling: (a) over-excavation, (b) ploughing/heading effect and steering, (c) lining deformation & inadequate grouting and (d) swelling/consolidation of surrounding ground.

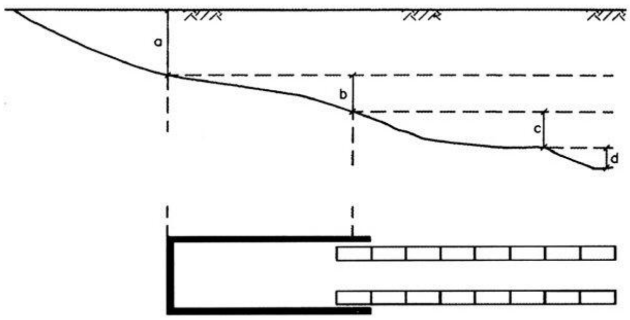


Figure 1 Evaluation of settlement along the shield [4]

Significant work [5] has been done on tunnels that are excavated through pre-stressed soils. Tunnels are acted upon by in-situ vertical and horizontal stresses. Babendererde [2] analysed boring machines specified for soft ground and he stated that if a tunnel is driven with a Slurry or an EPB shielded machine, additional action to improve or change the property of ground is not necessary. Babendererde [2] was almost correct, but there are many hidden or unforeseen factors which can occur during the construction, and or, excavation with a TBM. Therefore TBM manufacturers continually aim to improve their technology, so that they can reduce the factors of possible faults which may occur. Even if the machine is of a "perfect" build, it is always necessary to define precisely the geological conditions that the machine may encounter. In addition, tunnelling methods and the machine's systems, designed to meet the challenge of geological difficulties, must be tuned at the site and their effectiveness monitored during the whole construction.

II. EXCAVATION AND TUNNEL INTEGRITY

A. Introduction

"*Tunnels are built for rails, roads, passages, sewage, water, utilities, etc. For the majority of people the tunnel function is the most important aspect, but for a tunnel engineer the type of tunnel construction and geological picture are the most important criteria*". So began Mr. Garry Humphrey [6] in his opening speech at an ATS Tunnel Design & Construction short course in Sydney, Australia. The main purpose of tunnels is its function and therefore the final outlook of the tunnel reflects just that. Technical machine developments are now available which virtually allow us to drive tunnels in even very "difficult ground" [2]. By "difficult ground" Babendererde [2] was referring to difficult geological conditions in which, during the tunnel drive, the face is only partly or not at all stable, the tunnel lies in the underground water, the ground conditions often change, or the strength of the excavated material is extremely variable. Professor Barla [7] presented a problem of "difficult ground" conditions when TBM machines are used in tunnelling where an overburden can reach up to 2000 m. There are often geological layers with faults or natural effects such as high strength rock boulders, squeezing rock conditions, underground cavities, high-pressure water entrapments, Karst underground cavities and so on (see Figure 2). When excavating in soft ground, the surrounding material must be supported at all times and the cross-section of the tunnel secured [8]. The support medium of the face on Slurry Shield is virtually a frictionless fluid. It consists of water and additives that can filter out and settle on the surface of the face to form an impervious layer. While using the EPB, the cohesive soil loosened by the cutting wheel serves to support the tunnel face, unlike other shields which are dependent on a secondary support medium [9]. Even when the groundwater is included, the properties of the support medium are at best those of a non-frictionless, high-viscosity fluid. The more homogenous and consistent the soil is, the more successful tunnelling with EPB will be [2].

