Geophysical investigation on recultivated opencast mining areas

Zsolt Prónay
MinGeo Ltd., Budapest, Hungary, zspronay@mingeo.hu
Péter Nagy, Endre Törös, Bence Solymosi, Csaba Hegymegi

ABSTRACT: Kőbánya is the 10th district of the Hungarian capital, Budapest. The name means quarry showing the importance of this region up to the end of the 19th century. Not only limestone was exploited at the location but clay as well witch was excavated from pits up to the depth of 20 m. Later on the pits were filled by communal waste and debris. Most of the former opencast mines are parks now but some parts are industrial or residential areas.

The remains of ancient mining activities cause great problem for the city. Subsidence and collapses are everyday incidents and the decomposition of organic waste generates dangerous gases. All of them can endanger properties or even human lives. For this reason, Kőbánya is frequently investigated by different geotechnical and geophysical methods (mostly seismics, geoelectrics and GPR).

The main tasks for geophysics are:

- delineation of the pit (horizontally and vertically)
- characterizing the filling material (mechanical properties)
- weak zones (possible locations of subsidences and sinkholes)
- describing the material and the conditions of the bedrock (limestone or clay, watertight or not)
- presence and distribution of gases

In the presentation the use of different geophysical methods for solving the listed problems and the results delivered by the applied geophysical methods will be demonstrated.

Keywords: open pit mine; subsidence; sinkhole; urban area; geophysics

1. Introduction

For more than a century, Europe has been deposited its unwanted waste materials in landfill sites. There are more than 500,000 of these sites in the EU [1].

Kőbánya is a district of the Hungarian capital, Budapest. The name means quarry showing the importance of this region up to the end of the 19th century. Not only limestone was exploited at the location but clay as well witch was excavated from pits

In former times the sinkholes and subsidence happened at Kőbánya were handled immediately, the causes were clear, the remains of old mining activity, cellars and backfilled opencast mines. Later on, with the increase of traffic and load, more detailed investigations were required. At this point geophysical methods came into view. Since 1993 we are present at the site and many geophysical techniques were applied to solve different problems [2]. After a deadly accident in 2009 two pits were investigated in detail and the work on the others are still ongoing. Until now three waste disposals were investigated in detail.

Obviously seismic methods (refraction, diving wave tomography and MASW) were used to investigate the mechanical properties of the waste body and to delineate the pit itself both in vertical and horizontal direction. DC resistivity was applied to get information about the substrata and its moisture content. Resistivity was employed for delineating the pit as well. GPR was used to investigate the situation below roads and pavement and to detect if utilities are distorted or even broken by the irregular compaction of the fill. Microgravity was applied to map loose zones or underground voids.

1.1. Study area

At Kőbánya the bedrock is Sarmatian (Middle Miocene) limestone followed by 10-15 m Pannonian (upper Miocene) clay and cowered by 1-10 m fluvial sand and gravel. Adapting to the geological setting the depth of the pits are 10-25 m, while their extent can be up to 1000*800 m.

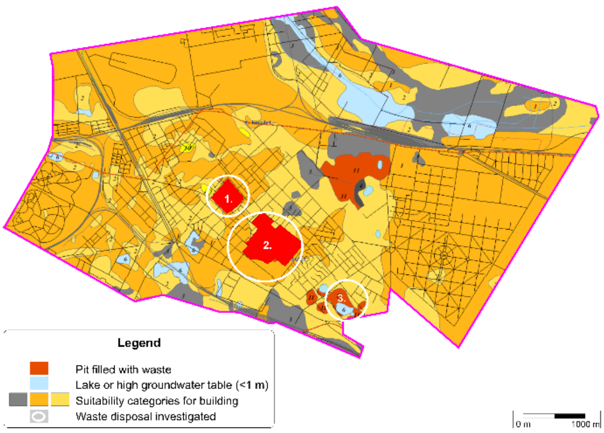

Figure 1. Abandoned pits filled with waste at Kőbánya

At the end of the 19th century more opencast mines and 8 brickyards existed in the area providing building material to the rapidly growing capital. The last opencast mine was closed in 1996. Fig. 1. shows the modified suitability zonation map of the district [3]. Corrections were necessary because the outlines of the waste filled pits are marked by red polygons. Lakes are the remains of old mine works as well but for some reason they were not filled in. White circles with numbers mark the waste pilled pits that were investigated in detail by geophysical methods.

