Geophysical alluvial exploration using the Aquares resistivity method

P.M. Brabers
Demco NV, Belgium

Traditional seismic geophysical methods always have had limited success in gravel deposits because of the tendency of gravel deposits to produce diffractions which tend to obscure seismic results and because of multiple reflections in shallow water reducing the useful penetration depth of the method. While electromagnetic methods have been successful in dry areas they suffer from the ‘skin effect’ in high-conductivity environments such as shallow groundwater or salt water.

For this reason, most alluvial diamond exploration programmes are usually based on borehole campaigns. As boreholes – especially in water – tend to be relatively expensive, in most cases insufficient information is available to delineate the sedimentary structures within the diamond concession, reducing the productivity of mining operations, which are constrained by operating blindly in unknown terrain with mining methods not ideally adapted to the actual geological conditions.

Aquares is a geophysical resistivity method developed about 20 years ago by Demco NV. It is commonly used worldwide on dredging exploration projects, port development projects, and pipeline route surveys in marine and fluvial environments. It is an advanced geophysical method capable of reproducing not only quantitative geological information (thicknesses and depths of geological structures) but also qualitative geological information (distinguishing between rock and sediment types), with all results presented in a georeferenced 4D model (X, Y, Z, resistivity value).

The principles and characteristics of the Aquares resistivity method are demonstrated using examples from a number of exploration projects worldwide. Case studies from the Sankuru and Tshikapa rivers in the Democratic Republic of Congo and from beaches and surf zones in South Africa and other countries illustrate the capabilities and limitations of the Aquares resistivity method as a geophysical diamond exploration tool.

INTRODUCTION

Geological site investigations are ideally based on a combination of geophysical mapping to define the horizontal and vertical extents of geological structures and a limited number of boreholes (or other sampling methods) to define the nature of the structures.
In the case of alluvial diamond exploration programmes in riverine and marine environments, the
traditional geophysical methods usually have had limited success in defining the extent of the
geological structures, due to gravel-related diffractions and multiple reflections in shallow water
reducing the penetration depth of classical seismic methods and high conductivity values generating a
‘skin effect’ in electromagnetic methods. As a result, most alluvial diamond exploration campaigns are
centred on often randomly selected sampling locations to try to locate the diamond deposits. As
boreholes in water generally are expensive and time-consuming, exploration budgets and time
constraints limit the number of boreholes that can be drilled, resulting in inadequate geological
information and reduced productivity of the subsequent alluvial mining operations.

The Aquares marine resistivity method is a geophysical method based on resistivity measurements. It
is not adversely affected by either gravel or by shallow water or high-conductivity environments. It can
distinguish between different rock characteristics and sediment grain sizes based on their resistivity
values, and produces results that are combined into a georeferenced 4D model (X, Y, Z, resistivity
value). As such it can be considered to be an enhanced geophysical method. The principles and
performance of this relatively new method are explained and illustrated based on survey examples
from dredging projects, port development projects, pipeline route projects, as well as a number of
diamond exploration projects.

GEOPHYSICAL METHODS

Marine/fluvial geophysical methods can generally be classified into (1) quantitative methods, (2)
qualitative methods, and (3) advanced methods combining high-quality quantitative and qualitative
results into a georeferenced 4D model.

1. Quantitative geophysical methods are methods capable of measuring sediment thicknesses and
depths. Single-channel seismic reflection methods using boomers, chirps, sparkers, and
parametric echo-sounders are examples of this type of method. As these methods do not
measure any physical value that distinguishes between different sediment and rock types, they
are not suitable for generating a 4D model of the survey area. The accuracy of single-channel
seismic results is somewhat limited by the unknown acoustic velocity values required to
accurately convert travel times to depths.

2. Qualitative geophysical methods are methods capable of distinguishing between different
sediment and rock types. These methods often generate quantitative (thickness/depth)
information as well, but are usually far less accurate than the truly quantitative methods.
Refraction seismics and most electromagnetic methods are examples of qualitative geophysical
methods. Refraction seismic methods use the sonic velocity to distinguish between different
sediment and rock types, while electromagnetic methods use conductivity for this purpose.
Although seismic refraction and electromagnetic methods would theoretically be capable of
generating 4D models, the accuracy of the depths and thicknesses provided is generally too
limited to be useful.