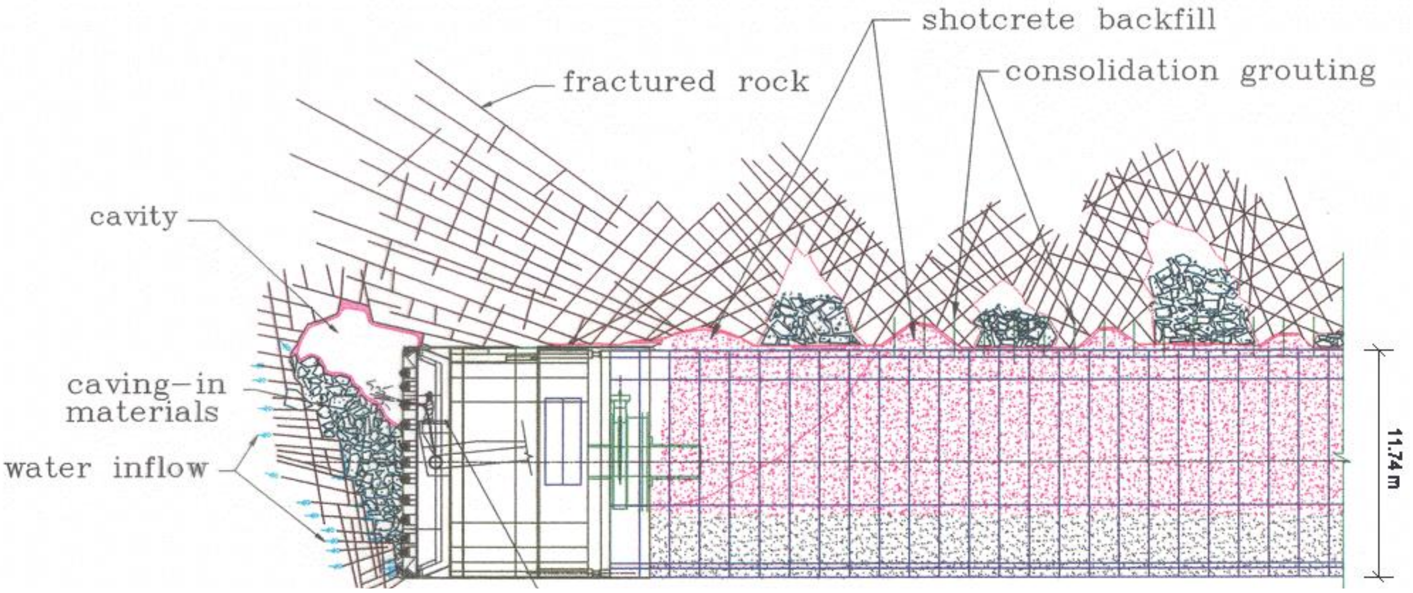


Figure 2 Examples of instability problems at the tunnel excavation [7]

B. Segment lining

Due to overburden pressures, underground water and consequently high hydrostatic pressures, tunnel lining requires prefabricated watertight reinforced concrete components with the highest degree of dimensional accuracy. When excavating, the fitness for use and durability of tunnels depends critically on the quality of lining segments [9]. In this matter high precision prefabricated curved concrete lining segments are assembled to form a lining ring. The TBM's vacuum lifting equipment lifts and positions the segments into the allocated place and locks it in with a smaller diameter "key" ring.

The faces of all segment joints need to be cleaned before bolting segments together. All bolts are tightened at the time of erecting each ring and then retightened prior to forward advance after erection. After the lateral loading on lining rings, due to the erection of the machine and the back support against the ring, the bolts can be removed as the lining only withstands hydrostatic compression loads. The procedure of tightening leaves a precise result in lining placement accuracy within a +-0.5 cm range. A lining that is unsatisfactorily bedded may result in bending or deformation, which can lead to local overstressing and possible cracking, damage or collapsing of the segment [2]. Stresses within the tunnel lining at critical locations are measured with strain gages.

C. Primary grouting

It is important that the lining is fully assembled and no voids exist between the surrounding ground and the concrete segment. In the shield tunnelling construction process, after the lining placement, primary backfill grout mortar is injected through the tail skin of the shield into the gap between the lining and the ground. The pressure due to simultaneous backfill grouting starts acting on the circumference of the lining immediately after the passage of the shield tail. The grouting pressure distribution becomes uniform shortly after the grouting because the grout is in the plastic state. With the hardening of the grout, the earth and water pressure are conveyed onto the tunnel lining. Before soil to lining interaction begins, these stresses undergo some changes resulting in displacements in the soil mass. The magnitude of the pressure change depends on the ground condition, e.g,. hard or soft soil, and also on the magnitude of the injection pressure. In the case of soft soil, the lining pressure approaches the initial stress through time regardless of the magnitude of the injecting pressure. In the case of hard soil, the lining pressure approaches the active earth's pressure [3].

This means, the stresses acting on the tunnel lining will be lower than the original stresses, particularly for the tunnels constructed at some distance from the ground surface [10]. On the other hand, when a twin tube tunnel is constructed, these pressures need to be taken into account, due to the influence on the neighbouring tunnel lining.

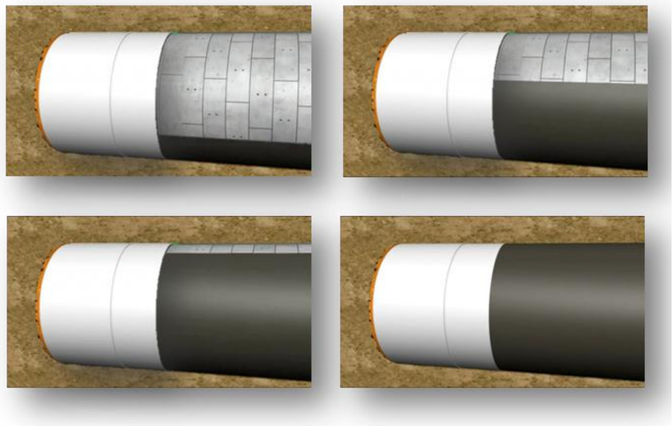


Figure 3 Simplified interpretation of TBM shield tail backfill grout mortar injection (modified from [11])

