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Leak detection in complex underground structures using an innovative geophysical method

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ABSTRACT: An increasing number of underground structures for transportation and buildings in urban areas often require deep excavations under the groundwater table. Surely the main problem connected is the final test of the water tightness of the resulting structure, *i.e.* of the diaphragm wall and of the plugs. Texplor's ECR®/EFT® technology is able to obtain quickly a reliable detection of potential leaks and to perform the quality control of horizontal and vertical cut-offs also in very complex and deep structures like metro tunnels or building pits, even before excavation. Further advantages are the non-destructive measurements from the surface, the flexible spacing of measuring grids, which can be easily adjusted according to each project and virtually no depth limit for the practical investigation. This paper describes the application of the technology in two building pits in Florence and Cremona in Northern Italy, which were carried out in accordance with RCT, a company of Trevi Group.

1 OVERVIEW ON THE TECHNOLOGIES

The ECR/EFT/FGM leak detection technologies were developed and patented by Texplor GmbH and are used for the leak investigation of:

- Deep foundations: diaphragm and sheet pile walls
- grouting areas
- reinforced concrete constructions
- gel-sealed basements
- underwater bottom slabs
- natural and artificial water retaining horizons
- geomembrane sealings

Leaks in sealing constructions are detected quickly and reliably with these methods. Leak areas are identified and displayed on a ground map. Horizontal and vertical sealings can be investigated either by temporary surveys or by stationary installations for long-term control. Groundwater movements are not necessary for the investigations.

1.1 *ECR®-multisensor leakage detection technology*

The method ECR is based on the physical principle that the groundwater flow in a porous subsurface medium ensures an electric flow by ion transport and creates a measurable electric field in the area.

If a leakage exists in a construction surrounded by groundwater, a natural or artificially enhanced local groundwater movement can be expected in the leakage area. This local groundwater stream is moving through the leakage and creates an electric field by this movement (known in physics as streaming potential), which is superimposed on the existing natural background field and, therefore, is a *detectable anomaly*.

For the accurate detection of these electrical fields caused by groundwater, a multichannel high speed–high resolution telemetric sensor system is in use. Depending on the size of the investigation area, several hundred non-polarizable, high-sensitive sensors form a grid or, in general, one array. A telemetric data recording system ensures fast and reliable data acquisition of the whole sensor array at the same time (see Fig. 1).

Hence, natural groundwater streams can be located and outlined in any underground sealing construction, dam or basin or natural geological seals by measuring the potential streaming anomalies. The results of the measurements are analyzed and displayed in maps (see Fig. 2).

1.2 *EFT®-active leakage detection technology in combination with ECR®*

EFT technology introduces an artificial electric field into the ground around a sealing system which is forced into the sealing construction to create a mechanical movement of ions. These movements of ions through the untight locations in the sealing

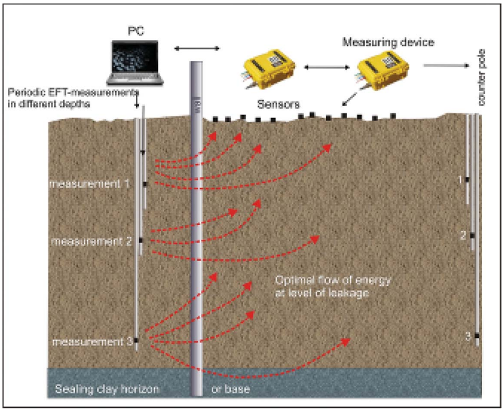

Figure 1. Schematics of ECR®/RFT® leak detection system.

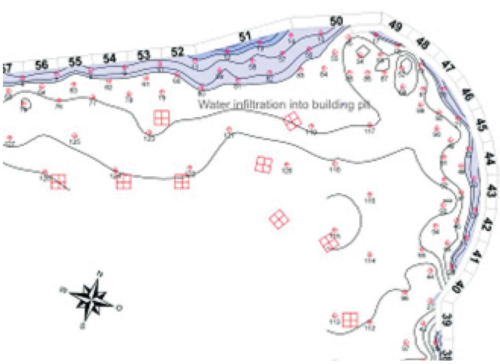

Figure 2. Display of results.

system create an intensified ion flow which can be detected by the ECR sensor system on the surface.

The created positive ions clash against the grains and take the water particles with them. This mechanical impact is very small with respect to natural groundwater flow, but is still present. This principle is based on the relation V = IR (V = voltage, I = current, R = resistance). EFT is based on this effect.