3. Advanced geophysical methods are high-quality methods combining the capabilities of
quantitative and qualitative methods into detailed georeferenced high-precision 4D models that
are accurate enough to be used for borehole siting purposes, in project design, and in mine
planning. An example of such an advanced geophysical method is the Aquares resistivity
method, which uses the resistivity value to distinguish between different sediment and rock
types. Compared to traditional resistivity methods, Aquares is significantly more accurate
because it avoids smoothing effects of finite element processing; it uses powerful noise filtering
algorithms, optimized electrode configurations, and seabed (river bed) towed resistivity cables.
Combined resistivity-seismic surveys ground-truthed with numerous boreholes on various
dredging projects have shown Aquares to be more accurate than traditional seismic reflection
methods.
PRINCIPLES OF AQUARES RESISTIVITY

Land-based Applications
The Aquares resistivity survey method is based on the principles of electrical sounding. For land-based applications the method of geoelectrical sounding is not new: it was described about 100 years ago by a French engineer named Conrad Schlumberger.

An electrical current is injected into the subsurface by means of two current electrodes. The voltage gradient associated with the electrical field of this current is measured between two electrodes placed in-between the current electrodes (Figure 1). Based on the measured values of current and voltage, the average resistivity of the subsurface is calculated for a subsurface volume down to a certain penetration depth. The penetration depth depends on the distance between the current electrodes.

If the measurements are repeated with progressively increasing current electrode distances, information is obtained from progressively deeper geological structures (Figure 1). As such, a field curve is obtained showing the resistivity as a function of the (horizontal) distance between the current electrodes. After computer modelling, this field curve is transformed into a real geophysical subsurface section showing the resistivity as a function of depth.

The resistivity of a geological structure depends on its porosity, water content, and the conductivity of the pore water. Unsorted gravel usually has a lower porosity compared to sand and therefore its resistivity value is higher. Clay, with generally very high porosities, shows very low resistivity values. Solid limestone has a low porosity and shows very high resistivity values. Weathered limestone tends to show lower resistivity values. In fresh water the resistivity value of the geological structures often is defined by its clay content rather than by its porosity. Every geological structure has its own specific resistivity value distinguishing it from other structures.
**Fluvial and Marine Applications**
For water-based applications the electrodes are placed on a multichannel cable on the seabed towed behind the survey vessel (Figure 2). The umbilical cable connecting the resistivity cable on the seabed with the electronic equipment on board the survey vessel carries a number of conductivity data-loggers that continuously measure the water conductivity. This allows the effect of the water column on the resistivity measurements to be calculated.

![Figure 2. Electrical sounding in marine/fluvial environments.](image)

**Data Processing and Interpretation**
The processing sequence consists of a number of steps.

First, the resistivity field data is edited and filtered to increase the signal-to-noise ratio. The bathymetric and positioning data is edited as well. Then, the resistivity data, positioning data, and bathymetric data are combined.

Geometrical corrections are applied to correct for the fact that the towed measured line (and the cable also) may show more or less significant curvatures. Measurements made with a strongly curved cable are rejected. The effect of the water column is subtracted.

An important step in the processing sequence is the resistivity data inversion. In this step the apparent resistivity data is transformed into a vertical section of the subsurface showing the depth and thickness of each geological structure.

The resistivity information is interpolated into a regular grid either on a cross-section or in two dimensions. Each interpolated grid point represents a complete geological profile of the subsurface showing the resistivity value as a function of depth. The results are visualized in colour on cross-sections showing the depth and geographical position of different geological structures. The results can be calibrated with information from a limited number of boreholes in order to verify and sample each geological structure.

The processing procedure described above is an interactive process. In order to extract maximum information from the raw survey data, the processing sequence has to be repeated several times to find the optimum processing parameters.