D. Secondary grouting

Although the conditions of grout injection are adequately controlled, there is no confirmation that primary grouting has filled all the available empty volume between the concrete lining and the surrounding ground. Efforts to estimate the grouted volumes are based on: (a) geometry, (b) permeability of the surrounding ground and (c) applied pressures. Regardless of the above factors and information, these parameters are still unable to supply reliable information [12]. Where there is an indication that primary grouting has not fully filled the annulus, then proof or secondary grouting is specified by the designer and carried out with the approval of the construction certifier. These indications can be shown as water ingress, wet patches on concrete segments, unexpected local concrete cracking or even ring sagging (over-stressed concrete, due to possible ground collapse). Because of the mentioned issues, every segment is equipped with one or two threaded cap grouting sockets. If additional grouting is required, tunnel ring is subjected to secondary grouting. The grout hole is extended through to the exterior surface of the segment by drilling in a manner that does not cause damage to the concrete beyond the intended diameter. If this is carried out, the maximum secondary grouting pressure should not exceed 7 bars of pressure (or pressure specified by the tunnel design/geology), due to the possibility of over-stressing the surrounding ground. These pressures have the potential to cause surface heave (at shallow excavations) or induce displacements by impacting on nearby structures such as the lining of a twin tunnel or the foundation of a high-rise building. Upon the completion of secondary grouting, each grouted hole is left in such a way so that the grout plug can be reused during the period of tunnel excavation.

Conventionally, the presence of voids within the grout are detected by drilling holes along the crown of the completed TBM tunnel *("blind grout injection holes")* in the location where any lack of grout is most likely to occur. The probe holes readily locate voids that the grout has not filled, although they do not reveal the extent of the void along or around the crown. The assessment of the efficacy of grouting is not trivial [13]. One way is core sampling, which of course is destructive and not representative of a large area.

Figure 4 Secondary grouting of every second segment (courtesy Mr. Michael Huber) and potential insignificant primary grouting (Image modified from [11])

III. NON-DESTRUCTIVE METHODS

*A. **Introduction***

A variety of manual and mechanical augers/probes have been investigated by Johnson et al. [14] as basic tools used in examining soils, marking a soil survey and for investigating hydrologic and geological characteristics close to the ground surface. The number of observations is limited by time and money; however, they are spaced to best define the area being surveyed, which helps geologists in their understanding of soil formation, vegetation, natural drainage topography, and other features in the landscape. Additionally, this work is highly labour-intensive and relatively slow [14]; the quality of the results is a function of the variability of the area being mapped. To improve the definition of a complex area, a greater number of observations are required per unit area. In these circumstances time limitations and costs may become unreasonable or prohibitive. Due to these reasons there should be a higher tendency in using geophysical methods that allow gathering subsurface information rapidly and economically, as well as providing continuous line coverage of an area.

Non-destructive geophysical measurement method can be used to detect and determine the possible anomalies or material changes. Anomalies may include the presence of foreign targets (e.g. rock, buried utilities, cavities), deteriorated materials, water infiltration within the structure or other undesirable elements (e.g. conductive ions) within the structure. The ability to detect a target depends on the contrast between the dielectric parameters of the target's material and the material that the radar energy had been travelling through before encountering it [15]. The magnitude and phase of the reflected wave can indicate the relative change in parameters of the anomaly relative to its surroundings. Changes in the travel time and attenuation of the propagating signals can also be used to detect and determine the properties of anomalies or material changes. The greater the contrast between the parameters, the more visible the target is. In applications where the target is made from metal (e.g. rebar, pipes) the contrast in comparison with soil is much greater and therefore the target's resolution is better.

B. Overview of Non-Destructive methods

Further on this topic, the Texas Transport Institute [16] combined and reviewed all high-frequency, as well some high-speed non-destructive, methods in order to interpret the mapping of: (a) tunnel leaks, (b) concrete creaking, (c) concrete spalling, (d) concrete delamination, (e) debonding, (f) steel corrosion and (g) improper drainage of existing tunnel structures. The main focus [16] was to propose a high-speed solution for tunnel monitoring and its structural properties. Based on the method, tunnel closure would not be necessary while under the monitoring / scanning stage.

Using the above reference, an overview of the non-destructive methods has been summarised in Table 1. The summary below discusses and focuses on non-destructive methods which could be of most effective use if or when implemented in a TBM, while still in the excavation phase of tunnel construction.

