Konzertierte Hohlraumerkundung unter einer dicht bebauten Industrieanlage

Concerted cavity exploration under a congested industrial plant

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Zusammenfassung - Summary

Over a period of several years subsidence of pavement and infrastructure of a gas plant located on an island in the Middle East were observed. It is known that various areas of the industrial plant were built on highly weathered sandstone and weathered limestone. Furthermore, to achieve a plane working surface the area was initially flattened by a cut and fill procedure resulting in inhomogeneous backfilled areas. Thus, loosening zones and cavities have two different origins. Foundation settlement already occurred, which made a large scale exploration and risk assessment essential for the continued safe operation of the plant. A combination of ground-penetrating radar (GPR), electrical resistivity tomography (ERT) as well as surface wave seismic (MASW) were used to benefit from the individual resolution, depth penetration and advantages of the geophysical methods. Accompanying small trial pits were excavated, as well as drillings were performed and the subsequently explored cavities were inspected using downhole video. All data gathered were presented in a user-friendly GIS format, which is now also available for the client for future projects.

1. Introduction

Natural gas recovered from various gas fields in the Arabian Gulf is fed from offshore pipelines into LNG (Liquified Natural Gas) plants located on small islands in the Gulf. The natural gas needs extensive treatment to remove water and chemicals like hydrogen sulfide, carbon dioxide and other components until it undergoes further processes to create LNG. LNG typically contains more than 90 percent methane.

The island and its infrastructure under investigation in this paper is located within the Arabian Sea, approximately 120 km north of the UAE. Geologically, the island is probably the erosional remnant of larger intrusion and the outcrops rises from a gentle dome formed by diapirism at Jurassic time. The deposited sediments above the diapir like Miocene rocks consisting of marl, limestone, sandstone and shale, which enclose the Hormuz Complex of all diapiric islands in the Persian Gulf, were uplifted and more or less completely eroded. The development of the island through salt diapirism causes severe tremendous complications for engineering purposes. The diapirism creates mechanical upheaval at the near surface and provides nucleation cracks for cavities. The karstification which is caused by dissolution of salt, carbonate and gypsum through the action of saline surface water, plays also an important role for the development of cavities.

There is an extensive history on cavities in connection to engineering works and plant operations onsite. Several local depressions and some already outcropped cavities give reasoned concern about new cavities suddenly encountering on surface. This forms a very severe risk not only to distinctive structures but even more for operation of the LNG-plant, see Figure 1.

Fig. 1: Nearly outcropped cavity on main road (left) and cavity found during excavations (right)

It is generally agreed by experts that geophysical methods are able to map potential cavities and weak subsurface layers. However, experience shows that a single geophysical method is not able to provide all investigation requirements, i.e. investigation depth and resolution (geophysical data can be ambiguous). Therefore, it is essential to use a combination of different geophysical methods to reduce uncertainties.

In 2012 decision was made to conduct a geophysical survey on two areas of the island, where a LNG plant and chemical process facilities are located. The two areas, i.e. the “LNG Plant Area” and the “Process Area” are located on the North-Eastern part of the island. It was proposed to map a total area of approx. 180.000 m^2 using geophysical methods. Both areas are known to have a large number of surface facilities (buildings, tanks, boilers etc.) as well as a high number of subsurface installations, such as cables, pipes, trenches etc.

We suggested the combination of three geophysical methods (GPR, MASW and ERT) with GPR and MASW to be applied on paved surface and ERT on soft ground. Within this paper we describe the geophysical methods, the cavity search methodology and surveying results.

2. Geophysical Methods

Geophysical methods have been proven to locate subsurface cavities or related subsidence phenomena, thus avoiding potential collapses and extending the safety and operational life time of constructions or industrial facilities. However, experience shows that a single geophysical method is not able to provide all investigation requirements, i.e. investigation depth and resolution. Therefore, we used a combination of several geophysical methods which are known to have great potential mapping subsurface cavities and weak subsurface areas.