Normally, if the current changes, the voltage also changes immediately. If the current is doubled, the current flow results in a doubling of the voltage and also of the resistance. In case a hole is present, a small flow is running without considerable resistance through the hole. As the electric flow increases, the mechanical resistance increases near the hole. Both electric and mechanical blockages take place in the vicinity of the hole. This increase in resistivity leads to the fact that the relation between flow (I) and tension (V) at a certain moment is no longer linear. The flow is no longer undisturbed and the sensor above the position, where this electrical anomaly is observed, indicates the location of the hole. An electrode in one or more observation wells induces an electrical field in the subsurface outside the building pit. This electrical field is forced through the outside sealing structure into the pit by a counter pole (see Fig. 1). On its way through the sealing structure, the induced current follows the least resistive path towards the second pole, which in most cases, is through water and the openings in the sealing construction. Therefore, the electrical potential field changes significantly at an opening, compared to the field in the rest of the construction. The areas of leakages are characterized by an increased local energy flow which can be detected and outlined by the surface sensor grid. Furthermore, the increased energy flow creates a structure at the leakage location, which is characteristic for the type of leakage (joint, underpass a wall, hole in a wall, hole in a bottom plug etc.). To avoid any disturbance by electrical noise in an industrial area, a reference is introduced, thus allowing this very accurate measurement also in highly noisy areas like railway stations, industrial buildings etc. (References: Admiraal & Geutebrück 2007; Brouwer & Veldhuizen, 2011; Geutebrück, 1997; Geutebrück, Hofmann & Ottomann 2001).

1.3 *Implementation*

The Texplor methods ECR and EFT and the combination of both methods FGM, a self-developed telemetric data recording system, are carried out to investigate all kinds of vertical and horizontal natural or artificial sealing system. The measurements are non-destructively carried out at surface level and/or in boreholes (with small sensors). The telemetric data recording system (FGM) ensures fast and reliable data acquisition of the whole sensor-array at the same time (see Fig. 3).

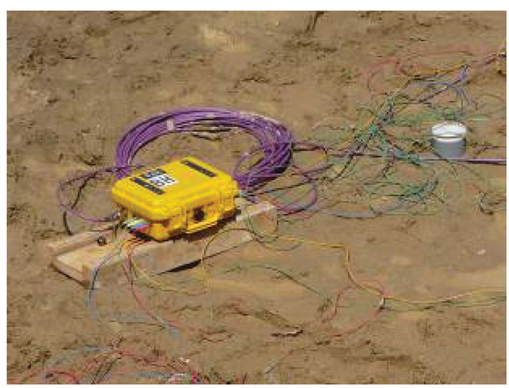

Figure 3. Telemetric data recording system (FGM).

Non-polarizable, high-sensitive sensors are placed on the surface of the investigated area in a pre-designed grid. Texplor uses special sensors, which are very stable against natural and artificial disturbances. The sensors are placed in measuring grids with flexible spacing on the surface of the measuring area which can be easily adjusted according to each project. The type of soil between source and sensor influences the detected electric field. Sandy subsoil (relatively low conductivity) behaves differently to a peat or clay layer (relatively higher conductivity). Therefore, we have to observe that the measured absolute potential can be different, depending on the soil type. As a consequence, zero reference measurements are carried out by both EFT and ECR methods. Because of that, it is possible to measure differences, as a result of which the properties of the ground between source and receiver can be neglected. The results of measurements are analyzed and displayed in maps.

The ECR technology was employed in many projects in Italy, Germany, Austria and Ireland and lately also in China.

This paper describes two projects carried out in Florence and Cremona by TEXPLOR in cooperation with RCT and Trevi. RCT is the commercial partner in Italy for TEXPLOR.

2 CASE HISTORY: BUILDING PIT IN FLORENCE

The building pit in Florence, central Italy, is located on the former FIAT company premises and covers an area of about 12,000 m^2. The entire perimeter of the pit is surrounded by streets and old buildings (see Fig. 4).

2.1 *General description*

In order to build a three-floor underground parking, under the new structures, a total of 11,500 m^2 diaphragm walls with an average depth of 26 m are installed to form the walls of the underground structure, which is excavated to a depth of 15 m. The entire area is divided into five sectors by means of self-hardening slurry walls. In three of the sectors, a 2.5 m thick jet grouted bottom plug with watertightness purposes is formed by means of 2.0 m diameter columns. Other structural works performed as foundations are *"barrettes"*, piles, micropiles and anchors (see Fig. 5).