C. Methods most relavant for TBM tunnelling

- ***Impulse Response (IR) and Impact-Echo (IE) – "Time-Trigger"***

At the Hallandsas Project in Sweden a non-destructive method has been applied, tested and implemented in the tunnel and approved by the Swedish Transport Administration, to check the backfill material in segment lined tunnels. Due to difficult ground conditions and groundwater pressures, a significant outwash of backfill material was experienced during construction. The outwash resulted in incomplete backfilling and consequently unacceptable movements of the tunnel lining. A Pea-Gravel was used with excellent "running" properties, filling up to 2/3 of the annular gap to allow the water drainage along the lining. Top part of the lining ring was grouted with mortar. At a later stage, Pea-gravel was eventually grouted to create a complete matrix. At the end, sufficient backfill was achieved by creating a large amount of backfill drill holes. Therefore, a strong ambition was created to reduce the number of backfill drills and implement a non-destructive method, which defined a range between "good" and "poor" grouting and sometimes something in-between, a "questionable" status.

With this method a fast and easy detection of voids behind the tunnel was achieved, but a great amount of measuring points is required to calibrate the system, to understand the limitations of the device as well as to indicate the right resonance frequency and associated amplification. The device is point wise / impact by nature, therefore it cannot provide a 100% coverage testing area. In addition, if the layers are not fully bonded, the signal cannot penetrate further into the medium, resulting in a possible misunderstanding of the size and extent of the void or cavity.

The implementation of the Impact-Echo method within the tunnel was given a 2011 Innovative use of Instruments Award in Tunnelling as well as an outstanding review from the judges: "*Like all great ideas this one is very simple. It is an advance in the industry's approach to cooling the tube, reducing the operational cost of the tunnel and making tunnel more sustainable. The concept is fantastic and it presents one of the biggest potential steps forward for the industry for many years*"[17].

Figure 5 Impact Echo Device (adopted from [16])

TABLE I. Overview of Non-Destructive Methods For possible testing of Tunnel's integrity in Bored Tunnels (revised from [16])

Method	***Pros***	***Cons***
GPR – Ground Coupled System	- Low frequencies / great signal penetration depth - High frequencies / excellent near surface high resolution - Detection of concrete cracks, reinforcement, corrosion, utilities - Evaluation of layer distribution / thicknesses - Detection of voids behind the segment - 3D mapping of areas with high moisture content	- Low signal penetration in cohesive / wet soils - High frequencies / poor in depth signal penetration - Low frequencies / poor resolution at low depths / hazy zone - Reinforcement disruption with signal penetration - Surface / ground coupling problems - Grid collection of data / hard pin point detection - Large equipment / antennas / stands - Long data acquisition / subjective data processing / large data
GPR – Drill Hole System	- High resolution for mapping of cracks - Evaluation of layer distribution / thicknesses - Detection and evaluation of reinforcement	- Destructive method / a drill hole needed - Point wise by nature - Low frequencies only
GPR – Air Coupled System	- Fast data acquisition - Repeatable and accurate measurements / monitoring - Works well with thermal camera / moist-water detection	- Quality of data / changing nature of signal can be caused by different heights / distances from the surface - Interference from other signal devices / large conductive objects - Large equipment / antennas / stands
Impulse Response (IR) and Impact-Echo (IE)	- Detects delamination of linings and their thickness - Detection of voids behind the segment - Fast and easy to use	- Discrete / Point wise by nature - Not feasible for rapid, 100% coverage testing - Cannot provide deeper layers if the layers are not fully bonded
Ultrasound	- Detection of cracks, voids, deterioration of concrete / grout - Pulse time can determine the thickness of concrete / grout - 100% coverage testing - Inexpensive in comparison to other methods	- Multiple measurements needed to obtain an image - Long data acquisition - Needs to be in contact with the structure to generate a signal - Poor repeatability and / or consistency
Ultrasonic Surface Waves (USW)	- Quality control of concrete's strength - Evaluation / forensic assessment to detect delamination, debonding and loss of strength due to internal concrete cracking - Fast data acquisition	- Qualitative variation of modulus with depth - Discrete by nature, not feasible for 100% coverage testing - Does not provide deeper layers past de-bonded or delaminated layers
Ultrasonic Linear Array (MIRA)	- Multi-sensor Ultrasonic Echo system - Detection of cavities, flaws, cracks, honeycombs - Ability to see beyond reinforcing or distinguish metal enclosures from voids by phase analysis - Grouting defects around tendons or behind tunnel lining - Extent of vertical cracks / or their repair - Real time 2D image with ability to scan over a rough surface - Fast data acquisition (less than one second for a scan)	- Physical contact with the surface is limiting the collection of data - Objects thickness cannot be less than 50 mm, shallow defects will not be detected
X-Ray monitoring	- Fully portable and compact, for rapid x-ray based inspections within structures - Detection of cables, voids within concrete	- Device needs to have a lead shield / perfect conductor on the other side of the investigated object to obtain a clear image - Radiation
Concrete Surface Resistivity Testing	- Estimation of concrete's permeability / steel corrosion	- Slow and point wise by nature - Good knowledge of the device and material to determine the permeability / corrosion rate
Percometer meter or Dielectric probe technique	- To obtain dielectric parameters of measured materials - Detection of free moisture in concrete - Monitoring changes of material under heavy loading - Fast data acquisition / Small / Easy to use - Possibility to indicate salt content due to conductivity change	- Point measurements / Grid collection of data to determine the contour map of an area - Surface probes need a flat smooth surface for good connection - Not good for shotcrete concrete investigation
Digital Photogrammetry	- Fast data acquisition / Low cost / Easy to transport - Continues monitoring of tunnel lining / deformations - 3D mapping / modelling of a tunnel - Possibility to characterize aggregate	- Camera calibration / Only surface visualization - Strait-line data acquisition - Multiple vantage points to avoid obstacles
Laser Scanning: Space Tunnel Scanner	- Contact free, high speed measuring method - Three different, simultaneous measurements - 360^{O} full-surface visual recording with a thermo recording - High resolution images to detect the smallest cracks and fissures on the tunnel surface - Conduct regular inspection of damage to plan repairs	- System requires a stand / vehicle to obtain (No-movements) - Compared images need to be taken, from the same location to post process the data
Thermal Camera (IR-Camera) System	- Possible crack / distress detection with high pixel cameras - Monitoring of drainage / leakage of structures - Freeze-thaw weakening - System quickly covers a wide range of surface - Low cost / Fast data acquisition	- Dust in tunnel air may interfere with readings / data acquisition - Only surface / visual interpretation. - Needs to be in a collaboration with a GPR or a different method
Structural health monitoring	- Strain gages within structures to control the deformations - Tilt meters to monitor the changes in angles / bending moments - Temperatures and humidity meters - Compressive and tensile strength of coating or concrete	- Imbedded within the segment structure prior moulding - Devices need to be wireless and run on battery - Installation of devices needs to approved before the construction