2.1 Georadar (GPR)

Georadar or Ground Penetrating Radar (GPR) explores the subsurface using electromagnetic radar waves which are being reflected at target objects and layer boundaries.

Radar impulses are sent out by a transmitter antenna. These pulses propagate downwards and getting reflected on buried objects and structures. Reflected or back scattered waves are recorded at a receiver antenna. Frequencies used ranging between 10 MHz und 1000 MHz, depending on target depth and requested resolution. The recorded data are presented in radargrams which display the reflection structures in terms of amplitude variations vs. travel time. With a known propagation velocity of electromagnetic waves in the subsurface, a correlation with depth is given. Typically, surveying is done along parallel profile lines, e.g. in a distance of 1 m.

After field survey digital processing is done for signal enhancement. The result is a radargram showing the reflection amplitude against travel time (depth) along the measured profile.

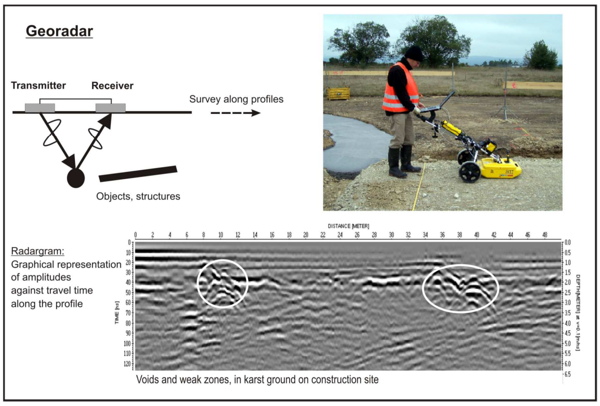

Fig. 2: Georadar (GPR) principle

Further on, all single radargrams are put together in their correct positional arrangement and horizontal slices (time slices) of the absolute signal amplitude are calculated. In that way, area covering images of reflected signal energy for different depth ranges are obtained.

Voids, cavities, pipes, etc. can be detected through their enhanced reflected amplitudes. The shape of such an anomaly typically is that of an inverted U-shaped curve. However, different fillings or geologic material variations can cause comparable signal changes as well. Strong reflections from a shallow object may lead to multiple reflections, thus appearing to have a larger depth extension or masking deeper lying objects.

The radar equipment used was of type “IDS Detector Duo” (see Fig. 2). This radar system works with two frequencies simultaneously, thus giving a high resolution (higher frequency) for shallow depths and additional larger depth penetration with the lower frequency. The two antenna frequencies are 700 MHz and 250 MHz. With the 700 MHz antenna a penetration depth of up to about 2.5 m could be achieved, the 250 MHz antenna yield results up to a depth of about 4 m in average. The sampling frequency in profile direction was 3 cm.

Processing of the georadar data and creation of time slices were done with ReflexW (Sandmeier Software, Germany). Processing and interpretation were carried out for the 250 MHz measurement only, as this frequency provided already a good resolution, but gave a significantly higher penetration depth.

To estimate the depth of a target the radar velocity in the subsurface had to be determined from reflection hyperbolae (in average 0.1 m/ns). This value was then used for all depth calculations.

2.2 Surface Wave Seismic (MASW)

The multichannel analysis of surface waves (MASW) method was first introduced into geotechnical and geophysical community in early 1999 (Park et al., 1999). MASW is a seismic method which generates a shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing surface waves of the Rayleigh type on a multichannel record.

The method utilizes multichannel recording and processing concepts widely used for several decades in reflection surveying for oil exploration. MASW utilizes energy commonly considered as noise on conventional reflection seismic surveys. The fundamental mode of ground roll (the Rayleigh-type surface wave event) is without a doubt one of the most troublesome types of source-generated noise on reflection surveys. Rayleigh wave energy is defined as signal in MASW analysis, and needs to be enhanced during both data acquisition and processing steps.

Once a seismic record is prepared dispersion curve analysis has to be done. This step is the most critical because it has the greatest influence on the confidence in the final Vs output. In other words, the Vs output will have, at best, as much confidence as the dispersion curve provided to the inversion step.