Soil conditions are described as a succession of different layers in recent alluvium (bottom to top): Group GP, composed by gravel and cemented sandy gravel, and Group SS, composed by silty sand, silt and silty clay in the bottom part of the area to be excavated. There is a single level of water table in the backfill (–5 m from the street level). Due to the cemented layers, foundation technologies are modified, preferring piles to the single foundations *"barrettes"*. Moreover, thanks to the presence of a clayey thick layer in the central part of the area, the bottom plug is substituted with a deepening of the outer structures.

2.2 *Leak detection*

The target of this investigation was a quality control of the present status of the sealing construction of three measuring areas consisting of:

– diaphragm and self hardening slurry walls;
– jet-grouting bottom plug.

with the following types of possible failures:

1. Open joints at the diaphragm elements;
2. "Windows" in the diaphragm elements;
3. Open contact between jet-grouting bottom plug and diaphragm walls;
4. "Holes" in jet-grouting bottom plug;
5. Connection of the extension to the clay horizon;

Figure 4. Plan view of florence site.

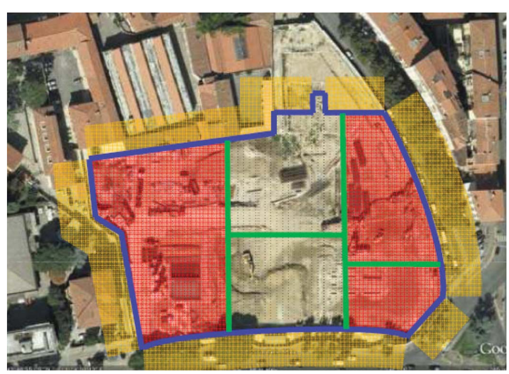

Figure 5. Sketch of works.

6. Investigation of the natural clay horizon for "holes";
7. "Windows" in the self hardening slurry walls;
8. Open contact between injected jet-grouting bottom plug and self hardening slurry walls;
9. Connection between piles or *barrettes* and clay horizon.

The prerequisites for a leak detection measurement are the installation of wells inside and outside at different depths. The surface must be smooth and may not dry up and must be watered in warm or hot weather conditions. Texplor technologies were employed to investigate three different areas for a total surface of about 5500 m^2.

Subsequently the measurements of area Z3 are described. To investigate the sealing construction, an array of approx. 200 sensors was positioned in area Z3. A cross-section of the investigated area is shown in Figure 6.

The general areal sensor-array had a distance of 4 × 4 m for the investigation of the natural clay layer-area; in the diaphragm wall areas a more tight sensor grid of 2 × 2 m was installed for a better evaluation of local events like joint leakages, for example. The sensor grid is shown in Figure 7.

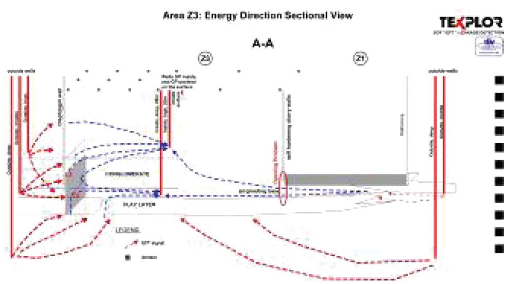

Figure 6. Sectional view of sealing construction and outside well situation for wall extension and clay layer investigation.

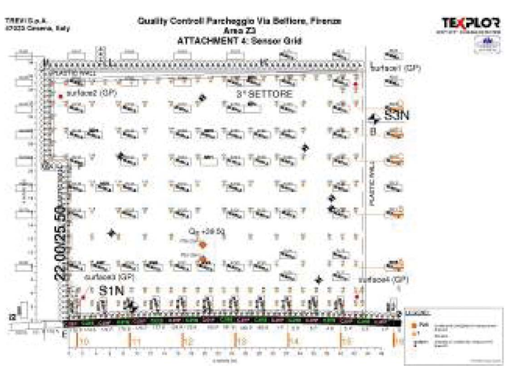

Figure 7. Sensor grid in Z3 area.

The general surface (street) levels are around El. 43.0 m above sea level. At the time of the measurement, the excavated surface of the Z3 pit-area had an elevation of approx. 39.6 m. The bottom of the jet grouting Z1 and Z2 was approx. El. 13.0 m. In the Z3 area, additional columns were installed to extend the diaphragm walls' base from El. 14.0 m to 7.0 m. For the active measurements with EFT tracers, 14 wells in the outside of the Z3 area were geometrically positioned. The geometry is necessary to provide special directional views on the different wall sections. Each geometrical location for EFT tracer input consists of 2 or 3 wells with different depths. For the investigation of the walls and plastic walls, well depths between 15 and 18 m were used. For the investigation of the natural clay layer, well depths between 42 and 46 m were used.