- ***Ground Penetrating radar***

The National Cooperative Highway Research Program, America [18] did an overview research of the GPR implementation in tunnels for the purpose of monitoring and retrofitting evaluations. Both ground coupled and drill-hole GPR antennas have been used to observe bedrock stratification and identification of major fracture zones in bedrock. Other applications have been used for measuring concrete wall thickness, locating rebar or detecting voids between concrete and the bedrock and leakage of drainage water. GPR has also been used to test grouting behind tunnel walls [18].

Parkinson and Ekes [19] had an opportunity to investigate a working 2.3 m diameter water tunnel, which was closed for retrofitting, in order to investigate the tunnel's integrity and water tightness. Half of the tunnel was built using a drill and blast technique and the other half with a TBM. The whole tunnel was fitted with segment lining to create a water pipe. Segments were imbedded within the pre-excavated hole with non-grouted alluvial gravels or filled/wedged with concrete. The total length of the investigation was 8.8 km and the anomalies found were: (a) concrete honeycomb, (b) steel reinforcement and mesh roof support, (c) embedded square set wooden timbers (used to help with the alignment of the segment lining while under construction), (d) Liner-Rock contact, (e) voids empty or filled with water, (f) faults in concrete causing water leakage and (g) faults in surrounding rockmass. The archived depth of the radar signal at the crown of the tunnel was 1 m using a conventional GPR. Interpretation of obtained data was point post-analysed, using a destructive method, which drilled though the segment lining and investigated the routed hole. The average radar velocity in the concrete was approximately 1.06 m/ns and the air velocity within the open tunnel was 3.33 m/ns.

A method based on GPR to detect grout thickness behind the concrete lining and to evaluate the effectiveness of the shield tunnel backfill grouting technique had been proposed at the Shanghai Metro Line, China [20]. Tests were conducted on the lower side of the tunnel ring to enhance the integrity of the grout. Due to the concrete segment and to the grout and soil being within an overall distance of 1 m, GPR non-destructive technique was well chosen. As laboratory knowledge of the dielectric parameters of each material had already been established and the thickness of the concrete segments was already known, only the boundary between the grout and the soil needed to be found. Three GPR antenna frequencies were initially used (250 MHz, 500 MHz and 1 GHz), with 500 MHz showing the most promising results. To obtain the figure 7, multiple filters and signal gain were used in a post-process phase of the raw data signal obtained by the GPR [20].

