

Merits and potential of Georadar as a subsurface investigation tool - experience at NGI during the past ten years

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ABSTRACT: Based on more than ten years experience within georadar development and testing at NGI, possibilities and limitations of this technology are summarized. A number of field test results are shown, including transmission measurements/ cross hole radar tomography and classical radar reflection techniques. Data corresponding to different depth ranges and resolution are shown: from measurements of polar ice thickness (1000m) to imaging rebars 2 cm below a concrete surface. Field measurement examples of karst cavity detection, soil-rock interface mapping and ground water surface mapping are also presented. It is shown that the georadar in some cases reveal the most unbelievable details of the subsurface. In other, the results obtained are not so promising.

1 INTRODUCTION

At NGI there has been a continuous activity in developing and testing radars for different subsurface mapping tasks since 1989. The work has included development of hardware and software for data acquisition and algorithms for data processing and interpretation. In parallel with the development work, NGI has carried out more than hundred service jobs, gaining a lot of practical experience. Examples are presented in this paper.

The georadar used at NGI is a continuous wave stepped frequency system, in contrast to most of today systems that are pulsed. The advantage of the stepped frequency system is the high sensitivity and dynamic range provided by the HP- network analyzer, which is the main system unit. A more detailed description of the system can be found in Kong and By (1995). Another advantage is the broad frequency band and the general analyzing capabilities making it a very flexible instrument that can be used for many different types of radar applications. NGI design and construct the transmitter and receiver antennas for each specific application. The different antennas cover the frequency range from about 10 MHz to 10 GHz. The physical size varies from several meters, maximum 15 m, to a few centimeters.

A stepped frequency system is a continuous wave system where the total energy radiated is distributed in time. This is an advantage in situations where equivalent high power is needed in order to account

for high attenuation loss, because low cost high transmitter power amplifiers can be used. Another advantage is that “forbidden frequencies” can easily be avoided by controlling the frequency steps in software, as needed for example in connection to georadar work close to airports. The main disadvantages of the system are the relative slow speed of measurements (around two per second), and the need for analog electrical signal cables to the antennas. Figure 1 shows the step frequency radar in use.



Figure 1. Pavement mapping using stepped frequency radar.

Subsurface imaging by georadar may be carried out by standard reflection measurements, as in tradi-

tional surface georadar measurements or transmission measurements as in crosshole tomography. The parameters recorded and utilized in georadar subsurface imaging techniques, are the magnitude and phase (time delay) of the transmitted and/or reflected electromagnetic wave.

Reflection occurs at interfaces where the dielectric properties and/or the conductivity change. If the change is large and the interface area of the object (or layer) is big, the reflections will also be large. The largest reflections occur between air and metal. For a plane wave (a wave at some distance from the source), the amplitude of the wave reflected from a larger metal surface is equal to the amplitude of the incoming wave, i.e. 100% reflection (total reflection) occurs. Between air and water, the reflection will be about 80 %. The reflection between air and ground will depend on the surface geology, but typically be in the order of 50 %. In the subsurface, the reflections are normally smaller than those mentioned above, except for buried metal where total reflection may occur. Subsurface metal objects may be old barrels, pipes, electrical cables and so on. Other big reflectors may be: major geological interfaces for example the ground water interface, the soil – rock interface, interface between ice and rock or water, interface between sedimentary units such as sand-clay or interface between two different hard rock units. Larger subsurface cavities, for example karst cavities or tunnels, may also produce considerable radar reflections.

The received reflected signal from a buried object depends not only on the dielectric and conductive contrast, but also on the size and shape of the object relative to the wave length of the radar waves, and to the distance. High frequency radar generates waves with small wave lengths which can resolve small objects in ideal conditions. However, high frequencies attenuate fast and the range is therefore limited. The maximum propagation distance normalized with wave length tends to be relatively constant for a given material. The relationship between frequency and wavelength is: $V = f \lambda$, where V is the wave speed. The wave speed is high in dry rock with low electric conductivity. In air the speed is about 30cm/ns, in crystalline granitic rock about 10 cm/ns, in dry porous sand around 12 cm/ns, in fresh water saturated porous sand about 7 cm/ns and in fresh water about 3.5cm/ns.