Figure 2. Photo of a pit with ten story houses in the background (location No. 2)

To imagine the dimensions of the abandoned pit, a photo of it in its prime with ten story buildings in the background is presented on Fig. 2.

The pits were later filled by communal and industrial waste, debris, and even slag, later on it was simply covered by humus. Now there are mostly public parks over the pits but some parts of them are industrial or residential areas.

1.2. Tasks and methods

The first parameters of interest are the extension and depth of the pit which determine the volume of waste buried. The outlines are important for determining the distance between pit and surrounding buildings for stability calculations. The thickness and mechanical properties are also important to take the compaction into account. Seismic methods are suitable to deliver the required parameters. In most cases, waste material is characterized by low densities and low seismic wave propagation velocities. The internal variation of the waste can be characterized by multielectrode resistivity sections. Resistivity decreases by increasing moisture content and by the increase of temperature resulting from biodegradation of the organic waste. In most cases the electrical resistivity is low, due to the high electrical conductivity of the leachate.

Seismic and electric parameters are generally in contrast with the characteristics of the surrounding environment, so those geophysical methods can be used to characterize landfill geometry (size, shape and volume) and the internal characteristics of the waste mass (composition, humidity, temperature, compaction, density).

The heterogeneous material and hence the compaction of waste influences the seismic parameters: the higher the compaction rate, the higher are the wave velocities. In unsaturated solid waste P-wave velocities are between 180 and 700 m/s. In saturated medium the velocity is slightly larger or equal to the P-wave velocity in water (1450 m/s) [4-6].

In the unsaturated zone, the electrical resistivity is generally expected to be >30 Ωm, except in the presence of metal objects or ashes, while in saturated media the electrical resistivity of waste is generally between 0.5 and 30 Ω.m [4,7-9].

For characterizing the bedrock its material and the conditions of it is important. Fractured rock can leak pollutants to the groundwater while clay can seal it. Separating clay and rock is a classical geoelectric task but below groundwater table resistivities show little variation although the fractured rock and clay have quite different electrical characteristics (matrix resistivity) [4,10]. In that case seismic methods can help but only if the P-wave velocity of the refractor is much higher than the velocity of the water and offsets are great enough to distinguish layer velocities. S-wave seismic can overcome this problem.

Delineating weak zones where collapses and sinkholes are more likely to form seismic methods are essential. In that case the favorable propagation characteristics of surface (Rayleigh) waves can be utilized. This means that due to less attenuation, comparing to body waves (inverse square root vs. inverse square of the distance), [11,12] smaller energy sources can be applied preferably a sledgehammer.

The presence and distribution of gases can increase DC resistivity but it is not possible to separate this phenomenon from other factors. The ratio of seismic P- and S-wave velocities (v_p/v_s) is a promising method to trace gases in the unsaturated zone. Since a gas and a liquid can transmit compressional waves but not transversal ones practically only P-wave velocity is affected by their presence. The v_p/v_s distribution can be interpreted in terms of water or leachate bearing (high v_p/v_s) and gas bearing (low v_p/v_s) zones [4].

2. Results

In the following chapters the use of geophysical methods to solve geotechnical problems related to abandoned opencast mines will be illustrated by case histories.

2.1. Delineation of a pit

Due to low attenuation surface waves are proper tools to map velocity changes in bigger areas. Rayleigh waves can be generated even by a single horizontal hammer blow and can be recorded by low frequency vertical geophones. This is just the setup of a normal P-wave measurement so surface waves can be recorded together with refraction or reflection profiling, as a byproduct. Covering the area of interest by a set of parallel lines and a similar set perpendicular to the first one can produce high resolution tomographic image of the near surface. The Rayleigh wave velocity map of a small part of location No. 1 can be seen on Fig. 3. Surface wave tomography is well suited to delineate the horizontal extent of a landfill having strong velocity contrasts between the waste mass and the natural formation.