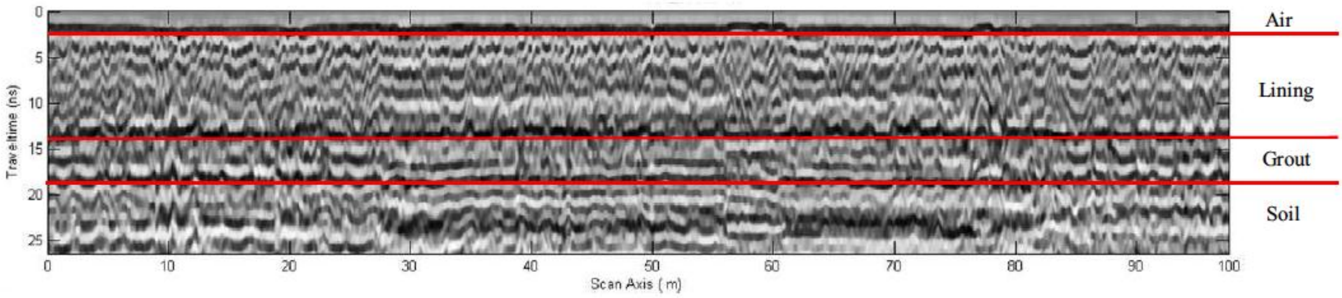


Figure 6 GPR Radargram (Row data) collected from the site (adopted [21])

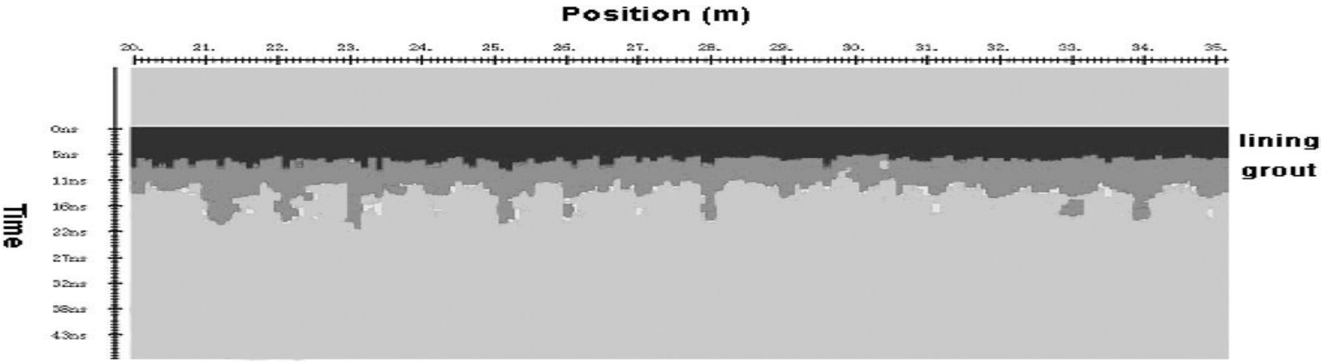


Figure 7 Post-Processing GPR radargram image (adopted [20])

D. Interpretation of raw signal data obtained by a non-destructive method

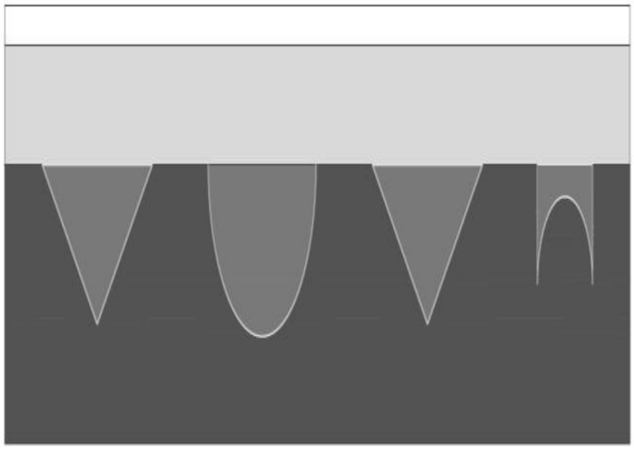
The extraction of information from non-destructive methods is often not a simple process (see figure 6). This is mainly due to the complexity of the factors involved in the method's detection mechanism. Interpretation of data is strongly dependent on the experience and expertise of the user. Difficulties arise when just going beyond the stage of detecting underground features using non-destructive methods to extract specific information about the nature, type, size, location and other characteristics of targets obtained by the method. This is mainly due to the complexity of the factors involved in the detection mechanism and how the transmitted signal is propagated within the medium [22].

There is a wide range of different modelling methods available with applications falling into two broadly defined research fields: the 'antenna modeller' and the 'propagation modeller' [23]. Antenna modelling is almost exclusively the domain of the electrical engineer and thanks to the technological demands of the mobile telecommunications market, this has provided the GPR antenna designer with a wealth of sophisticated modelling tools. Propagation modellers, on the other hand, are usually more interested in the mode, form and scattering / reflection characteristics of the propagating, electromagnetic GPR wave rather than the specific properties of the antenna. They are driven by the need to interpret GPR survey data and are less likely to be concerned about the absolute accuracy of the modelled results.