Reflections and scattering lead to energy transmission loss, but the most severe attenuation of radar waves (or EM in general) is normally due to high electrical conductivity of the ground. For example in clays, where the conductivity normally is high, the wave energy is mostly converted to con-

duction currents (and eventually heat) just after a small propagation distance. The radar penetration in conductive ground is therefore limited to only a few or a fraction of the wavelength. The fact that different soils/rocks have different conductivity suggests that the attenuation of radar wave can also be used as a subsurface mapping tool. As described later, the attenuation tomography has been successfully used in several occasions. For more information on expected range and resolution, see Annan & Cosaway (1992).

2 FIELD TEST EXAMPLES

2.1 Mapping snow, ice and frozen soil

Ice is a very low attenuation material due to its low conductivity (0.01 mS/m) and is normally quite homogenous. Consequently radar waves penetrates quite easily. The georadar results from mapping of ice thickness are therefore usually very good, with excellent range and resolution. For 100 MHz signal the attenuation could be expected to be in the order of 0.01 dB/m, which is a very small attenuation value.

We have seen several good data examples from mapping ice thickness and structure of ice. As an example, the results from mapping the thickness of an Antarctica glacier using radar from helicopter is shown in figure 2.

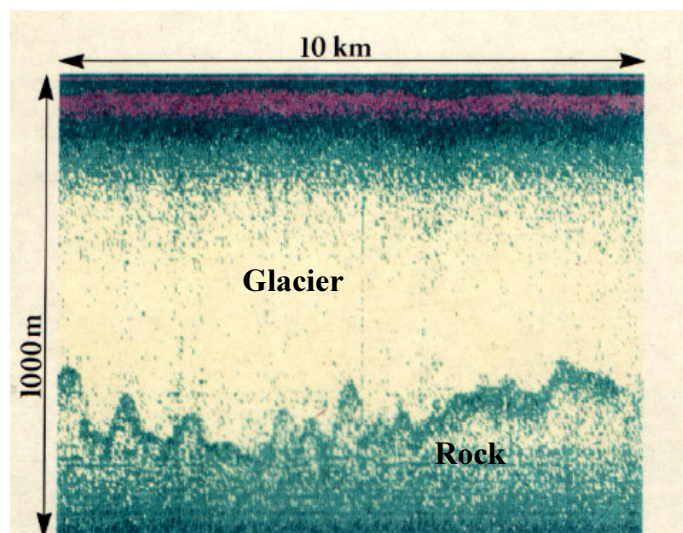


Figure 2. Georadar section showing variations in glacier thickness. Data acquired by NVE (Mike Kennett), 1990.

The section clearly shows the rock topography below the glacier, varying between 700- 800 meters in depth. The frequency used is about 10 MHz. The next example is from mapping the ice cover of a frozen lake in Norway during the winter period, figure 3. The radar section shows that the ice thickness

is about 0.5 meters. The frequencies used are around 1500 MHz. Note how sharp the reflection between ice and water is visualized in the section. The section shows that the ice thickness increases towards land and that the base of the ice is uneven. Note also that the snow layer on top of the ice is visible in the data, demonstrating the fact that radar can be successfully used for snow thickness mapping.