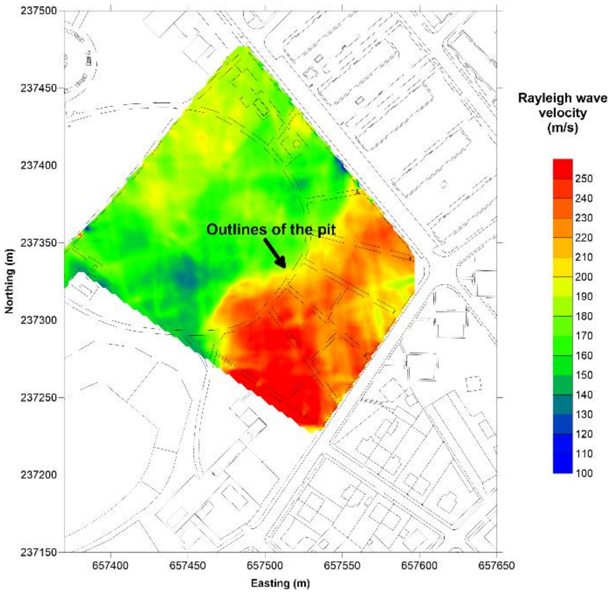

Figure 3. Delineation of a pit by surface wave tomography

Applying refraction method by dense source spacing (sources at all geophones) diving wave tomography can be measured. Diving or turning waves are generated when the velocity is increasing with depth. It has the same advantages and limitations as refraction but the velocity model is more sophisticated no abrupt change in velocity between the layers is required. Fig. 4 shows the results of diving wave tomography over a backfilled pit. The velocity changes at the bottom of the pit is clearly visible.

Using a set of multielectrode geoelectric measurement the pit on the location No. 2 can be delineated in both horizontal and vertical direction. The results can be seen on Fig. 5 in the form of a fence diagram. The bottom geometry and the depth of the landfills has been successfully estimated with ERT (Electric Resistivity Tomography). However, difficulties in estimating the exact thickness of the waste can be problematic because of the loss of resolution with depth. On ERT sections the layer interfaces are always smeared because of long distances between electrodes comparing to depth. With the equivalence phenomenon in view it is ambiguous to evaluate resistivity sections without borehole information. Borehole data are represented by blue (clay) and yellow (waste) cylinders on the figure.

The area covered by geoelectric measurement is about 650*500 m and the maximum depth of the sections is 60 m. The resistivities vary between 10 (dark blue colors) and 120 Ωm (red colors).

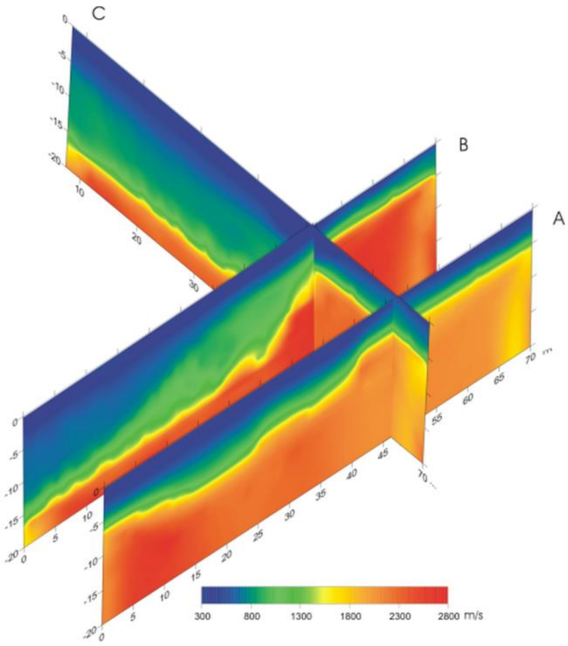

Figure 4. Delineation of a pit by diving wave tomography

2.2. Characterizing waste body

Filling material is always imaged when investigating the vertical extent of a waste disposal because seismic waves and currents cross it on their way to the bottom. The main task to characterize the filling stuff are the investigation of the material itself and its mechanical properties. Electric resistivity is influenced by the moisture content, pore fluid conductivity and waste temperature. Those parameters often dominate the contribution of waste body for electrical properties and control the distribution of the electrical resistivity of the waste itself [4]. Resistivity is influenced by more parameters and they are not separable, for that reason geoelectric methods can be used to interpolate or extend parameters known from boreholes. The main task for solely geoelectric methods can be the investigation the existence and continuity of clay top sealing of the waste. Some features of the internal structure of the waste can be seen on Fig. 5 as well as the distribution of leachates.

Seismic method cannot give direct information about the composition of the filling material as well as geoelectrics but it can deliver mechanical parameters of it, at least in the unsaturated zone, and the depth of the groundwater table. In lucky cases, when compaction is in direct connection with the deposited material e.g. concrete, the identification can be possible, but always preliminary information is required.