As a result of MASW a 1D shear wave profile with depth is obtained. Shear wave velocity is directly related to the soil stiffness, thus MASW is a method to find weak subsurface zones.

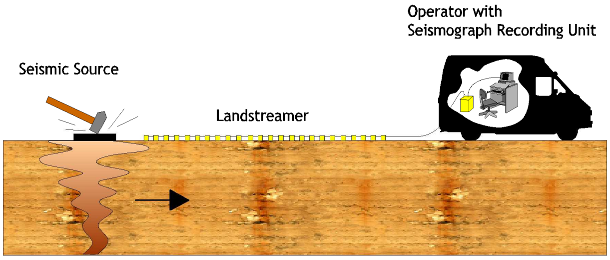

Fig. 3: Surface Wave Seismic (MASW) principle

Seismic waves of very small amplitude were generated by a sledge hammer strike. The seismic signals generated are recorded using the seismograph recording unit DMT Summit Compact. At each shot point the records of several repetitions of hammer strikes were stacked at least 4-6 times in order to reduce the disturbing influence of environmental noise. A timing trigger was attached to the hammer to provide exact trigger time to the seismograph.

A landstreamer was used to acquire the seismic signals on the paved ground. A landstreamer is a sensor unit consisting of 24 single sensors mounted on steel sledges. The sledges are attached to a high-tech belt at a half meter separation. The belt is hooked to a car or pulled manually from one to the other receiving point. To obtain a better signal response (broader band width) Geotomographie GmbH developed a landstreamer receiver system using accelerometers with a wide frequency band starting at around 1 Hz and going up to more than 1 KHz. In such a case lower frequencies (larger investigation depth) as well as higher frequencies (better resolution) can be detected. Two streamers of this type were used.

Fig. 4: Landstreamer LS-ACC with full cover protection

The in-situ gathered seismic data need further analysis. Seismic processing was made using SURFSEIS® software made by Kansas Geological Survey. In the first processing step of the seismic records the so–called dispersion curve is determined for each shot point with help of a slant stack transformation. The dispersion curve contains the information of the vertical distribution of the dynamic stiffness of the soil at the centre point of the landstreamer.

By means of a numerical inversion calculation based on the elastic wave equation the dispersion curve is converted into a 1D profile of the S-wave velocity. Due to the frequency range of the determined dispersion curves, in average between about 20 and 100 Hz, and the velocities at the site, S-wave velocity profiles could be obtained down to depths of about 10 m.

2.3 Electrical Resistivity Tomography (ERT)

For the investigation of shallow sediments geoelectrical resistivity methods are most common as they offer a rapid profile mapping and reliable results. Modern geoelectrical equipment is light-weight and can be operated by one or two persons in the field.
The principle of geoelectric (or resistivity) methods is to measure the apparent electric resistivity of the subsurface using a four-electrode array (see Fig. 5, top). In this case the current I is injected between two steel electrodes and depending on earth resistance an electrical potential U is measured between the two other steel electrodes. If the distance between the electrodes is increased a larger penetration depth can be achieved. So, the subsurface can be mapped at different depth levels.