During the first step, base-measurements were performed to collect the natural existing electrochemical field at site, no active energy was induced during these measurements into the ground. These data were collected as baseline data and compared with the following active data, where EFT-energy was directionally forced from the outside wells into the pit to detect locations where the energy (and also groundwater) can pass through the sealing construction. During the second step, an active ECR/EFT measurement was performed to visualize the leakage situation by observing and locating any enhanced energy flow through the sealing structure. Multiple geometries were used with different wells to induce energy in the subsoil and force it into the pit construction. Basically for each investigation of a special wall area and the neighboring bottom plug area, three various deep wells outside of the pit were strategically used to induce the electrical EFT-tracer into the subsurface. To cover the complete Z3 area, four different geographic points inside the pit (on the surface of excavation level) and 2 wells inside Area Z3 were used for the counter pole positions.

The results of the leakage detection measurements in the Z3 area were shown in different maps in which the position of all leakage anomalies through the walls or below the walls are displayed in blue color on the base map. In Figure 8 the results of the investigation of the clay horizon including the wall extensions below a depth of –25 m are displayed.

Figure 9 shows the results of the investigation of the walls and extension from surface level to –25 m. After having finished the measurements, the data are analyzed and interpreted so that the results are already available directly at the site. Hence, the necessary and targeted sanitation works can start immediately afterwards.

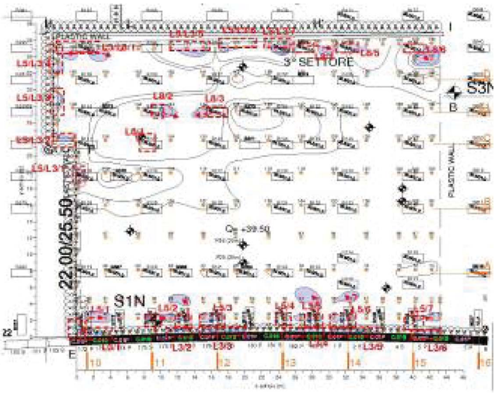

Figure 8. Map of leakages below –25 meters—clay horizon including wall extension.

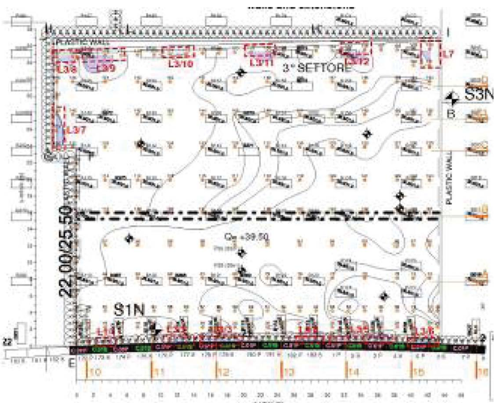

Figure 9. Map of leakages from surface to –25 m through walls and jet grouting extensions.

3 CASE HISTORY: BUILDING PIT IN CREMONA

A new underground public parking area is about to be built in the centre of Cremona, northern Italy. A 43.0×74.0 m area has to be excavated for a depth of 14.0 m, in order to create the pit for a four floors underground parking.

3.1 *General description*

A continuous diaphragm wall with a maximum depth of 26 m is built to protect the pit that has to be excavated. The diaphragm walls are embedded in a natural silty clayey bottom plug. The excavation of the pit highlighted some leakages through joints between diaphragm walls. These leakages are not admissible, due to the short distance between pit and existing buildings. The client asked Trevi Group to find an efficient method for assessing the extent of leakages so as to design any possible corrective actions (see Fig. 10).

The soil conditions are a succession of backfill (up to 8.0 m thick) of anthropic nature, recent alluvium (sandy and clayey sand with some gravelly layer from –8.0 to –24.0 m from working level) and a succession of silty sand and sandy silts up to –28.0 m in the bottom part of the area to be excavated.

3.2 *Leak detection*

The aim of the complete diaphragm wall area's investigation was to detect any leakage in:

– the joints of the wall segments;
– the diaphragm wall segment body itself;
– the sealing contact between the segment and the clay.

The investigation was performed in 2 areas having different depths—shallow (street level to approx.—10 m depth) and deep (approx.—10 m down to end depth of diaphragm segments—26 m) in order to estimate the depth development of the detected leakages. Texplor technologies were employed to investigate different areas for a total amount of about 4400 m^2.

