Development of a geophysical method for quantitative risk assessment

Innovative methods for the quantification of mine tailing in roads

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Beneficiary: Actief Bodembeheer de Kempen

Beneficiary:

Introduction

Risk assessment of polluted sites asks for objective and quantitative methods for site investigation. Small sites are often mapped by coring, sampling and successive laboratory analyses used for the assessment of chemical pollutants. For larger sites, sampling is virtually impossible because of time and costs involved whilst geophysical mapping systems give only a qualitative image of the site of study. This qualitative image is often not suitable for a quantitative risk assessment and decision making for local authorities.

We have managed to developed a strategy for quantitative, spatially-detailed mapping of zinc concentrations originating from mine tailings (zinc slags) distributed over an area of 2.600 km^2. The results of this mapping allow for calculating direct risks related to health, risks related to leaching to groundwater, and as a result a ranking of the various sites in terms of priority for remediation.

The area “De Kempen” in the Netherlands and Belgium, was well known for its production of zinc from ore delivered from all places over the world. In the process of zinc production, zinc is removed from the ore and the remaining waste product is zinc slag. This zinc slag is light, and contains high concentrations of all types of heavy metals. Until the 1970’s these zinc slags were spread all over De Kempen in to improve public and private roads. The potential ecological risk of the heavy-metal containing asks for measures to remediate these zinc slags.

One of the major challenges in the pollution problem of zinc slag in “De Kempen” is in the estimated area of 2.600 km^2, charged with heavy metals from the zinc industry. This large area is a potential hazard giving problems to ground water, or possessing treats to human health. However, mapping this potential hazard by traditional sampling methods was impossible due to lack of financial resources and time involved. Given the size of the area, there is an apparent need for a rapid, synoptic method to locate the zinc slags. When information is available, public can be informed on risk involved and measures that will be taken.

Figure 1: overview of the study area (in green), 2.600 km² located in the southern part of the Netherlands.

A project for "Applying a geophysical technique for the verification and quantification of zinc slags in roads in De Kempen" was commissioned by ABdK, in cooperation with the provinces of Noord-Brabant and Limburg and the the Ministry of Housing, Spatial Planning and the Environment (VROM) in The Netherlands. This study aimed at the development of a method by which the presence or absence of zinc slags in the roads of De Kempen can be quantified and verified. Initially the study focused on four municipalities in the Kempen in Belgium and in the Netherlands: Lommel, Overpelt, Cranendonck and Reusel De Mierden. In a later phase 31 municipalities were added to the project, resulting in a study of more than 1.200 km of investigated roads.

Approach

In the project, we used an iterative approach where geophysics was use to locate samples. These samples were used for calibration and quantification. Geophysical methods were used to map the roads of interest (1 in Figure 2). These results were searched for anomalies in the road constructions (2 in Figure 2) and were used to ‘zone’ the roads in areas with similar characteristics (3 in Figure 2). Within these zones, samples were taken that were used for validation (4 in Figure 2).