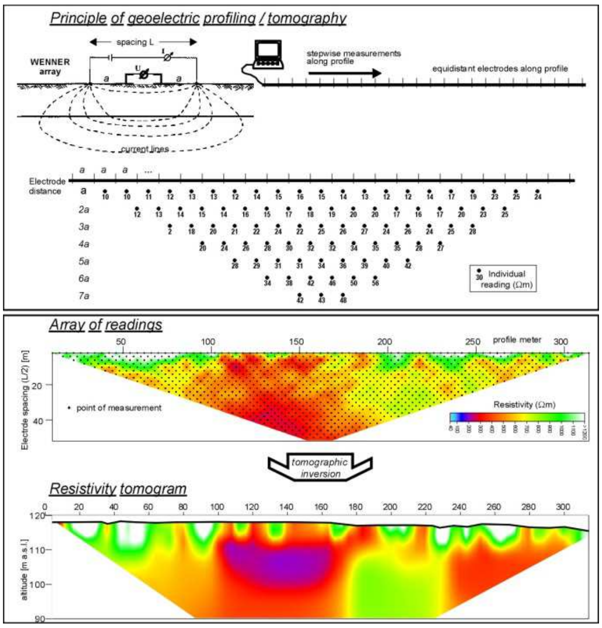

Fig. 5: Geoelectrical (ERT) principle

In the case of the geoelectric profiling method (geoelectric tomography) the measurement is automated. Along a profile equally spaced steel electrodes are placed. Resistivity readings are taken all along the profile starting with a small electrode spacing and subsequently increasing the electrode spacing to reach larger depth.

The measured earth resistivity is an averaged value. In order to obtain true resistivity values located at a true depth a tomographic inversion routine is applied. The calculation uses a numeric reconstruction algorithm and assigns resistivities to a given grid of x-z values. The result is a so-called resistivity tomogram. The interpretation of tomograms is usually referenced to drillings or outcrops.

The geoelectrical equipment used was of type "Multielectrode resistivity meter: 4Punkt Light HP" (LGM). It consists of a main control unit, 4 electrode cables (80 m long) each having 20 programmable switch boxes and 80 steel electrodes. The unit outputs around 100mA @ 38V.

The steel electrodes were spaced at regular intervals. At a first test stage two different electrode configurations (Wenner-Schlumberger, Dipole-Dipole) were tested over the same survey line. It was found that the Dipole-Dipole configuration showed a higher noise level. So, it was decided to use the Wenner-Schlumberger configuration for all further ERT lines.

After placing the steel electrodes and connecting the cables to it the measuring scheme was selected depending on the length of the survey line. Penetration depth was approximate 15-20 % of the survey line length. After starting the surveying program routine readings were taken automatically. Erroneous readings with errors larger than 10 % were re-measured after completion of the surveying line. In most cases significant error reduction was reached. The data were stored on laptop. Data were analyzed using the geoelectrical software "ResistivityImager2D" (Geotomographie).

Processing of the data was done line by line. First a statistical test was carried out to check whether the data still contain outliers or not. Second, outliers of implausible high and low resistivities were removed from the data set. Finally, the subsurface was divided into a numerical grid and a tomographic inversion was carried out. The output was processed and displayed using SURFER software.

2. Cavity Search Methodology

GPR has most potential to detect cavities with high resolution down to about 3..5 m. MASW is superior to GPR detecting deeper anomalies but with less resolution compared to GPR. Anyhow, the MASW parameter (S-wave velocity) is directly related to soil stiffness and therefore it is an excellent indicator for loose subsurface soil conditions.

It was supposed that cavities could be detected directly by GPR if they were close to the surface. Observed geophysical anomalies showing clear indications such as

- Strong signal diffractions from isolated anomalies
- Strong amplitude variation with steeply dipping reflections
- Signal coherency indicating subsidence or trench building,

were ranked into category 1 equal to "highest probability for cavity".

As GPR signal energy decays with depth only weak indications could be expected from deeper cavities. Further, MASW can show soil stiffness variation but at a scale larger compared to GPR. Thus, geophysical anomalies showing weak indications for cavities due to intensity of the signal and the depth were ranked into category 2 equal to “medium probability for cavity”. Signal indications could be such as

- Weak or only partially signal diffractions from isolated anomalies
- Dipping reflections with small amplitude strength
- Very low seismic S-wave velocity in the upper 5 m

GPR signal completely disappears once it gets too deep. In contrast to this MASW shows more anomalous geological features such as trenches or buried valleys also for greater depth. Further, subsurface installations might influence GPR signal propagation and often side effects may hide a potential cavity. Thus, anomalies with indications such as

- Partially signal diffractions from isolated anomalies
- Very low seismic S-wave velocity at larger depth

were ranked into category 3 equal to “low probability for cavity”.

A fourth category was finally added containing GPR signal anomalies found very close to the surface only (0 to 0.5 m). Here, we found strong indications for superficial voids immediately beneath concrete slabs (category 4).