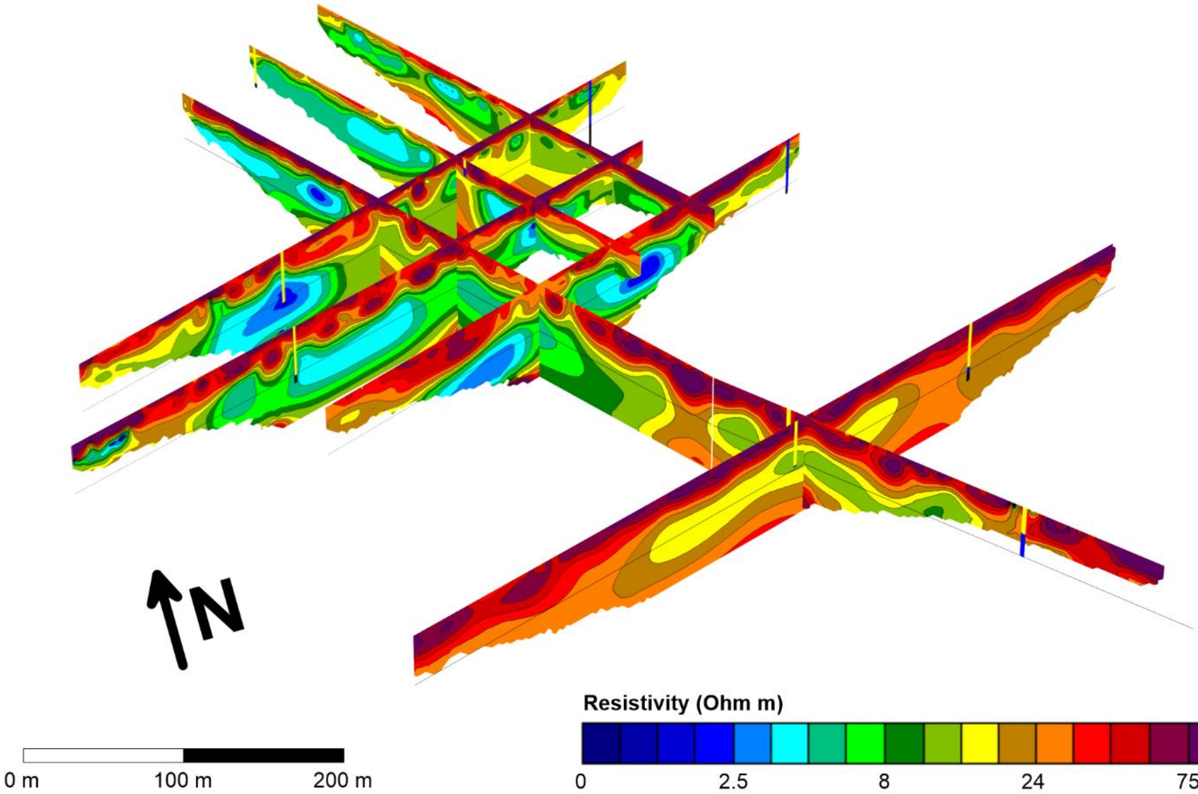

Figure 5. Delineation of the pit by geoelectric sections

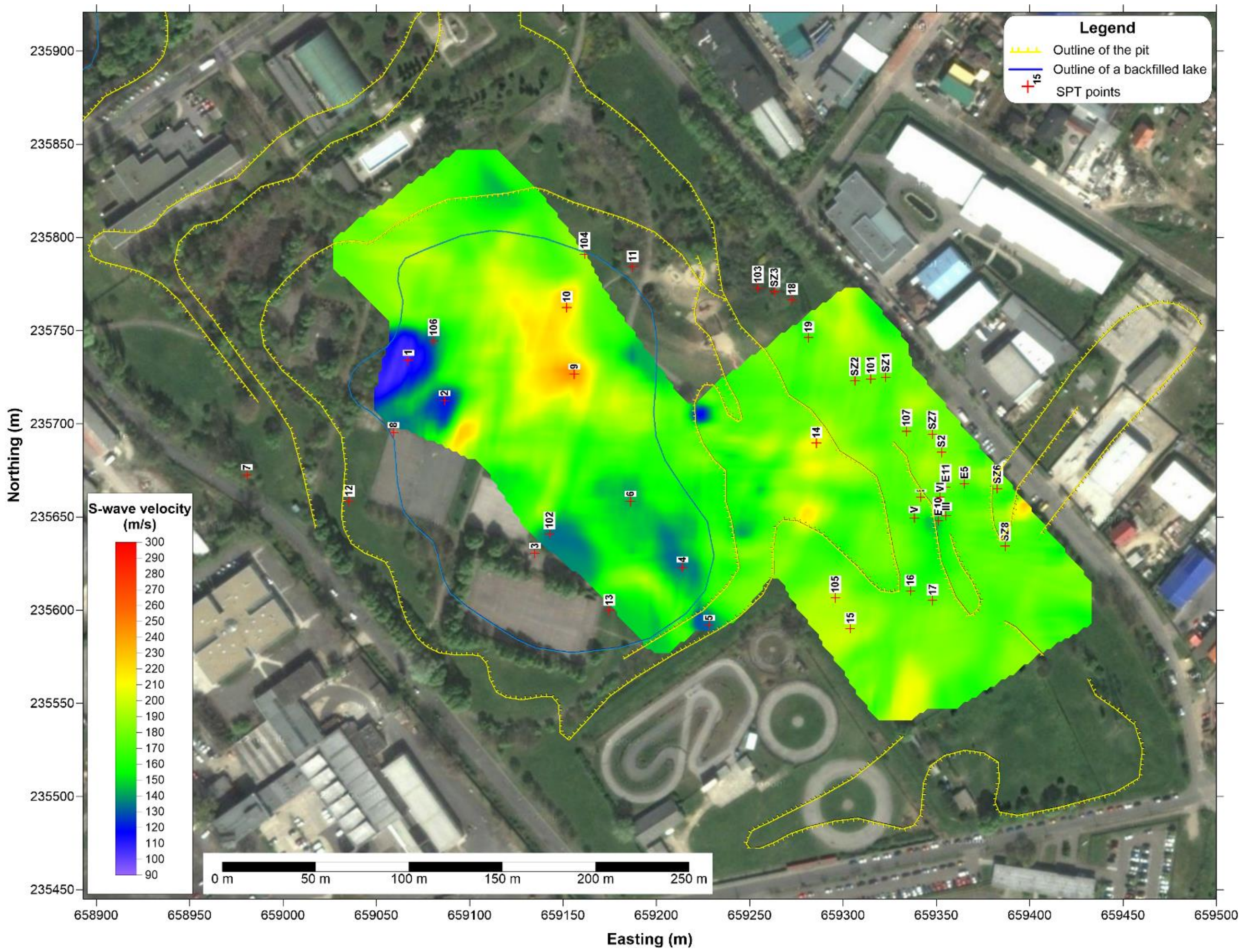

Figure 6. Mapping near surface anomalies by surface waves

The application of S-waves can help in the saturated zone because transversal wave velocities are not or only a little affected by the water content, even the groundwater table.

The mapping of near surface loose/weak zones, which can directly endanger lives and properties can be examined by using surface waves. Rayleigh wave velocity is very close, practically equal to S-wave velocity, for that reason the shear parameters of the top 5-6 m, which is essential in this task, can be investigated using them.

Using the spread and shot system described in Paragraph 2.1. with 40-60 m line and 2 m geophone spacing a relatively great, 450*400 m, area can be investigated in a short time. The resulted S-wave velocity map of location No. 3 is shown on Fig. 6 on a Google Earth satelite image. Low velocity (blue colors) loose, zones can be identified easily.

A few SPT soundings existed on the site but some more were completed on the velocity anomalies to prove interpretation. Two typical SPT N_{20} graphs are visible on Fig. 7. On the left hand side a near surface loose zone can be identified between 1.8 to 3.8 m, while on the right side a deeper one appiers near 6 m as well. Both anomalies are considered to be caused by the degradation of organic meterial. Loose zones were in good coincidence with surface wave velocity anomalies.

Other methods, like microgravity, elektromagnetics and magnetics can be hard to interpret because of the size and inhomogeneity of the waste, but for particular tasks they can be applied.