E. Finite-Difference Time-Domain (FDTD) modelling

Extraction of information such as underground features obtained from a radar gram as well as simulated with a Finite-Difference Time-Domain (FDTD) model GprMax V2.0 . presents us with a dilemma. When analysing the radargram, detection of material with high permittivity contrast can be clearly seen, but due to strong reflection of transmitted signals from the perfect conductor (steel bars), deeper targets or different layers can be easily neglected or not even recognisable. For this matter and for a better understanding on how the signals propagate though the medium, a FDTD GprMax V2.0 simulation was created by placing a concrete slab on wet sand with voids of different shapes and sizes within the sand [a-b]. The purpose of this model is to present the complexity of the simulated radargrams and their interpretations [e-f]. This complexity occurs when trying to extrapolate data from the radargram [f]. Therefore simulations of radargrams are very important tasks, which help us understand real radargrams obtained from the construction site. By adding just the conventional reinforcement to the concrete slab [c-d], the simulation becomes difficult to understand and objects (targets / voids) are less recognisable to an untrained user.

Due to GPRMax being a perfect model, there is no noise interface at lower depths of the model. The model gives us a perfect radargram even at high depths of signal penetration, which is not the case with in-situ testing. Furthermore, radar is not a continuous measurement along a survey line. The system takes readings (scans) at a set spacing. If the scan spacing is too wide, there exists a risk of not hitting the desired target with enough scans which can result in a distraction within a scan, or worse, it could miss the target completely. Generally a minimum of 10 scans is needed to draw a recognisable hyperbola. The rule of thumb [24] is to have 10 scans divided by the depth of the shallowest target. Using lower frequencies requires coarser scan densities



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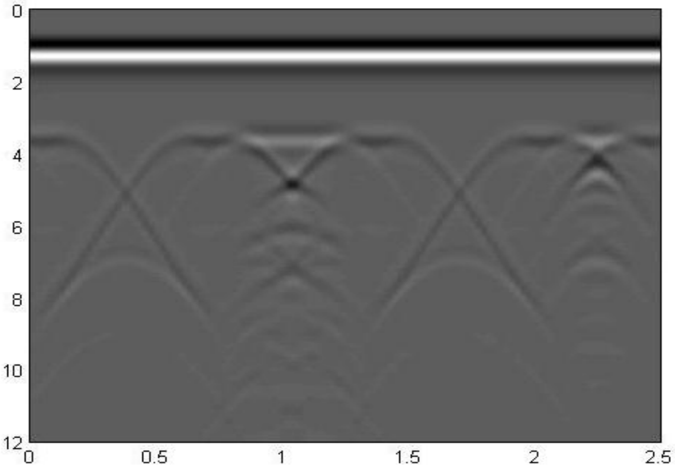

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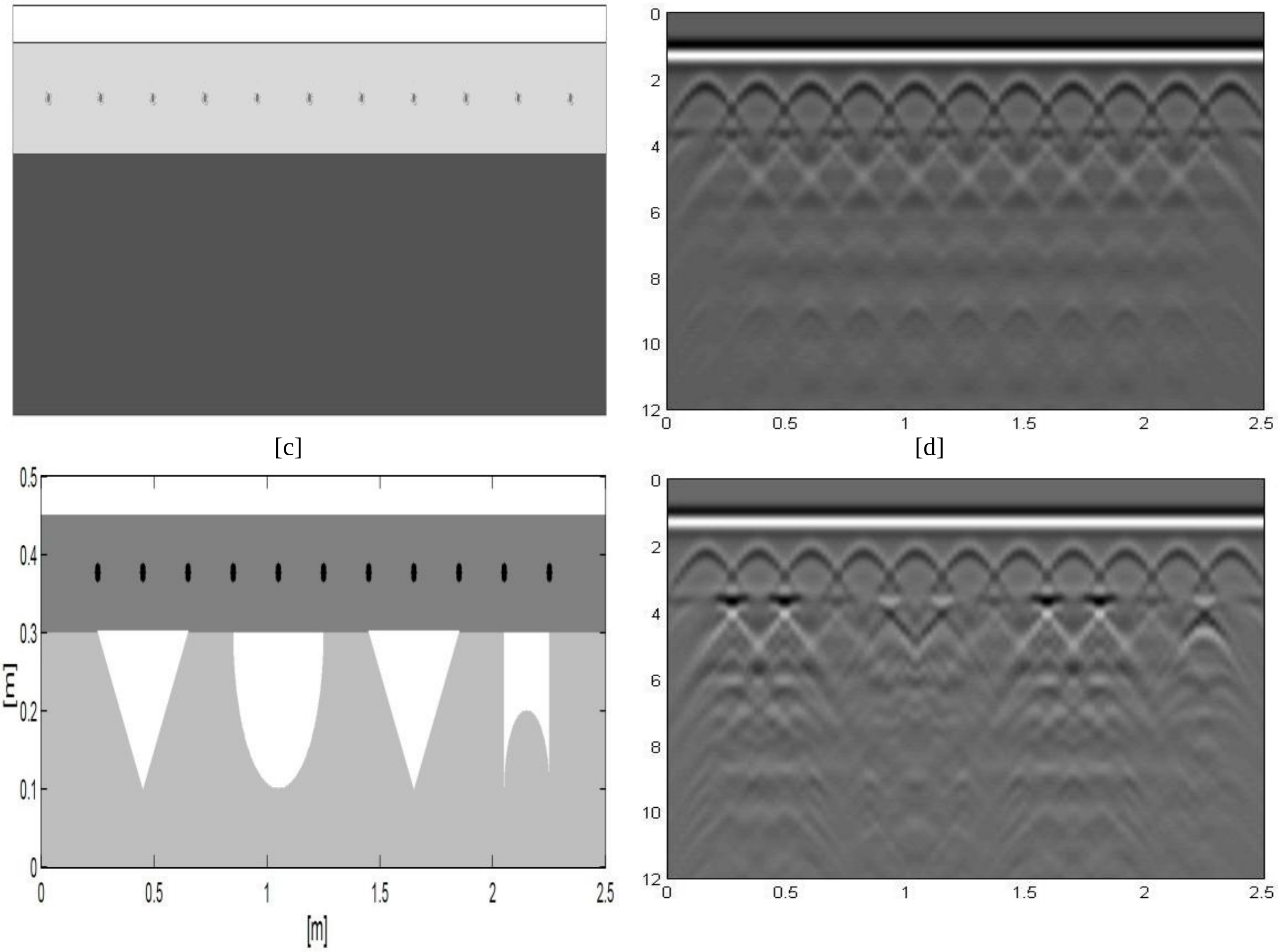

