Georadar: Locating dangerous zones prior to drilling the 57 km long Gotthard Tunnel in Switzerland

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Key words: Georadar, Ground Penetrating Radar, GPR, geophysics engineering survey; mine surveying; remote sensing; risk management; tunnel surveying

SUMMARY

Fifteen years prior to the tunnel breakthrough of the longest tunnel in the world, the Gotthard tunnel in 2010, several dangerous rock formations had to be explored. Georadar (or Ground Penetrating Radar) was one of the tools used to locate the most critical zone “Piora Mulde”. This zone showed no mechanical stability at all. For that purpose an investigation tunnel was drilled 300 m above the final tunnel elevation in order to check the feasibility of such a tunnel construction.

Georadar, a geophysical method for subsurface mapping, is explained. Recent results as well as the data recorded in front of the tunnel boring machine 15 years ago are presented.

ZUSAMMENFASSUNG

Fünfzehn Jahre vor dem Durchschlag des längsten Tunnels der Welt, dem Gotthard-Tunnel im Jahr 2010, mussten mehrere gefährliche Felsformationen erkundet werden. Georadar (oder Bodenradar) war eine der eingesetzten Methoden, um die kritischste Zone, die sogenannte "Piora Mulde", zu lokalisieren. Diese Zone zeigte überhaupt keine mechanische Stabilität. Zu diesem Zweck wurde ein Erkundungstunnel 300 m über dem endgültigen Tunnel gebohrt, um die generelle Machbarkeit zu prüfen.

Georadar, eine geophysikalische Methode für die Kartierung des Untergrundes, wird erläutert. Aktuelle Ergebnisse sowie die vor 15 Jahren vor der Tunnelbohrmaschine an der Tunnelbrust aufgenommenen Daten werden vorgestellt.

SOMMAIRE

Quinze ans avant la percée en 2010 du plus long tunnel au monde, le tunnel du Gotthard, plusieurs formations géologiques très dangereuses ont dû être analysées. La méthode géoradar a été une des méthodes utilisées pour pouvoir localiser la zone critique de la «Piora Mulde», qui ne présente aucune stabilité mécanique.

Pour cela, un tunnel pilote a été foré environ 300 m au-dessus du tunnel projeté pour pouvoir définir les possibilités de faisabilité de l’excavation.

Le géoradar, une méthode géophysique pour cartografier les sous-sols est expliquée. Les résultats actuels ainsi que ceux obtenus il y a 15 ans devant le tunnelier sont présentés.

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1. INTRODUCTION

The Gotthard Base Tunnel with its 57 km is the world’s longest railway tunnel (Fig. 1). It is located beneath the Swiss Alps and consists of two single track tunnels, several cross-cuts and shafts with a total length of 153.5 km.

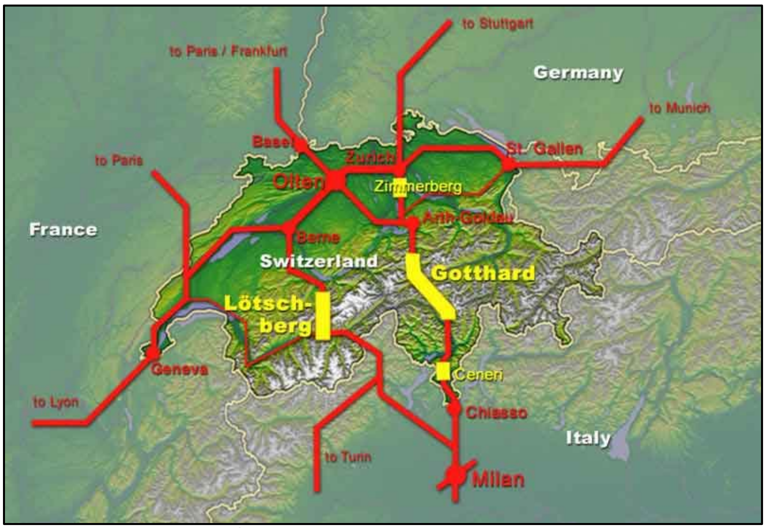

Fig. 1: Location of the Gotthard tunnel transect (by Cooper.ch).

The constructions started in 1996. The eastern tunnel was completed on 15 October 2010 and celebrated with a cut-through ceremony (Fig. 2). The constructions are planned to end by 2016 and the opening to the traffic by 2017 [1].