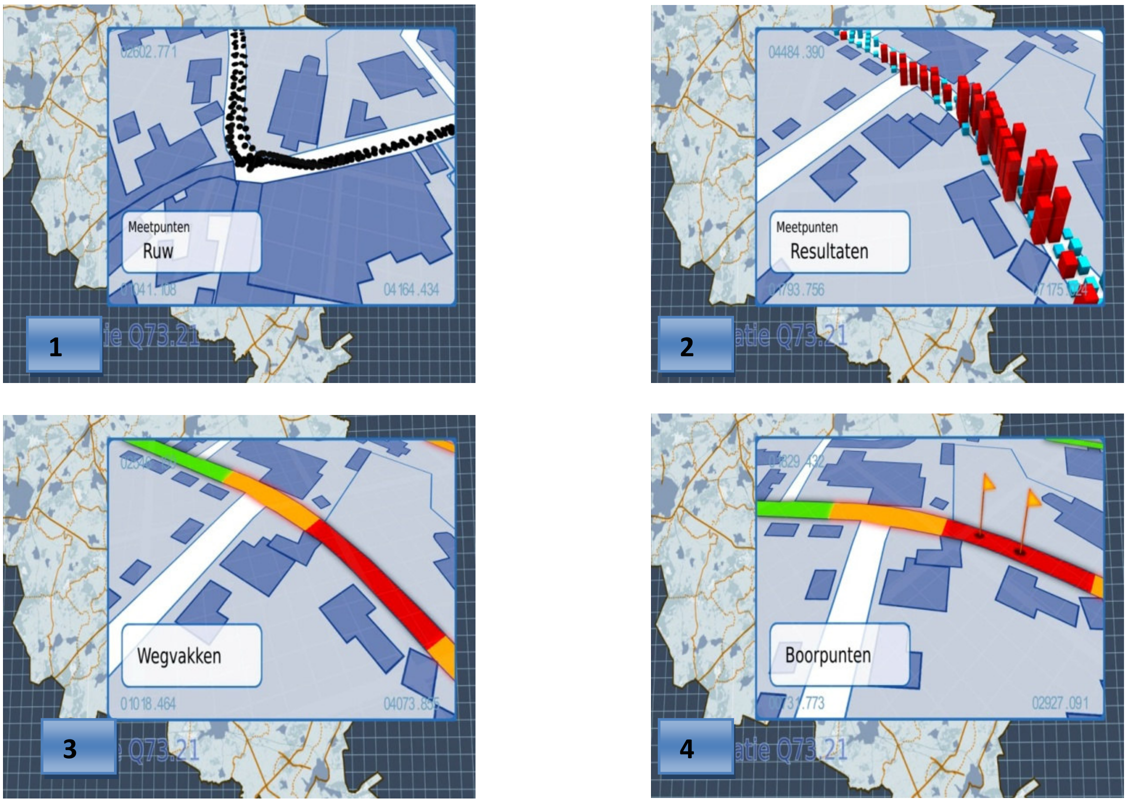

Figure 2: overview of the approach used in the project

Geophysical technologies

Gamma spectrometer

Since the mineral composition of ores will differ from the mineral composition from the soils in De Kempen area, we expect that the concentrations of natural occurring radionuclides will also differ from the soils found in the area of study. Therefore, one of the main parameters used in the pilot, was the concentration of radionuclides measured with a gamma spectrometer. In this project we used the gamma spectrometer as a geochemical tool, which passively measures material properties in the field (the concentration of K, U and Th). Exactly the same measurement that is done in the field can be repeated on samples in the lab. This allows for setting up a physical model relating radiometry and other material properties (texture, chemical properties) in the lab. This model can then be used to translate the field measurements into the wanted soil property.

The reduction of the measured spectral information into concentration of radionuclides, is mostly done using the Windows analysis method (Grasty *et al*, 1985). In Windows, the activities of the nuclides are found by summing the intensities of the spectrum found in a certain interval surrounding a peak. In “classic” windows, three peaks are used to establish the content of ^{232}Th, ^{238}U and ^{40}K. A major flaw of the Windows method is the limited amount of spectral information that is incorporated into the analysis. Another weakness is the inherent use of ‘stripping factors’ to account for contributions of radiation from nuclide A into the peak of nuclide B. Our system incorporates a different method to analyze gamma spectra. In contrast to the “Windows” method described before, our Full Spectrum Analysis (FSA) method incorporates virtually all of the data present in the measured gamma spectrum. In FSA, a Chi-squared algorithm is used to fit a set of “Standard Spectra” to the measured spectrum. The fitting procedure yields the multiplication factors needed to reconstruct the measured spectrum from the standard spectra of the individual nuclides. The multipliers equal the actual concentrations of the radionuclides that led to the measured spectrum. The method is described in detail in Hendriks *et al* (2001) and Koomans *et a*l (2008). Hendriks *et al* (2001) shows that the uncertainty in the FSA method is at least a factor of 1.7 lower compared to the Windows method.

Figure 3: Spectral gamma sensor mounted on the front of the measurement vehicle.

To determine if natural radioactivity can be used as a proxy for the presence or absence of zinc and zinc slags, 300 soil samples from the area were analyzed on both their content of the naturally occurring radioactive elements Uranium-238 and Thorium-232, and zinc / zinc slags (Figure 4). This study showed irrefutably that such a relationship exists: samples that contained zinc slags are also enriched in uranium, and the ratio between the uranium and thorium deviates from 1 (the background ratio found in “clean” samples). These radiation measurements are not only limited to laboratory situations. Using modern equipment, the concentration of radionuclides can also be determined quantitatively in the field (Figure 3), in this case on the roads crossing De Kempen. Using such non-invasive field measurements and a geochemical model relating radiation and pollution, predictive maps could be made of the zinc slag enriched areas (Figure 3).