**CASE STUDIES – 4D MODELING**
As each unit volume in the earth has a specific resistivity value attached to it, the Aquares method is an ideal method to develop georeferenced 4D models of any survey site. As such, it has been applied worldwide for this purpose on dredging projects, port development projects, and pipeline route projects. This is illustrated in the following examples.
The decision was taken to build a port in Limbe, Cameroon for the maintenance of offshore oil drilling platforms. In a first instance the port was designed and tendered without any detailed knowledge of the geological characteristics of the construction site. A marine construction company bidding for this project and understanding the importance with regard to their cost estimates, decided to carry out a resistivity survey to assess the geological situation.

A complete 3D model of the construction site was generated based on the resistivity results. A number of horizontal resistivity sections are shown in Figure 3 at –10 m, –12 m, and –16 m relative to the chart datum, as well as a vertical section showing the thicknesses of some of the geological structures. The construction site consists of solid basalt overlain by weathered basalt and fine to coarse sediments, as confirmed by a limited number of boreholes.

Based on the original design it appeared that dredging operations and construction of the quay wall would be extremely expensive due to the presence of very hard basalt. After some calculations and various communications with the client's consultants, it was decided to modify the design to take advantage of the location of the basalt for the foundation of the quay walls and softer rock and sediments for the turning basin and rehandling pit.

By adjusting port design to the geological conditions it was estimated that more than 50% of the construction costs were saved.
Two multinational construction companies interested in building a gas export facility in a mangrove swamp on an island near Papua New Guinea decided to carry out an extensive investigation campaign around the island to find suitable sand for reclamation purposes. Initial studies included various geophysical and geotechnical surveys involving seismics, sidescan sonar, multibeam bathymetry, 77 vibocores, and 116 boreholes costing about $12 million. Although the geophysical investigations were of reasonable quality, the technology was ill-suited to the geological setting and the aims of the survey. In addition, the vibrocores and boreholes were randomly sited.

After 2 years of investigations the final exploration report concluded that no significant volumes of sand were available.

The consultants then decided to carry out an Aquares resistivity survey, hoping for better results. After 10 days of survey work the resistivity results showed the location of more than 200 million m³ of sand deposits close to the site. Moreover, the resistivity results also showed the proposed navigation channel leading to the island to be cutting a number of areas containing rock as well as stiff clay (Figure 4). By changing the design of this channel and shifting it about 300 m to the east, very expensive and unforeseen dredging costs were avoided.

Cost savings based on the resistivity results have been estimated at many tens of millions of dollars: more than 1000 times the survey costs.

Panama

After a detailed site investigation involving a number of classical geophysical surveys and a borehole campaign, ACP (Autoridad del Canal de Panama) tendered a dredging project in the access channel
leading to the Miraflores locks. A group of dredging companies interested in the project conducted an additional investigation, including enhanced geophysics (Aquares resistivity).

Some of the results are shown in the horizontal and vertical resistivity sections in Figure 5. The vertical section shows the location and extent of hard basalt, softer mudstones, and soft mud. The horizontal section shows the lateral extent of the geological formations at dredge level. A natural palaeochannel, formed by the Rio Chagres during geological times when sea levels in the Pacific were far lower than they are now, is seen cutting into the basalt.

This type of high-quality geophysical information, complemented with a limited number of well-targeted boreholes, allowed the dredging contractor to accurately calculate the geological risks. As a result, this dredging project was awarded at only 30% of the original budget estimate suggested by ACP in the tender documents, based on their original site investigation which did not utilize enhanced geophysics.
A power plant on the coast in Ghana requiring a cooling water intake and outfall needed detailed geological information for the pipeline routes. The water conducts were to be drilled by tunnelling in rock, with the end point preferably in soft sediments in order for the expensive drilling head to be recoverable using simple inexpensive dredging methods. After an inconclusive seismic survey and an expensive drilling campaign failed to define the major geological structures, it was decided to carry out an Aquares resistivity survey.