Fig. 2: Cut-through of the TBM on 15 October 2010.

The tunnel leads through largely disturbed granite and gneiss massifs interrupted by weak and instable rock formations (Fig. 3, top). The maximum overburden is up to 2500 m, the hydrological situations are highly variable. The most dreaded geological formation was the so-called “Piora Mulde” (Fig. 3, yellow marked). The material of this formation has the consistancy of sugar and is therefore called sugar grained dolomite. It has no mechanical stability at all. At the beginning in 1995 nobody knew whether this formation would reach down to the planned tunnel level. In order to gain more detailed information a sounding tunnel was built prior to the construction of the base tunnels.The sounding tunnel was built 300 m above the planned base tunnel [2].

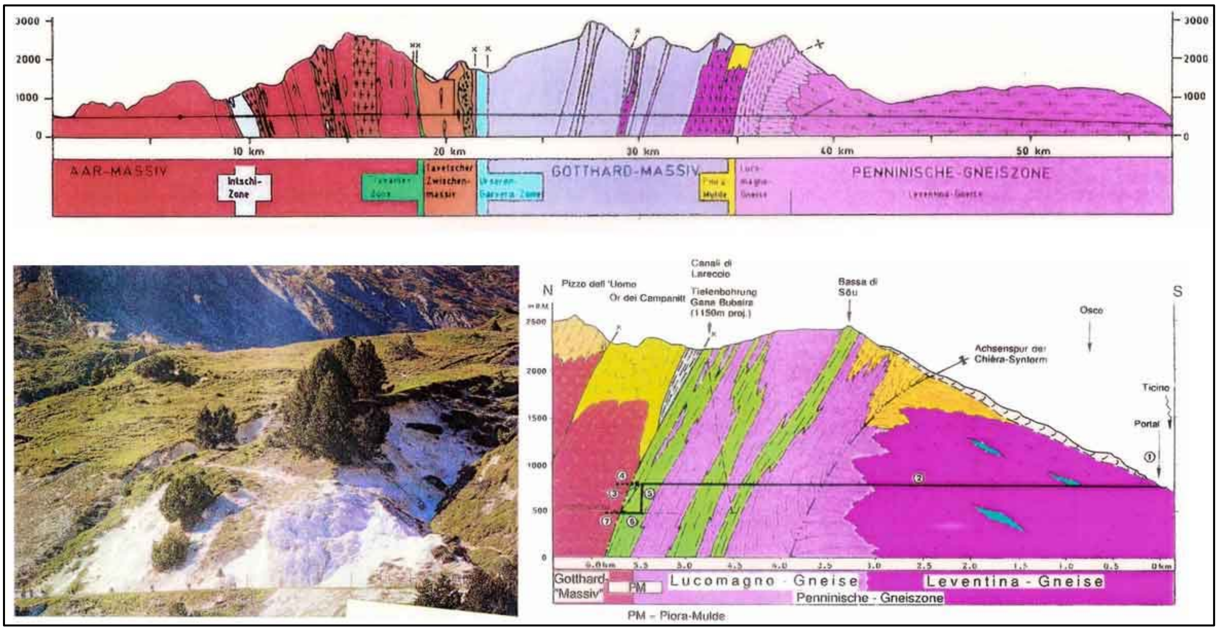

Fig. 3: Geological cross-sections of the whole tunnel area published before 1995 (top, by Alptransit) and of the yellow marked critical section (right). Picture of the Piora region at the surface (left, by R. Steinegger, Lauener, 1997).

For safety reasons it is important to identify a problematic rock formation before the Tunnel Boring Machine (TBM) reaches it. To prevent unexpected hazards a Georadar or Ground Penetrating Radar (GPR) measurement in front of the drilling face was used for prognostic purposes.

2. GEORADAR PRINCIPLE

GPR is a geophysical investigation method. Its principle is similar to that of Seismics but instead of emitting elastic waves, it emits electromagnetic waves. They are much shorter, which leads to a much higher spatial resolution. GPR is sensitive to the electromagnetic properties of the material under investigation. Interfaces of rock formations, fissures and aquiferous areas are displayed.