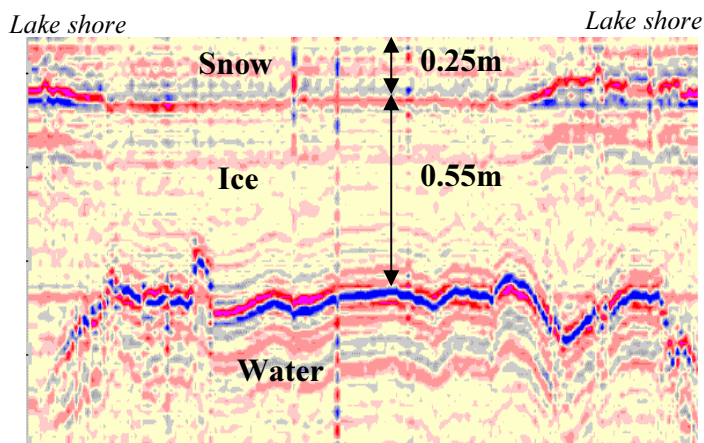


Figure 3. Georadar section from crossing a frozen lake

The electrical properties of soils change with temperature and a major step occurs when the soil freezes. Here, the electric conductivity decreases considerably. The decrease depends on the soil or rock type, but a factor of 10 is not unusual, Zhadanov and Keller (1994). The dielectric permittivity also decreases at this point. These changes makes it possible to use radar to map for example the boundary between frozen and not frozen soils, i.e. the frost crust thickness. In wintertime inland eastern Norway the frost crust thickness is typically 1 to 2 meters, but with large local variations. The thickness depends on the local ground condition, snow cover and temperature history, and may vary considerable laterally. NGI has several data examples where georadar reveals detailed variation in frost crust thickness. From Svalbard (close to 80 degrees north), we have cross hole tomography radar data from a section under a building in permafrost, showing clearly temperature effects. From another area on the polar island we also have good quality surface georadar data showing variations in the interface between coarse surface debris (colloivium, frost erosion) and the underlying undisturbed rock.

2.2 Sand, gravel and ground water

In sand and gravel, the radar attenuation normally is low and good results are therefore expected. Georadar equipment salesmen often show data examples from clean sand deposits to impress the potential buyers. In these conditions, for example fluvial (or glaci-fluvial), there are internal structures like bed-

ding planes with different dip, erosion surfaces, old slide faults, channel fill and the ground water surface. These structures will be visualized by the georadar and the image can be quite impressive. In sand/gravel deposits, georadar may be used for mapping the ground water surface, finding the geological depositions history and predicting the sediment character and hydrogeological parameters (expected flow directions etc.).

An example of a surface georadar section in a Norwegian sand/gravel- deposit (glacifluvial deposits at Gardermoen) is shown in figure 4. This georadar section clearly shows the soil structure (dipping beds) and the ground water surface which cuts through the dipping beds at about 8 meters depth below surface.

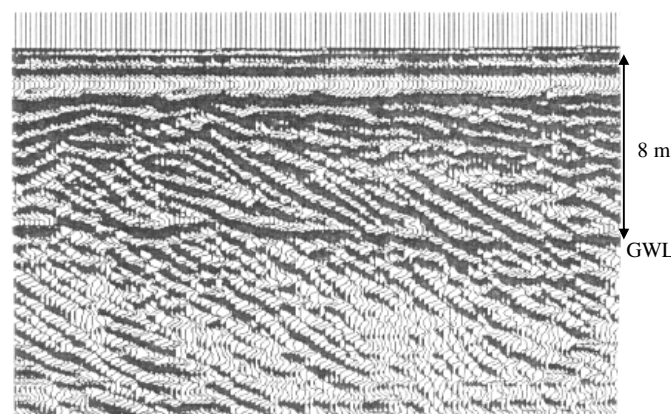


Figure 4. Georadar section in glaci-fluvial deposits (sand and gravel) with the ground water surface at 8m depth.

In certain projects one may be interested to know the depth to the hard rock surface. When clean sand overlays hard rock, the hard rock surface may be mapped by georadar. In clean sand the attenuation is quite low and the radar detection range is quite long. Figure 5 shows a radar section from Haslemoen Norway, that clearly shows the hard rock interface through more than 30 meters of sand (deepest part on the left side of the picture). In such situations the georadar is a very efficient "depth to bedrock"-mapping tool.

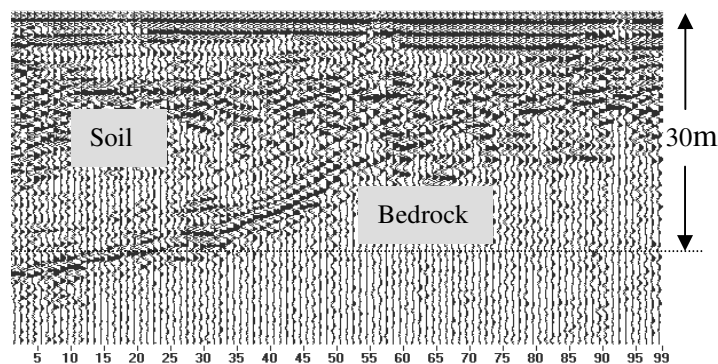


Figure 5. Georadar section in sand showing the underlying bedrock surface topography down to more than 30m.