As for Florence, during the first step, base-measurements were performed to collect the natural baseline electrochemical field at site. During the second step, an active ECR/EFT-measurement was performed to visualize the leakage situation by observing and locating any enhanced energy flow through the sealing construction.

To investigate the sealing construction, a quantity of approx. 370 sensors was positioned, with an array of 2×2 m along the walls, for getting complete information on the tightness situation.

Figure 10. View on the job site.

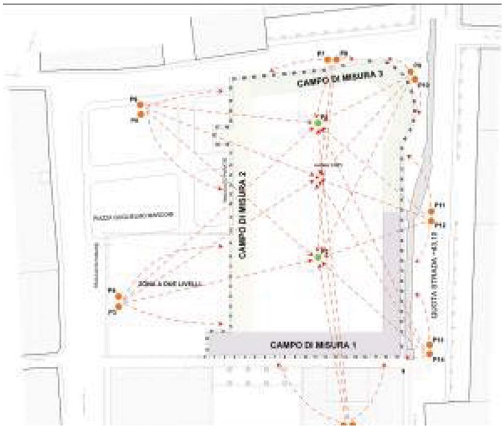

Figure 11. Detailed energy directions.

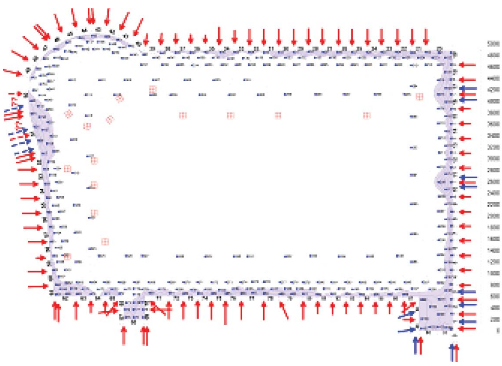

Figure 12. Map of leakages below –20 m—clayey horizon.

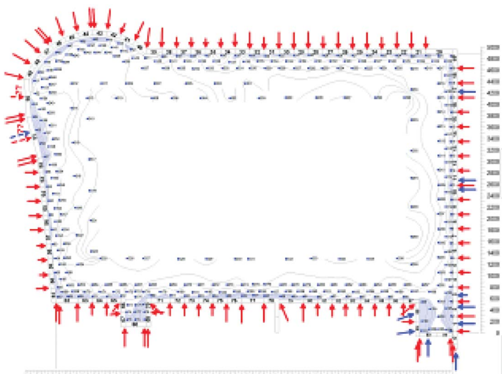

Figure 13. Map of leakages from surface to –20 m through diaphragm walls.

EFT-tracer injection was performed from 14 wells positioned outside, 2 wells inside were drilled for positioning antipoles, 42 different energy arrays combined with 75 measuring cycles were performed, for a total amount of over 3500 single measurements (see Fig. 11).

The results of the ECR/EFT-leakage detection measurements were shown in different maps in which the position of all leakage anomalies through the walls or below the walls are displayed in blue color on the base map. Figure 12 shows the results of the investigation of the clayey horizon below a depth of –20 m.

In Figure 13 the results of the investigation of the walls and extension from surface level to –20 m are shown.

4 CONCLUSIONS

The Texplor ECR and EFT technologies and the combination of both methods were developed for the quality control of any kind of artificial or natural impermeabilization systems.

Clients receive a base map of the construction with colored areas (points of energy paths through sealing construction) indicating the leakage locations and a description of the constructional reasons and size of leakage. The leakages where energy can migrate through the walls' joints or bottom plugs are colored in blue.

The above-described technologies allow to detect the points from where water flows through the structures and to work out any possible corrective actions.

Finally, listed hereunder are the main key points of the described technologies:

- Quality control of horizontal and vertical sealing-systems
- Fast and reliable detection of leakages
- Non-destructive areal surveys, flexible measuring grid, high sensor density
- Immediate control of renovation procedures
- Pumping of groundwater is not necessary
- Single investigations or stationary installations for long-term control
- Leakage areas are localised, identified and spatially displayed in a base map
- Thanks to the fact that works are carried out by measuring minimum potential differences (mV) and minimum currents (mA), currents are prevented from being affected or absorbed by any underground conductive object
- When using the Texplor method, data interpretation cannot be disregarded. Despite a rigorous quality control on the equipment's operation

and on data acquisition, the detection of permeation or weak areas—and most of all the causes—(presence of a hole; lack of connection between vertical works and bottom plug, etc. …) require the interpretation of a technician, who will investigate the anomaly's geometry.

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