The interpretation scheme of the different categories is shown in Tab. 1.

Tab. 1: Geophysical Risk Assessment

Category	Cavity Risk	Description
1	High	Strong indication for cavities
2	Medium	Weak indication for cavities due to intensity of signal and depth
3	Low	Indications for weak subsurface soil state or side effects from underground utilities
4	High	Strong indication for superficial and very shallow voids immediately beneath concrete slabs

3. Surveying Results

In order to plan the geophysical surveying layout CAD drawings available for the LNG Plant Area and the Process Area were utilized. It was supposed to use local coordinates as basis for a general grid line layout. Geophysical profiles were meant to be aligned to these grid lines. Surveying was done using a Trimble M3 DR 3“ total station.

For example, within the LNG Plant Area a 50x50 m grid based on local coordinates was set up. Grid points were marked on large and open areas using spray paint wherever it was possible.

Base lines for geophysical profiles were aligned either North-South or East-West whatever was more convenient. Geophysical surveying was performed perpendicular to the base lines. Readings were taken along lines marked with tape measure.

For example, for Georadar the measuring tapes were laid out along an East-West base line from one grid point to the next one (50 m further away to the East). Additional measuring tapes were laid out perpendicular to the next grid point 50 m to the North. GPR lines were measured then South-North with profile steps of 1 m eastwards.

For single lines the starting and ending local coordinates were surveyed using the Trimble system. In most cases GPR and MASW could use same markings.

3.1 GPR Results

The total length of georadar profiles was 47050 m for the LNG Plant Area and additional 11340 m for the road encircling the LNG Plant area. About 1500 individual profiles have been measured. The standard length of each profile is 50 m. Shorter profiles occur due to limited space, thus the average profile length is 39 m.

The GPR line coverage of the Process Area was much less compared to the LNG Plant Area. The total length of georadar profiles is 21760 m for the Process Area and 11030 m for the adjacent Utility Area. About 864 individual profiles have been measured. The average profile length is 38 m.

Within the radargram the reflection amplitude is shown as colour-coded image. Blue and pink colours correspond to high positive/negative signal amplitudes whereas light grey correspond to low signal amplitudes.

In general, strong reflection amplitudes not coinciding with known cable channels, single cables, tubes, pipes or other subsurface structures are potential evidences for cavities. However, such anomalies might be caused also by fillings with varying materials or local changing geology as well.

Each radargram was inspected visually to identify structures indicative for cavities. Such indicative factors are strong signal amplitudes, hyperbolic geometry or funnel shaped layer structure.

Figure 6 shows a typical example of anomalies indicative for cavities.

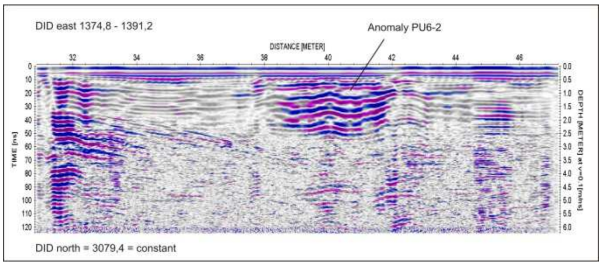

Fig. 6: Radargram showing shallow anomaly PU6-2

Radargrams were also processed as areal 2D time slices to represent a certain depth (=time) horizon.

3.2 MASW Results

Seismic records were analyzed using the software SurfSeis® from Kansas Geological Survey. A total of 5000 seismic shots was processed for the LNG Plant Area and about 2500 shots for the Process Area.