Radar may be used as a monitoring tool in salt-water injection projects. The salt water acts as a "contrast fluid", denying the radar wave to easily penetrate the salt water infiltrated sections. NGI has carried out radar crosshole tomography (boreholes about 10m apart) to study the movement of injected brine in sand deposits to map the permeability distribution of the section. Repeated attenuation tomography showed the movement of the brine as time lapsed. The images showed the in-situ relative permeability of the soil section, an important parameter in many environmental projects.

2.3 Silt, clay and saline water in porous rocks

Clay and Silts are often too conductive to give good georadar data. In dry conditions however, e.g. frozen clay, the conductivity will be less and the possibility for getting good data increases. In general however, one should not expect good georadar data in clays.

In porous rock, like most soils, the electrical properties of the pore fluid will affect the attenuation of radar waves. If sea water is present, the conductivity of the porous or fractured rocks may increase to an extent that georadar will not perform very well. Georadar for mapping sub-sea fractured rock conditions, for example in connection with sub-sea tunnels, therefore often gives poor results. NGI has several examples of high radar wave attenuation in crystalline rocks from sub-sea tunneling projects.

Georadar may be used for mapping the seawater – fresh water interface in shore areas, where the fresh water overlays the sea water. By measuring georadar profiles from land towards the sea, one can observe how the maximum radar distance range reduces as one approaches the shore.

2.4 Georadar in hard rocks

Georadar in hard rocks may be used for mapping the rock quality, including localization of fractures, cavities and lithological boundaries or mapping the rock cover thickness.

In hard rock, one may find both good and bad conditions for georadar measurements. Rocks that contain major portions high conductive minerals, such as metal sulfides, graphite or clay mineral, have high conductivity and the georadar will not perform well. In rocks like black shale and dark mica schist we often experience high radar wave attenuation. Good quality georadar data often can be obtained in, for example, gneiss, granite, sandstone (quartzite) and marble.

An example of successful application is mapping the thickness of the rock cover above tunnels (up to about 25 meters) where the measurements are per-

formed from inside the tunnels, and with the antennas are placed on the tunnel wall or ceiling. NGI has carried out such measurements in hydropower tunnels below glaciers, in gneiss, where the tunnel rock cover is not easily measured from the surface, Westerdahl et. al (1992). Several hundred meters of tunnels were investigated, but good data could not be obtained for the whole profile length. The electrical properties of the crystalline rock may change quite fast, and for parts of the section no reflections from the rock surface could be seen. It was found that the gneiss in these sections contained graphite, a major absorber of radar waves.

Another example is mapping of fresh water filled fractures in marble and gneiss below a dam foot. By crosshole radar tomography with borehole distance 30 - 60 meters, a section of the dam foot was investigated prior to and after cement injection. (NGI also performed crosshole seismic tomography at the same time). The results showed in which part of the sections the injection had made a change, and where another round of injection was required.

2.5 Concrete, asphalt and stonework

There are many applications for georadar in concrete. NGI has just finished an European research project for non-destructive testing of building materials, demonstrating the potential of the georadar as a mapping- and non-destructive testing tool. Concrete changes its electrical properties as it hardens. Wet concrete has relatively high conductivity and consequently the radar attenuation is high and the detection range is low. In dry concrete however, the range is improved and the high frequency georadar can then be used as a mapping tool for internal structure. Internal structure may be layers or objects such as cavities, re-bars and pipes. Figure 6 shows a high frequency (1-6 GHz) radar section of a concrete slab with 10mm re-bars at different depths, 2 cm, 4 cm, 6 cm, 8 cm and 10 cm. The figure clearly demonstrates the ability of such high-frequency radars to map rebars with sub-centimeters accuracy (data from one of the EU-project tests).