The System consists of a transmitter antenna, a receiver antenna and a control unit. The GPR transmitter antenna produces high-frequency electromagnetic energy pulses. These pulses penetrate the ground and are reflected at interfaces of media with high contrasts in electrical conductivity. The reflected waves are captured by the receiver antenna and are displayed continuously on the control unit, producing a so-called radargram (Fig. 4).

Depending on the required depth of penetration and spatial resolution, different antennas are used: The lower the antenna frequency, the deeper the penetration.

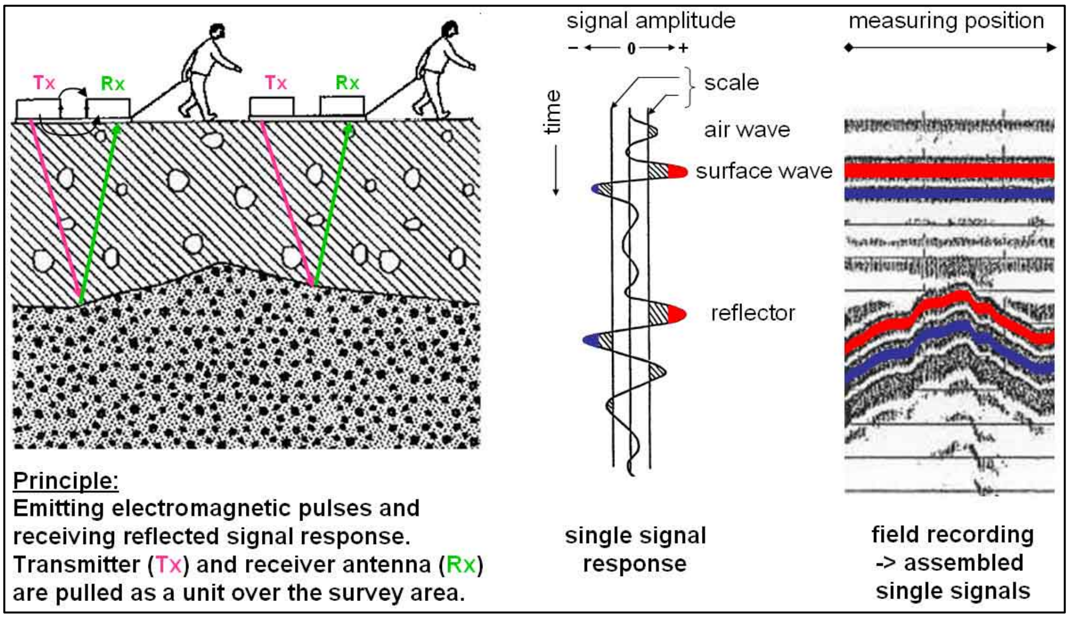

Fig. 4: Georadar principle [3]

Prior to the measurements the antenna configuration was calculated in order to achieve the necessary depth of penetration. The excavation performance in the hard gneiss was about 14 m per day. The requirement was 20 m penetration depth, which is 1.5 times the excavation performance of the TBM. Whether a target is visible or not depends on the material in the expected fault zone. Calculations of the achievable penetration depth using 100 MHz antennas and a rock model ‘gneiss’ and target ‘water’ resulted in a value of 61 m for a specular and 37 m for a rough target.

3. SURVEY

For the required penetration depth only unshielded antennas with frequencies of 100 MHz and 50 MHz could be used. We choosed the “pulseEKKO” system built by the canadian company Sensors&Software Inc. That Georadar equipment was small enough to fit through the narrow manhole of the TBM to get to the drilling face (Fig. 5).

Fig. 5: Close-up of the rotary bit. The borehole diameter is 5 m. Photo E. Meier.

Prior to the measurement the TBM was pulled back 1.5 m at a time. Then the first man crawled through the several meters long manhole, while the second man pushed the equipment through the manhole and prepared the recording unit afterwards (Fig. 6).

Fig. 6: GPR 100 MHz antennas (top left), Manhole with fibre optics (top right), engineers passing GPR equipment through a manhole (bottom left) and carrying protection tubes for the vulnerable fibre optics (bottom right). Photos: E Meier, U. Sambeth.

The profiles always run from left to right. The centre of the profile coincides with the centre of the bore hole. The measurement in front of the TBM could be performed by two people in a few minutes. It could be combined with the check of the rotary bits.