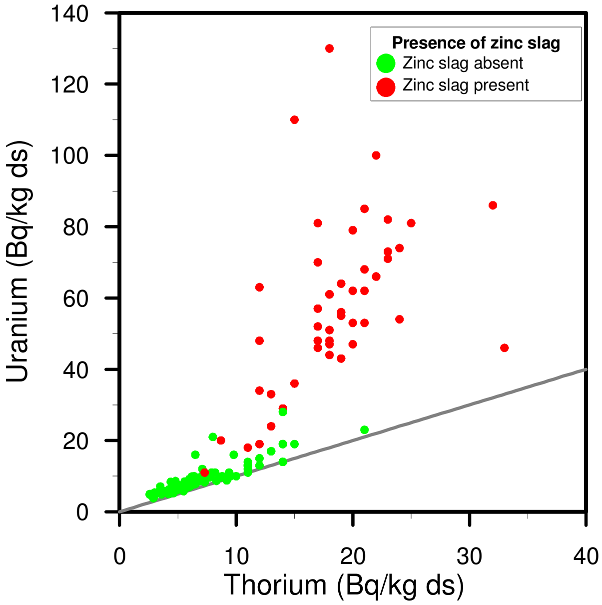

Figure 4: Scatterplot of uranium vs. thorium for zinc slag containing material and material that does not contain zinc slag.

EM

EM fingerprinting complemented the GPR and radiometric fingerprinting techniques. Most construction materials used for pavements including bitumen, asphalt and concrete are highly electrically resistive. An electromagnetic fingerprinting investigation was a key part of the overall investigation strategy. Slags/ashes are generally electrically conductive due to metal content and associated weathering products. When sufficiently thick within a resistive host, zinc slag/ash can be detected by measuring apparent electrical conductivity from electromagnetic profiling. This measurement is largely derived from the quadrature[1] component of the transmitted and received electromagnetic energy. For most geological materials, the signal received from the ground is largely quadrature in nature.

For this investigation, that part of the signal 180 degrees out of phase (termed ‘in-phase’) was also measured; such a component can usually only arise from the presence of very good electrical conductors, such as metals.

In the presence of zinc slag and ignoring buried rebars, EM profiling yielded an anomalous in-phase response (equivalent to a several parts per thousand change) that was invariably coupled to elevated conductivity values, providing a strong diagnostic for the presence of slag/ash. Electrical conductivity alone did not provide a unique diagnostic owing to the presence of other conductive media such as rebars, bricks, moisture and clays within the subbase materials.

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[1] Quadrature means that the measured electromagnetic signal is time-delayed by a shift equivalent to ninety degrees or about ¼ of a cycle.

Figure 5: the EM sensor is mounted behind the vehicle in a non-conductive carriage.

EM fingerprinting is clearly demonstrated in the examples below. Zinc/ slag/ash is present below the leftmost and rightmost thirds of the example profile.

The top plot shows a null EM in-phase response over the section free of slag/ash and a generally low conductivity response. Over the sections of slag/ash, the in-phase response profile shows significant deviation from the null response and conductivity values are generally elevated.