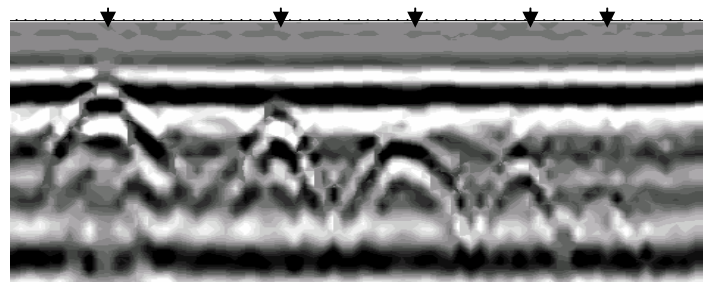


Figure 6. High frequency (6 GHz) radar detecting rebars 2, 4, 6, 8 and 10 cm deep in concrete. The rebars are located at the apex of the reflection hyperbola.

In many situation there is a need to search for cavities behind or under a concrete layer. For such

problems NGI has several examples where high frequency radar investigation has been successful. One example is from the subway in Seoul (Korea), where several water filled cavities behind the concrete lining were pinpointed by the georadar. The thickness of the concrete in these cases has been 15- 30cm. Note that radar may penetrate a rebar mesh layer, if the mesh spacing is not too small compared to the radar wavelength and distance.

As a demonstration project at Sarawak in Malaysia, NGI conducted cross hole high frequency radar tomography test in a 1.5 meter diameter concrete pile with known faults. The distance between the two parallel boreholes was about 1m and the total depth about 2.2 meters. Artificial objects, a brick work cube and a sand layer, were put in known positions during the casting, serving as "known faults" in the pile. The faults were not known to NGI in advance. The resulting tomography image (attenuation tomography) together with a sketched of the known faults, is shown in figure 7. The tomography results, shows the areas with sand and brickwork (dark colors) as the radar waves attenuates less in these areas compared to the surrounding concrete (light colors). The sand layer image seems a bit distorted, but this is most probably due to settlements before the concrete is hardened. A similar successful test was also conducted with a thinner pile where the distance between the boreholes was 0.3 m.

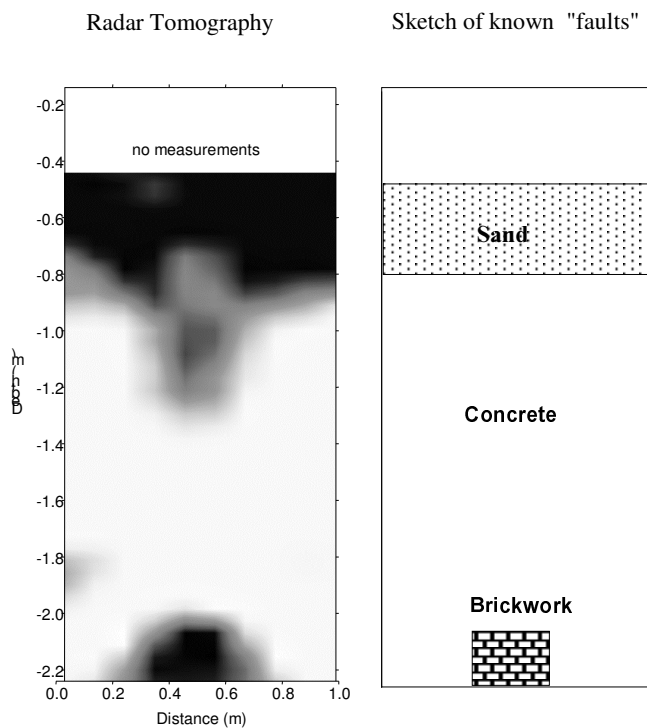


Figure 7. High frequency georadar crosshole tomography test to find faults in concrete pillars. A controlled field experiment, Sarawak, Malaysia.

Asphalt attenuates radar waves less than concrete and is considered to be a good radar material. NGI has performed several asphalt thickness measurements using high frequency radar. The radar tech-

nique has demonstrated its ability in many road maintenance projects, mapping the asphalt thickness, fractures in asphalt and sub-grade structures.

In ancient monuments, stone building block deterioration, abrasion and chemical wear, are major concerns. Sometimes radar can aid in determining the interior status of the structure, for example decide if certain sections are damaged or not. An example of such a measurement is the georadar tomography test at Hamar Cathedral ruin, where 1.5m diameter stone pillars were checked for faults by radar screening, producing horizontal tomography sections/slices of the pillars, Kong & By (1995). An example of an interpreted tomography image from the cathedral pillar test is shown in figure 8. Here we can see that the pillars consist of several stones, and that parts are apparently damaged.