First, two test measurements were carried out at tunnel meters 3397 and 3411. After satisfying results, a second field campaign was conducted from tunnel meter 4840 to 5120 (Fig. 7, 8).

4. RESULTS

Unlike a normal GPR measurement the display of the radar signals in the radargrams is forward oriented, towards the progress of drilling.
Figure 7 displays a colour image of a radar section at tunnel position 3397 m and one at position 3411 m. At 24 m distance in the record at the left side a fault zone is clearly visible. In the figure on the right side this fault zone has approached, it is now at a distance of only 14 m from the drilling face. The evaluation of the events is based on the radargram interpretation and the geological outcrop [4].

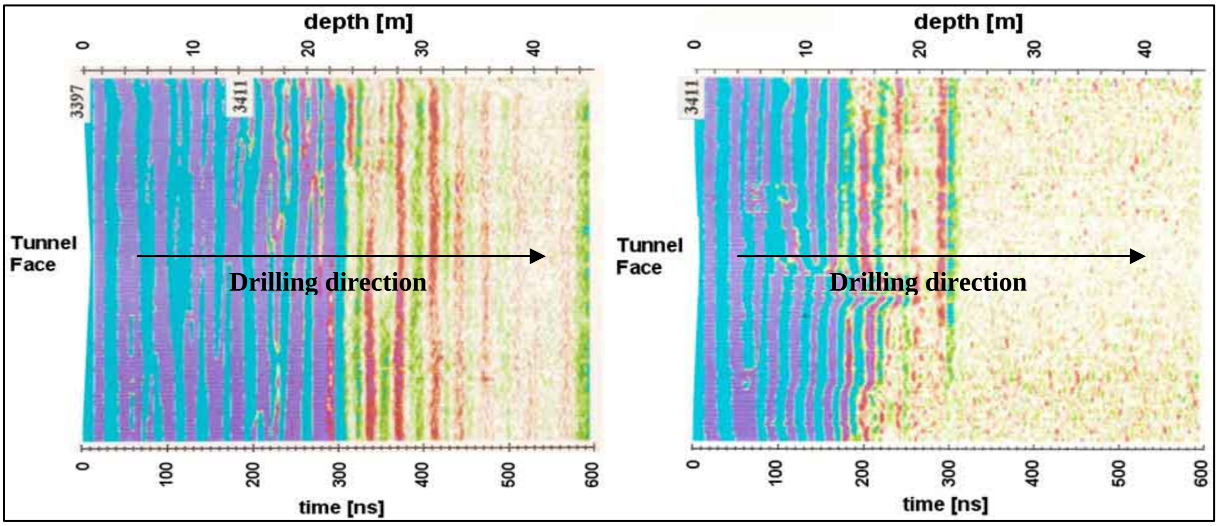

Fig. 7: Coloured profiles of the two test measurements at tunnel meter 3397 m (left) and 3411 m (right). In the first record the blue range (reflections with big amplitudes) is reaching 24 m deep, in the second record 14 m deep.

Figure 8 demonstrates different georadar images of different rock qualities. Images like the one on the left represent a high quality rock. In critical zones where water intrusions were present, already after a few meters no reflectors were visible any more (Fig. 8, right).