[c] [d]

[e] [f]

Figure 8 GprMax V2.0 simulation: Concrete block placed on wet sand with different shape voids underneath [a-b]; conventionally reinforced concrete block placed on wet sand [c-d] and conventionally reinforced concrete block placed on wet sand with different shape voids underneath [e-f]

In complex, heterogeneous environments, the evaluation, interpretation and analysis of ground-penetrating radar (GPR) data is often complicated by the influence of near-filled antenna coupling or induction effects, variations in antenna radiation patterns, the presence of inhomogeneous, anisotropic and loose materials and the inevitable ‘survey error’ that arises during data collection [23]. These complexities can make data interpretation a hit-and-miss affair and unfortunately many of the advanced signal processing analysis methods are poorly suited for use in a complex, near surface environment.

IV. CONCLUSION

GPR has the potential to non-destructively identify or differentiate grout once it has begun to set, a process which occurs rapidly due to the addition of accelerators to ensure rapid support of the ground around the excavated tunnel. Furthermore, GPR is a preferred method to identify voids and cavities in the ground around the tunnel lining. In order to test and further develop a GPR antenna and its performance, the knowledge and understanding of signal propagation through different media as well as the difference in material dielectrics needs to be further analysed.

The future focus of research is to further develop a GPR application in tunnelling, investigate the possible unknowns in dielectrics and most importantly to investigate a possible correlation with multiple non-destructive devices in order to overlay or strengthen the electromagnetic signal reflections. This research will involve further investigation of potential new combined GPR equipment, which would be dragged along the crown of the machine (+- 30^{O}), to rapidly identify any disturbances (e.g. cavities, over-excavation, geological faults, poor grouting, water ingress, etc.) that would facilitate the machine’s immediate re-injection or stronger grouting. The rectification of TBM's integrity is proposed to drastically reduce or even abolish the need for drilling through the segment and the use of secondary grouting.

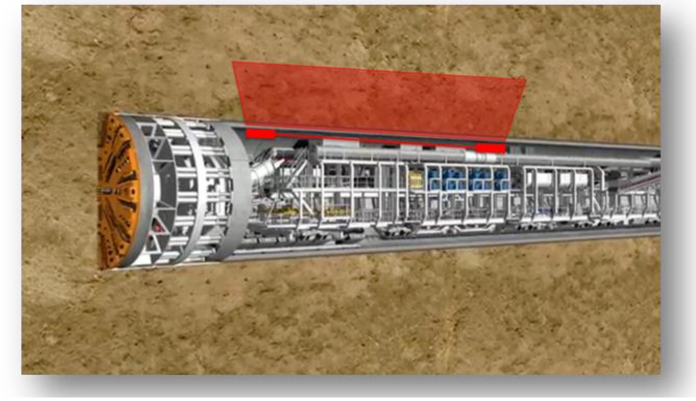

Figure 9 Proposed new online combined GPR equipment, which would be dragged along the crown of the machine (+- 30^{O}) (adopted from [11]).

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