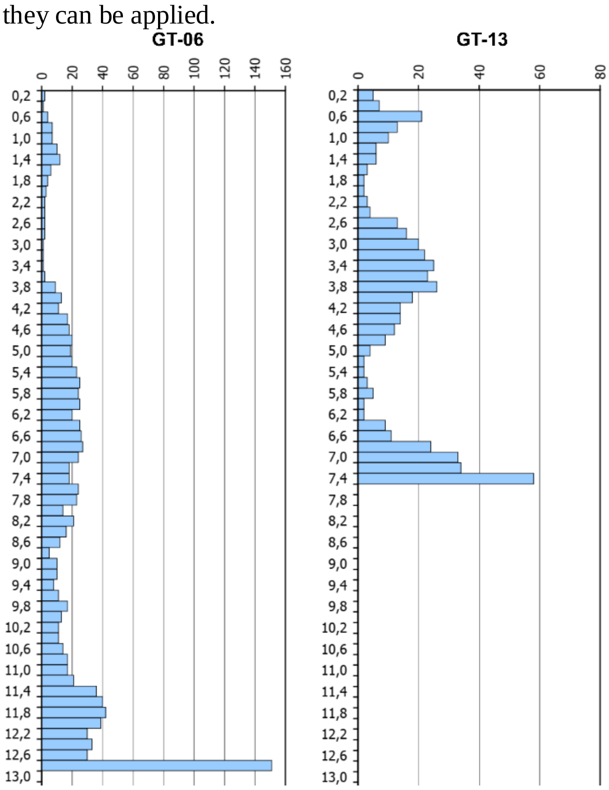

Figure 7. Typical SPT N_{20} graphs (N scales are different)

2.3. Bedrock

The geological setting and the material of the bedrock is very important to investigate the sealing on the bottom of the pit. In our case the bedrock can be clay or limestone. Clay is practically impermeable so it can retain leachates from polluting the groundwater while limestone, especially fractured one cannot seal the pit.

In the ‘60s and ‘70s communal and industrial waste was deposited to the pit No. 1, unfortunately just at the deepest part of it, where the limestone has no clay cap. From borehole data it is known that the groundwater table does not appear in the holes only polluted leachates were found.

Geoelectric measurements were not successful it could not separate clay and limestone on the bottom of the pit presumably because of the homogenizing effect of the high conductivity leachates on the resistivities.

From preliminary investigation we had some knowledge about the depth and location of clay deposits and the velocity of it. The assumption was that clay has lower velocity than limestone, but higher than water, in that way the spread of the two materials can be investigated by P-wave refraction. It was also supposed, that if water table exists in the pit, no higher velocity can be measured then 1500 m/s, then impermeable clay exists below or this is a soft clay layer. If water table exists, the location of the clay layer is correct, but the depth estimation is not.

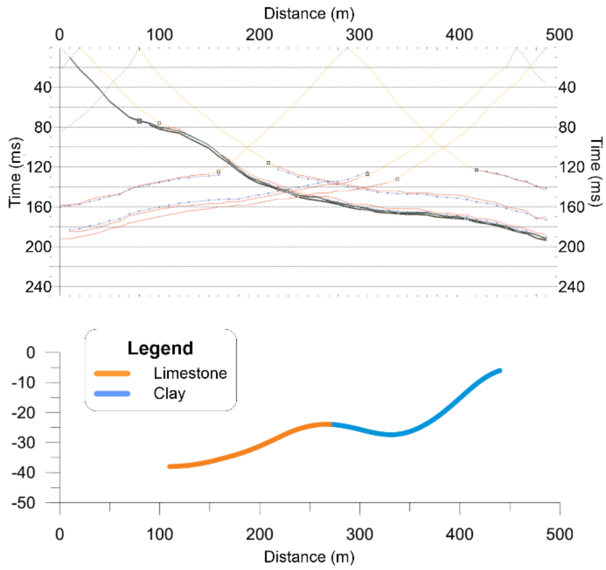

Figure 8. Refraction first break processing and interpretation

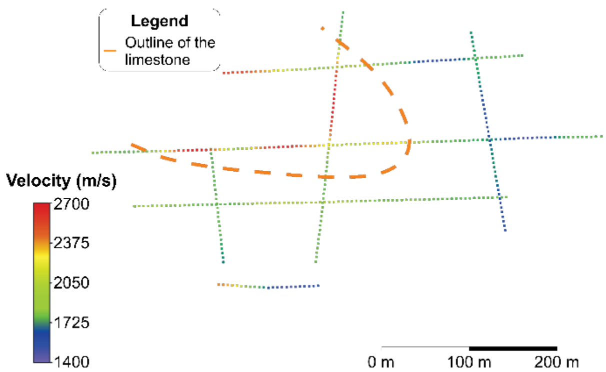

Figure 9. Final interpretation of refraction data showing outlines of the limestone

The overall thickness of the waste was expected more than 35 m. For the separation of the velocity of refracted waves arriving from water and clay long offsets were necessary. For the reason a seismic vibrator and a 260 channel telemetric data acquisition system was applied.