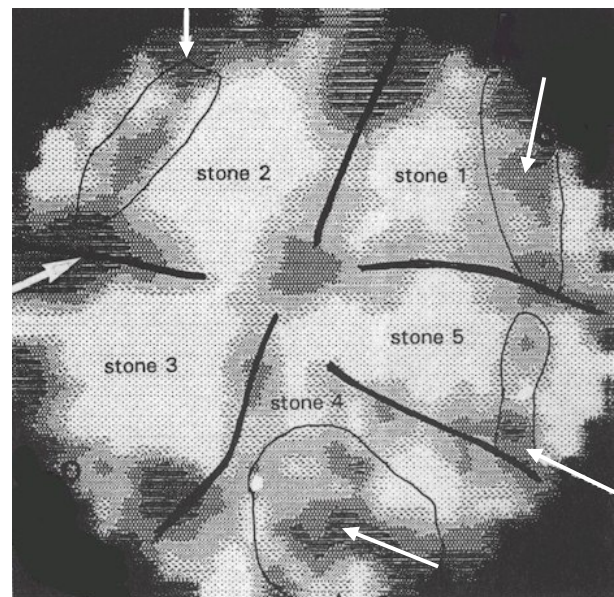


Figure 8. Interpreted radar tomography image, horizontal section of a 1.5m diameter stone pillar at Hamar Cathedral ruin. White arrows mark damaged areas, black lines mark stone joints.

2.6 Buried objects and cavities

Mapping subsurface cavities is an important problem. Examples of cavities are dissolved limestone (Karst), soil sinkholes, old mining excavations and tunnels. Whether radar is a suitable tool for cavity mapping or not, depends on parameters such as the size of the cavity, the material properties of the soil or fluid fill, the position of the cavity relative to the georadar antennas, and the properties of the surrounding rock/soil. In cases where the overburden soil is relative conductive, as in clay, georadar measurement from surface would probably not give good results. In such situations, crosshole radar tomography may be the only choice with reasonable success potential. This method needs boreholes on opposite sides of the expected cavity. The optimum

distance between boreholes depends on the geological conditions. If the surrounding rock/soils are conductive (i.e. attenuation is high) and/or the cavity size is small, the distance between the boreholes should be small. We normally do not recommend a borehole distance greater than about 5 to 10 times the cavity size in any instance. In conductive soils, the distance should be less. One may argue that such a survey geometry is not very efficient. In reality however, there may be no alternative methods.

In addition to ordinary cavity mapping projects, NGI has experience from mapping cavities and other “isolated” buried object from several controlled field experiments, where the cavity size and locations are known in advance. Such experiments are very important in order to understand the possibilities and limitation of the methods. Figure 9 shows a radar diffraction tomographic image from a controlled field experiment mapping a tunnel between two boreholes at Gjøvik Norway, Kong et al. (1993). The surrounding rock is gneiss and the distance between the boreholes is about 25 meters. The tunnel, which is empty (air-filled), is about 8 meters in diameter. In the tomogram the tunnel is imaged as a low attenuation, high velocity area (light areas on the figure).

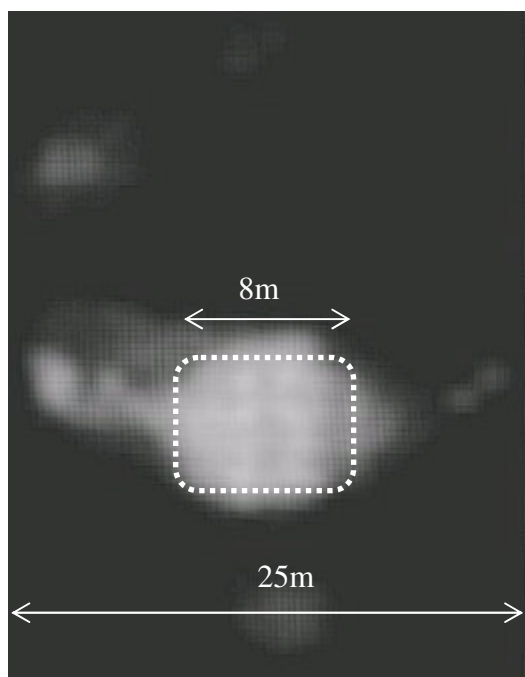


Figure 9. Cross hole diffraction tomography image of an 8m diameter tunnel, field test at Gjøvik Norway.