Figure 6 shows a horizontal resistivity section at 2 m below seabed level as well as two vertical resistivity sections following two possible routes for the intake and the outfall. The vertical sections clearly show the location and depth of solid rock, weathered rock, and soft sediments. The horizontal section shows a palaeoriver system connected to an existing river mouth west of the survey site. Keeping in mind the importance of buried channels in diamond mining, one can imagine what similar survey results could mean for diamond exploration in similar environments.
A more detailed horizontal and vertical resistivity section in the surf zone shows a number of gravel-filled gullies cutting about 2 m deep into soft rock (Figure 7). These gullies can be interpreted as swash gullies cut into soft bedrock due to the erosive action of quartz gravel continuously moving with the swash. As for this project no particularly high resolution was required, the horizontal resolution in this case was limited to one sounding every 2.5 seconds. Again, one can imagine the importance of this survey example if a more optimal resolution were to be used of one sounding every second in an environment involving diamondiferous gravels.

**Luderitz Combined Resistivity and Seismic Survey**
In view of a pending port development project at Luderitz, Namibia, Namport ordered a detailed geophysical survey combining Aquares resistivity, a boomer sub-bottom profiler, and side-scan sonar. Figure 8 compares the seismic and resistivity results for one of the sections surveyed. The resistivity results clearly show a high-resistivity surface structure (blue) associated with gravel on top of finer sediments (grey) and rock heads at deeper levels marked by very high resistivity values (red-yellow-green). The seismic results in the northern reaches of this section are similar but lose the bedrock level towards the south due to gas masking effects associated with the decomposition of organic matter in diatomaceous silt. The capability of the Aquares resistivity method to detect rock heads was not affected by the presence of gas in the sediments.
Figure 8. Comparison between seismic and resistivity sections, Luderitz.

Sand Mining

As the resistivity value of a sediment depends on its grain size, Aquares is an ideal method for distinguishing between sediments with different grain sizes. This is illustrated in Figure 9, showing high-resistivity gravel associated with strong river currents underneath a highway bridge and progressively finer sediment grainsizes downstream of the bridge and closer to the shore where the current velocity is slower.

This aspect of the Aquares resistivity method makes it the preferred method for sand searches involved with reclamation projects. The following examples illustrate this.
A bauxite mining company interested in building a bauxite handling plant in the port of Kamsar, Guinea-Conakry needed sand to fill up the swamp where the plant was to be built. Figure 10 illustrates a vertical resistivity section showing low-resistivity silty sediments (grey) overlying higher resistivity (green-red) weathered rock with sand deposits (blue) at the seabed surface, and a horizontal section at 2 m below seabed level showing the extent of the sand deposits. After confirmation of the resistivity results with a limited number of well-sited vibrocores, the reclamation project could be carried out based on the 4D resistivity model provided.

A reclamation project to fill up a beach in the Persian Gulf required sand and a drilling campaign was undertaken to find it. Figure 11 (left) shows the boreholes that intersected sand (numbers in red). Even
more than 40 boreholes were not conclusive in delimiting the sand volumes on this project. Only after comparing the drilling results with Aquares resistivity results from a horizontal section at 1 m below seabed level (right-hand illustration) did it become clear that only limited sand thicknesses were available on the limestone rock in the eastern reaches of the survey area (green), while the main sand volumes were to be found in the western reaches of the survey area (blue). This example shows the ineffectiveness of boreholes in delineating geological structures as compared to advanced geophysical methods.

ALLUVIAL DIAMOND EXPLORATION

The fact that resistivity methods – contrary to seismic methods – are capable of penetrating gravel and measuring gravel thicknesses makes the Aquares resistivity method very attractive for alluvial diamond and gold exploration applications.

Sankuru River

Figure 12. Horizontal resistivity section 2 m below river bed level (top) and gravel thicknesses (bottom).

About 33 km of the Sankuru River in the East Kasai, DRC was surveyed using the Aquares resistivity method with a line spacing of about 10 to 15 m. Figure 12a shows a 4 km horizontal section at 2 m below river bed level. The low resistivity values (blue-purple) correlate with siltstone while the high resistivity values (cyan-green: > 80 Ωm) correlate with gravels. In a fresh water environment such as the Sankuru River the high clay content of the (weathered) siltstone bedrock generates lower resistivity values than the high-resistivity quartzitic gravels overlying it. Diamondiferous gravels are found almost everywhere on the river bed. However, the surface gravels are mobile, moving over the river bed during the rainy season when flow rates are high. They generally show relatively low diamond concentrations. Thick older gravel units with higher diamond concentrations are usually found at deeper levels in
depressions in the bedrock. The horizontal resistivity section in Figure 12a marks the location of these richer deposits, while Figure 12b shows the actual thickness of the same deposits.