In total 219 geophones were planted on seven lines and 107 shot/vibrator points were used which means a very dense refraction system.

Fig. 8 top part shows a system of first breaks separated to layer data.The bottom part shows the result of GRM (Generalized Reciprocal Method) refraction processing together with the interpretation based on velocities. The outlines of the limestone are marked by dashed line on Fig. 9.

2.4. Gases

Gases are the product of the decomposition of organ materials. Methane is a poisonous and inflammable gas, so it is dangerous in two ways but it can be useful as well because it can be burned in small power plants to produce electricity as hot water. As mentioned before the ratio of P- and S-wave velocity is a good indicator for the presence of gas bearing zones. Because those zones are not layers, not all seismic methods can be used to detect them. In our case diving wave tomography was applied.

Fig. 10 shows P- and S-wave velocities, v_p/v_s and potential gas bearing zones characterized by low velocity ratio on the western part of area No. 1.

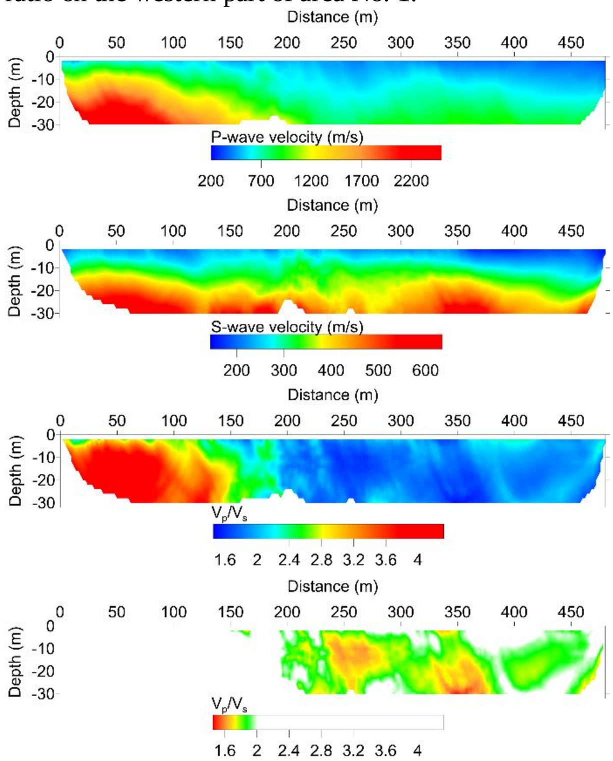

Figure 10. P- and S-wave velocity and v_p/v_s sections

Estimating seismic velocities on a set of lines the distribution of gas bearing zones can be identified. The results are shown on Fig. 11. The colors mean low v_p/v_s values, while white color means high velocity ratios which by great chance do not represent gases. The surface projection of the interpreted gas bearing zones are marked by red ribbons.

The results were proven by 24 boreholes and a drainage system was built to gather methane and a small power station is proposed to utilize the gas.

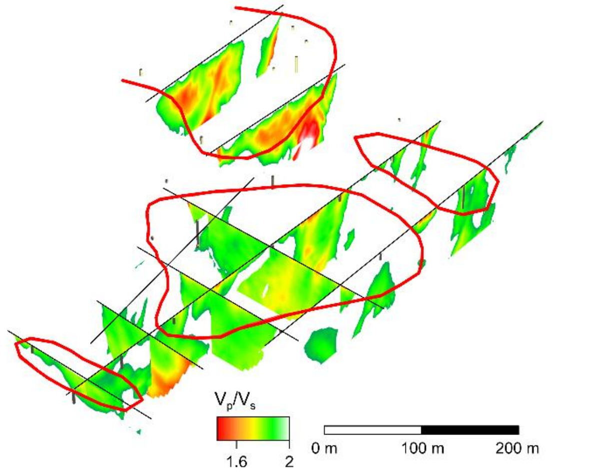

Figure 11. Gas bearing zones from v_p/v_s

The interpreted outlines of the gas bearing zones are displayed on the Google Earth satelite image as well. It is shown on Fig. 12. It is clearly visible that some of the zones are very close to, maybe spread below residential areas.