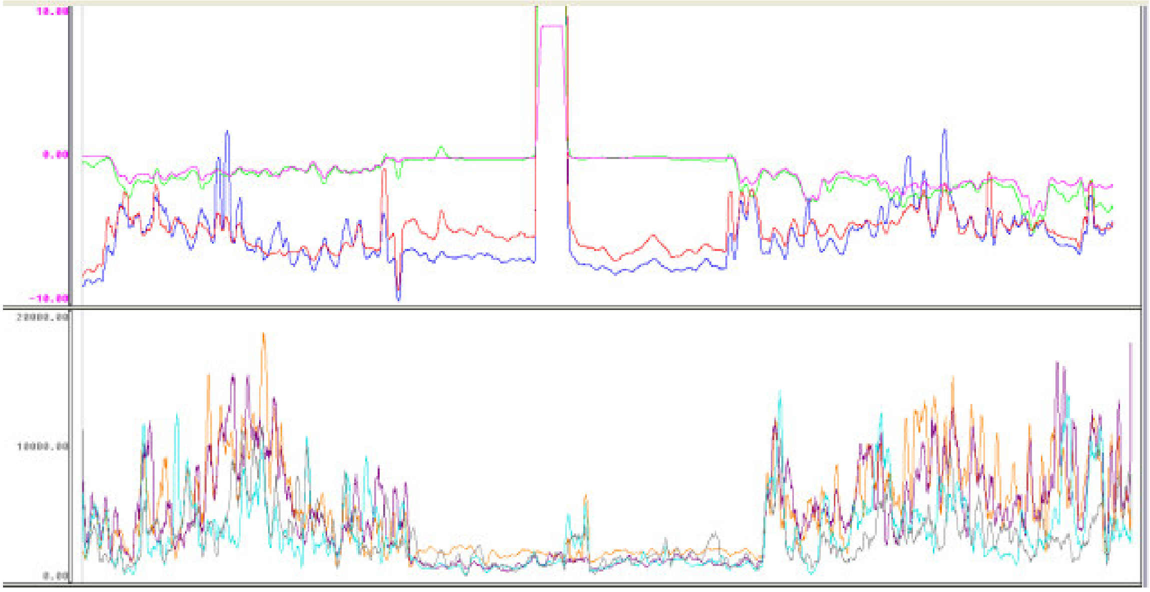


Figure 6: the top plot shows the EM in-phase response over the section. The lower plot shows the conductivity values.

GPR

GPR fingerprinting complemented both the radiometric and electromagnetic fingerprinting techniques.

The high resistivity of common pavement materials such as bitumen, asphalt and concrete allows the propagation of radar energy into the pavement structure. Where the propagating energy encounters changes in the (dielectric) properties of the ground, then energy is reflected back to the surface. Pavement structure evaluation is a very common GPR technique. When radar energy encounters a material with a very high capacity to hold electrical charge, then the material can behave like an antenna, the result being a characteristic ‘ringing’ appearance. The most common ringing phenomena are associated with the presence of surface or buried metal. For this investigation zinc slag, depending upon its specific composition, either generated a very strong reflection event or was characterised by ringing. In order to diagnose the presence of slag/ash it was necessary to a) determine anomalous increased average reflection amplitude and b) determine those locations where ringing was visually present.

Figure 7: the GPR (black box under the car) is mounted under the vehicle.

GPR fingerprinting is clearly demonstrated in the example below. Zinc slag / zinc ash is present below the leftmost and rightmost thirds of the example profile.

The plot shows subdued GPR reflection amplitude over the central section free of slag/ash, but significant reflectivity over those sections underlain by slag/ash.

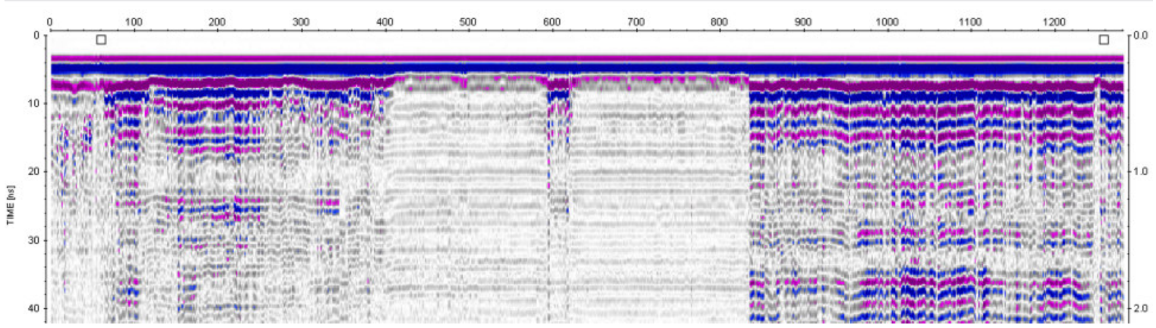


Figure 8: radargram of GPR measurements over a road section. The 'ringing' of the signal on the side of the figure points to the presence of zinc slag.