**Tshikapa River**

![Image of the Tshikapa River](image)

Figure 13. Vertical resistivity section – Tshikapa River.

A section of about 15 km of the Tshikapa river in the West Kasai, DRC was surveyed using the Aquares resistivity method. The general resistivity values encountered were very high due to the high resistivity of the river water as well as the very high resistivity values of the compact migmatic gneiss constituting most of the bedrock. Figure 13 shows a vertical resistivity section along part of the river. Hard migmatic gneiss outcrops are found exposed in the rapids, while old (diamond-rich) gravels are found on slightly softer rock types. Mobile washed-out gravels with lower diamond concentrations are found as a thin layer on the river bed.

A georeferenced 4D resistivity model of the entire concession allowed gravel volumes to be calculated and helped in selected the most promising mining areas.
Along the coastline in South Africa’s Northern Cape Province there are various diamond mining projects targeting rich diamondiferous gravels associated with a system of palaeochannels cut into the bedrock. In this particular case a local diamond mining company was interested in mining one of these palaeochannels and wanted to know if an existing channel could be traced westward towards the beach.

A trench was excavated using a tractor equipped with a regular agricultural plough. As the trench was situated near the water line it automatically filled with seawater. The power generator and resistivity equipment were mounted on a regular pickup truck equipped with a sideways-extending 3-inch steel pipe for attaching the resistivity cable. As the pickup truck moved at walking speed parallel to the trench while keeping the resistivity cable in the trench, the resistivity measurements were carried out at a rate of about 1 sounding per second, covering 3 kilometers of beach length in half an hour and resulting in a sounding about every 1.5 m. As the tide moved up or down additional trenches were ploughed following the moving water line to higher or lower levels until the entire intertidal area was covered by resistivity measurements.

Figure 14 shows an example of one of the resistivity profiles obtained following the procedure described above. This profile shows low-resistivity (light green: $<1.5 \, \Omega m$) marine sediments covering high-resistivity (red: $>3 \, \Omega m$) rock. Whereas in general rock levels are found at 4 to 6 m penetration depth, two channels are visible with rock levels at about 18 m depth. The wider channel on the right-hand side
was identified as the extension of the known palaeochannel mined further inland, while the narrow channel on the left-hand side was completely unknown and came as a pleasant surprise and a bonus to the client.

CONCLUSIONS

The main features of the Aquares resistivity method are summarized as follows.

1. High precision: Thanks to the use of seabed-towed cables, powerful noise reduction algorithms, and no need for additional acoustic velocity information, Aquares resistivity results are usually quite reliable compared to other geophysical methods.

2. Georeferenced 4D models: As each unit volume in the earth is characterized by its specific resistivity value, georeferenced 4D models can be constructed that form the base of information for mine planning, selection of mining equipment, environmental control, and budget planning.

3. Flexibility: Aquares operates on small and big survey vessels, in shallow and deep water, fresh and salt water, in gravel, and in rough water such as surf zones.

4. Economical: High-precision resistivity information presented in a georeferenced 4D model reduces the need for expensive sampling campaigns. Sampling is only required to define the nature of the geological structures and diamond concentrations, and not the extent of the geological structures.

Various survey examples described above show the Aquares resistivity method to be extremely useful in defining geological structures associated with diamondiferous gravels.
Dr. IR. Peteralv Brabers
Managing Director
Demco NV

Dr. Brabers is a mining and geological engineer with worldwide geological, geophysical and mining experience. In 1996 he founded Demco NV a geophysical company involved with the development and worldwide applications of the Aquares marine resistivity technology from offices in Belgium, Australia, Florida and Colombia. Dr. Brabers has been involved with diamond exploration projects in DRC Congo, Namibia, South-Africa and the Central-African Republic.