Figure 12. Surface projection of the gas bearing zones together with the seismic lines

3. Conclusions

For the investigation of abandoned pits filled with waste the main tasks are in general the horizontal and vertical delineation of the pit, the characterization of the mechanical properties of the bottom and the filling material and to trace the presence and distribution of gases and leachates. Geophysical methods are suitable to answer those question despite having many limiting factors. For that reason the careful selection of methods is essential. In many cases one method is not enough because all techniques measure different physical properties and one parameter can not characterize the whole waste disposal with plenty of problematic features. In the paper successful jobs were presented but in all cases multiple methods were applied and the best one was demonstrated for the selected task.

References

[1] Hogland, W., Hogland, M., Marques, M. (2011). Enhanced Landfill Mining: Material recovery, energy utilisation and economics in the EU (Directive) perspective. Proceedings of 2nd International Academic Symposium on Enhanced Landfill Mining, Belgium, 2011. pp. 209-222. https://doi.org/10.13140/RG.2.1.4576.9763

[2] Gőgh, É. "Pincekutatás mérnökgeofizikai módszerekkel a Budapest X. ker. Mádi u. 4-6. óvoda területén és a Maláta u. felőli környezetében", (Exploration for Cellars Using Engineering

Geophysical Methods at the Nursery-school at Budapest X. Mádi str. 4-6 and its Surroundings in Maláta str.) Annual Report of Loránd Eötvös Geophysical Institute, Budapest, Hungary 1993. (in Hungarian)

[3] Geological Institute of Hungary, "Engineering Geological Map of Budapest 1:40000", [online] Available at: https://map.mbfsz.gov.hu/bpmg40/ Accessed: 18/10/2019].

[4] Nguyen, F., Ghose, R., Isunza Marique, I., Robert, T., Dumont, G. "Managing Past Landfills for Future Site Development: A Review of the Contribution of Geophysical Methods", In: Proceedings of 4th International Symposium on Enhanced Landfill Mining, Mechelen, Belgium, 2018. ISBN 9789082825909

[5] Abbas, C. P. "Deformation of landfill from measurements of shear wave velocity and damping", Geotechnique, 51(6), pp. 483-492, 2001. https://doi.org/ 10.1680/geot.2001.51.6.483

[6] Konstantaki, R. A., Ghose, R., Draganov, D., Heimovaara, T. "Wet and gassy zones in a municipal landfill from P- and S-wave velocity fields". Geophysics, 81(6), pp.75-85, 2016. https://doi.org/ 10.1190/geo2015-0581.1

[7] Meju, M. "Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach", Journal of Applied Geophysics, 44(2-3), pp. 115-150, 2000. https://doi.org/10.1016/S0926-9851(00)00011-2

[8] Bernstone, C., Dahlin, T., Ohlsson T., Hogland H. "DC-resistivity mapping of internal landfill structures: two pre-excavation surveys", Environmental Geology, 36(3-4), pp. 360-371, 2000. https://doi.org/ 10.1007/s002540050015

[9] Dumont, G., Pilawski, T., Dzaomuho-Lenieregue, P., Hiligsmann, S., Delvigne F., Thonart, P., Robert, T., Nguyen, F. T. Hermans, T. "Gravimetric water distribution assessment from geoelectrical methods (ERT and EMI) in municipal solid waste landfill", Waste Management, 55, pp. 129-140, 2016. https://doi.org/10.1016/j.wasman.2016.02.013

[10] Chambers, J., Kuras, O., Meldrum, P., Ogilvy, R., Hollands,J. "Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site", Geophysics, 71(6), pp. 231-239, 2006. https://doi.org/10.1190/1.2360184

[11] Rix, G. J., Lai, C. G., Foti, S. "Simultaneous Measurement of Surface Wave Dispersion and Attenuation Curve", Geotechnical Testing Journal, 24(4), pp. 350-358, 2001. https://doi.org/ 10.1520/GTJ11132J

[12] Woods, R.D. "Screening of Surface Waves in Soils.", Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, 94, pp. 951-979. 1968