Setting up a database and validation

The data from the geophysical sensors provide each information on the presence and on the concentration of zinc slag at individual datapoints or sections of road. Based on these results the roads are classified in sections where:

- Zinc slags are below detection limit
  (and where zinc slag is probably not present)
- Zinc slag is heterogeneously present
  (with an average concentration of zins slag for the section of road)
- Zinc slag is homogeneously present

Together with additional information on pavement type, classification of verges, photo's of the road and other GIS based information, the classification of the road sections is placed into a GIS database. In addition, each section of road is ranked on its accuracy by the number of geophysical sensors that point to the presence of zinc slag.

To verify the results of the geophysical mapping, samples from corings have been used for validation. In total 1.472 corings were taken and 8.697 samples were measured on its concentration of zinc by hand-held XRF systems. These results were compared with the outcome of geophysics and are presented in a false-negative and false-positive diagram (Table 1).

These results (Table 2) show that the presence and absence of zinc slag can be mapped with the geophysical methods used.

Table 1: Definition of false negatives and false positives in statistical research.

		Corings	
		Zinc slag not present	Zinc slag present
Geophysics	Zinc slag not measured	True negative	***False negative***
	Zinc slag homogeneously present	***False positive***	True positive

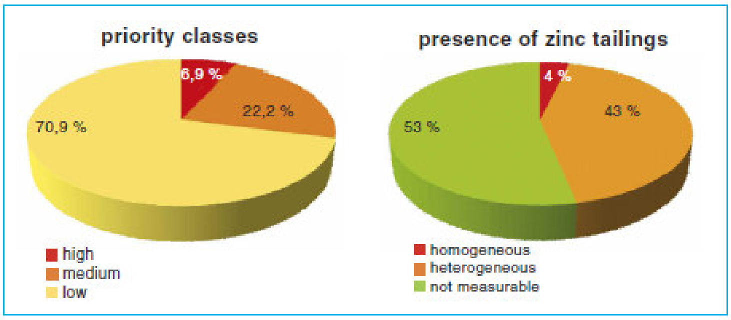
Table 2: determination of the percentage false positives and false negatives of the geophysical investigation

		Corings	
		Zinc slag not present: 100 %	Zinc slag present: 100 %
Geophysics	Zinc slag not measured	True negative: 92 %	***False negative:*** **5 %**
	Zinc slag homogeneously present	***False positive:*** **8 %**	True positive: 95 %

Using the database for a quantitative risk assessment

Ranking on health risk

All information from geophysics and field inspection was placed into a database and connected to a GIS. This dataset was combined with other geographically distributed information as soil type, distance from natural reservation areas, distance from urban areas. A GIS analysis based on this dataset led to a ranking of road sections on their potential risk to human health. From the sections with a high risk, the costs of remedation were determined. This risk based approach reduced the size of the problem in a way that remediation becomes feasible.



Development of an area-specific concentration profile

The ultimate goal of ABdK in the project, was to determine potential risk for leaching for each section of road containing zinc slag. Based on the risks for leaching a model to determine the site specific remediation depth has been derived from the database. Traditionally, groundwater sampling studies are used to determine these risks. In our project, we managed to combine spatially detailed information from the source of zinc (the amount of zinc slag measured by geophysics) with spatially detailed information of soil properties (e.g. acidity of soil) in a area-specific concentration model. The model describes the relation between the zinc load of the zinc slag on one hand and the relation between zinc concentrations in the soil and and pore water on the other hand. These relationships are based on a Freundlich-equation, which describes the relation between a concentration of zinc in the soil and general soil properties (e.g. pH, organic matter and clay content and zinc load of the slag). The relation between zinc load of the slag and the zinc concentration in the soil is derived by 20 sample locations. The relation between zinc concentration in the soil and the concentration in the pore water is taken from a general model including the area-specific soil properties. The calculation of the remediation-depths on a detailed scale was not possible without the geophysical measurements.

Conclusions

The project " applying a geophysical technique for verification and quantification of zinc slags in roads in De Kempen" shows how geophysical mapping methods can be used to derive *quantitative* information on the distribution of heavy metal pollution in a large area. The approach of combining different technologies and using ‘traditional’ corings for a thorough calibration of these technologies shows that the results are up to par with an approach of ‘traditional’ sampling but at a much lower cost.

The uniqueness of the project is though not only in the technical part of geophysics, but also in the use of the information. The outcome of the mapping has been used to determine risks on human health and risks for leaching at high spatial scales. This detailed investigation helps the government to prioritize remediation actions and gives society direct information on the risks involved.

References

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