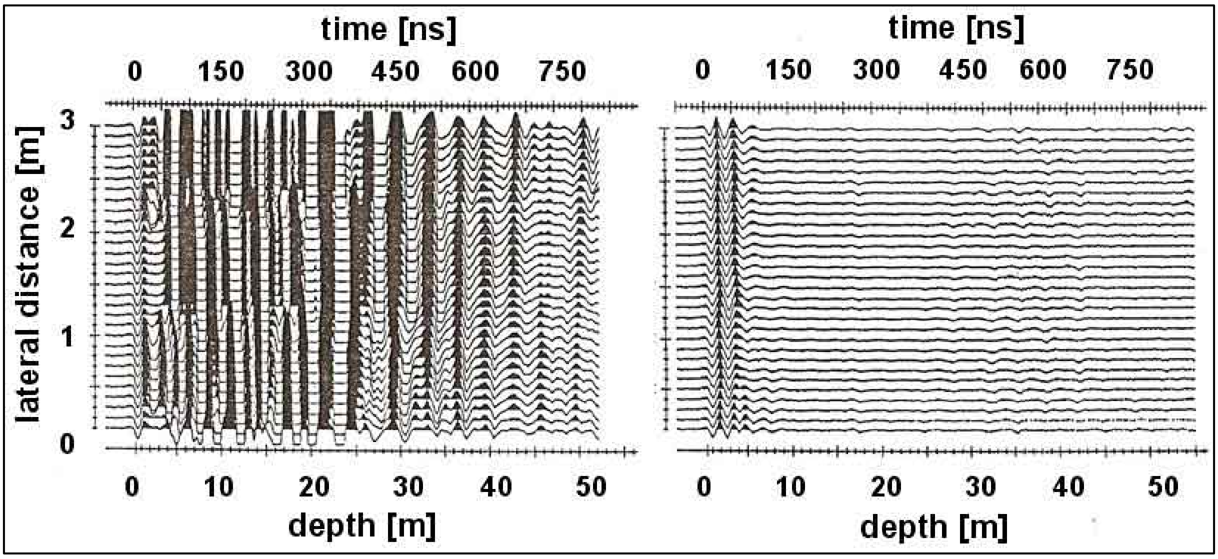

Fig. 8: 50 MHz Georadaprofiles representing high quality solid rocks (left) and rock at a fault zone (right).

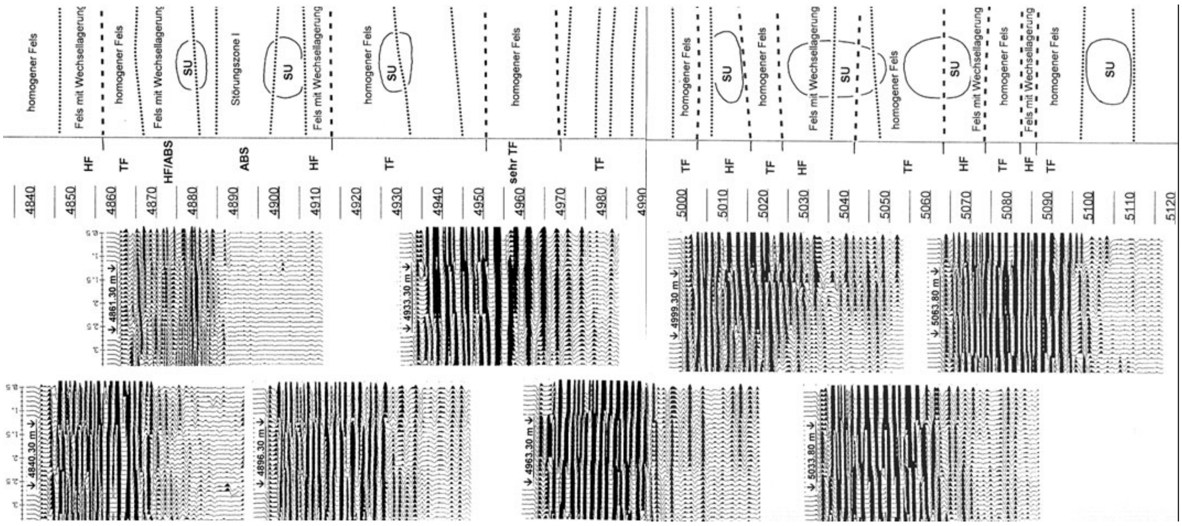

Fig. 9: Overview of overlapping series of georadar profiles recorded between position 4840 m and 5120 m

An overview of overlapping georadar profiles is shown in fig. 9. At position 4875 a small fault zone was detected. The georadar image of that zone shows a clear signal absorption halfway in drilling direction. This was verified by the geological outcrop.

The last Georadar record was taken on 28 November 1995. On 31 March 1996, between 12:30 and 17:00, during the pilot hole drilling from position 5553 into the critical zone, an operating error ocurred and the tunnel was filled with 2000 tons of water and sugar grained dolomite [5].

Fig. 10: Blow-out from borehole at 5553 m. A mixture of sugar grained dolomite and water with 1000 m overpressure filled the tunnel. Photo R.Volpers [6]

5. CONCLUSION

Georadar is a feasible tool for detecting dangerous waterfilled zones in granitic rocks. It is a very quick methode and can be carried out during the check of the drilling bits. Pilot holes are still necessary for safety reasons. However, the number of pilot holes can be reduced and limited to the critical zones, which also reduces the costs considerably.

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