As an example of a successful cavity-mapping project, we mention a karst cavity project in Gua Musang, Malaysia. Here cavities were expected in the upper part of a limestone section overlain by clay. Drilling showed that most of the cavities were filled with clay/soil. The radar crosshole tomography investigation therefore showed cavity structures as a high attenuation area relative to the surrounding limestone. The borehole distance was about 20 me-

ters and a total of about 70 sections were investigated. Cavities were found in more than 10.

3 RESOLUTION, ACCURACY AND CLIENTS EXPECTATION

The accuracy and resolution in georadar investigation vary considerably. It depends on local geological conditions, radar equipment used, survey geometry, number of calibration points (e.g. at boreholes if available), and interpretation tools and skills. The expected accuracy in depth estimation for good quality georadar data is normally better than 10% of the depth. The resolution, in the sense of the minimum target size which can be detected, could also be about 10% of the target distance from the transmitter/receiver antenna, assuming that the target is a moderate strong reflector. In monitoring mode, when recording changes from the initial conditions, the accuracy will be better.

Radar mapping is both fascinating and frustrating in the sense that it is hard to predict the outcome of an investigation in an unknown area. If a test survey is not possible, knowledge about the local geological condition should be acquired and evaluated by experienced geophysicists in advance to predict the georadar performance. In addition, where budget allows, we recommend performing radar data modeling to calculate the expected range, resolution and accuracy more precisely. Modeling means simulating the radar wave propagation in the computer to calculate synthetic data for the survey type and geometry in question. NGI has developed user-friendly finite difference time domain software, which calculate the EM-wave field for any models.

In case where the local georadar performance is not professionally evaluated in advance, there is always a chance that the results will be disappointing. Our opinion is that serious professional georadar contractors would and must inform potential clients about the risks and expected performance of a georadar investigation prior to the survey. This is the only way georadar investigation can maintain its reputation and develop further into new areas of application. Today georadar is the most accurate and highest resolution geophysical method available for shallow subsurface mapping in a whole range of geological conditions and the method deserves a prominent position also in the future.

4 FUTURE DEVELOPMENT

As technology continues to advance, new possibilities emerge. Compared to other geophysical methods, georadar is a “recent” technique and rapid development would be expected. Today’s equipment is

relatively costly, a fully equipped unit costs around USD 50.000. As digital electronic components fast become cheaper and more powerful, the price of georadars will also continue to drop. At the same time, the units will become more powerful, offering multi channel recording at high speeds, reducing the survey time and improving the data quality. Improved integration with accurate positioning technology, such as GPS, will continue, allowing for more data to be acquired in less time. 3D mapping will become more common, and data processing and visualization techniques will improve the georadar image and interpretation of the subsurface.

As equipment becomes cheaper, radars dedicated for monitoring purposes would be more common. At present NGI is working on development projects for the oil industry using radar technology for downhole monitoring of hydrocarbon reservoirs during production. Today such equipment would probably be too expensive for most engineering and environmental monitoring purposes, but as equipment prices drop, similar systems could be installed for example in monitoring of leakage in dams, integrity of constructions, frost crust development in soil reinforcements work, leakage of buried tanks and under garbage dumps. Radar for monitoring snow thickness in avalanche areas exists already, but will be more common in the future.

5 CONCLUSION

The performance of georadar as a high-resolution subsurface mapping tool has been demonstrated by NGI field examples. In non-conductive and homogeneous ground conditions, georadar performs very well and detailed pictures of the subsurface can be reconstructed. In more conductive materials, such as marine clays, or in very inhomogeneous conditions, the range and resolution becomes very low and the method is generally not recommended. To avoid disappointing results, the expected range, accuracy and resolution should be evaluated before proposing a survey in new areas. The georadar method, which in favorable conditions is today's most superior shallow subsurface mapping tool, will continue to develop fast, resulting in cheaper equipment, faster data acquisition rates and improved data quality.

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