Surveying was performed along 2D lines and if larger areas available using a “snake line surveying” (see Fig. 7)

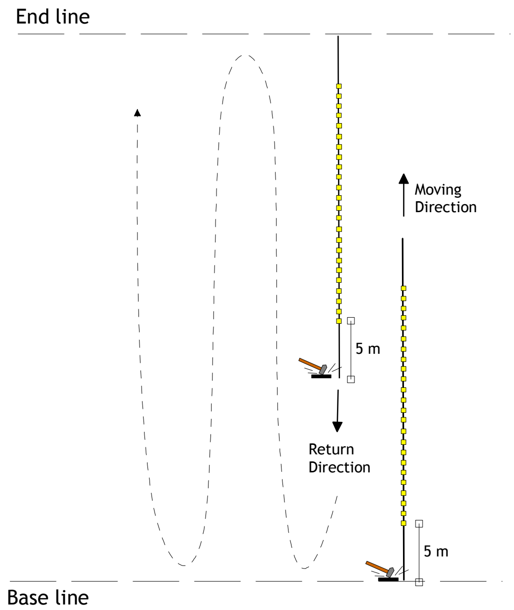

Fig. 7: MASW testing layout (snake-line surveying)

The same subsurface model, i.e. a 10-layer model was used for the LNG Plant Area and Process Area. Layer thickness was chosen to be smaller close to surface and larger with increasing depth. Depth to half-space was set to 10 m.

Fig 8: MASW Depth Slice at 5 m (LNG Plant Area)

From each shot point a 1D depth profile of the S-wave velocity was generated and geo-referenced. Finally, all 1D profiles were compiled to a 3D data set and depth slices were calculated. Depth slices were generated at 1 m, 2 m, 3 m, 5 m, 7 m and 10 m depth. Figure 8 shows an example depth slice at 5 m within the LNG Plant Area with facility information overlapped.

Low seismic velocities correspond to a less consolidated material (small soil stiffness) whereas high seismic velocities correspond to harder material. Unfortunately, there is no clear correlation between geology and seismic velocity. Typically, such a correlation is site-specific and has to be established based on a larger number of boreholes.

Anyhow, it is obvious that there are distinct areas where low velocities are present. There is a low velocity area in the North-West corner of the area and another low velocity area in the central part forming a somewhat channel-like structure. This structure could be an older channel filled in with material excavated while flattening the island in earlier times.

The low velocity areas are of major concern due to material with lower stiffness. Several drillings are recommended to access these zones. Anomalous zones are ranked in category 2 or 3 as they do not indicate an isolated single cavity rather areas of potential subsidence.

3.3 ERT Results

ERT measurements could only be performed on a small unpaved area located in the South-West of the LNG Plant Area. Surveying was carried along 3 profiles. Electrodes were placed in a regular distance of 1 or 2 m to each other along the profiles. The Wenner-Schlumberger array was used to measure ground resistivities.

Analysis of the surface ERT data was made using the geoelectrical software "ResistivityImager2D" (Geotomographie, Germany). After importation data were cleaned from buggy values. The filtering of the data also contains the setting of reasonable upper and lower bounds for resistivity values. A finite element based data modelling was performed.

To check the misfit between measured and modelled data the so-called pseudo-section display was used (see Fig. 9). The pseudo-section display shows in a graphical way how the misfit is distributed among the data values. It also shows areas with good and bad misfit. Considering the extreme field conditions (dry soil, profiles close to infrastructure) the data fit can be regarding as very good. The resulting tomogram was exported and plotted using SURFER software.

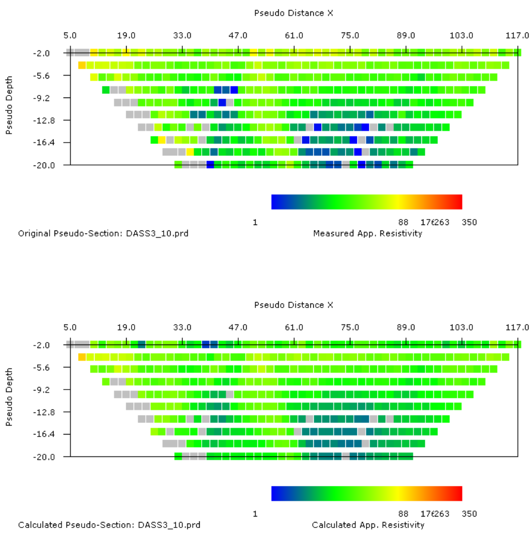

Fig. 9: Pseudo-Section display of original data (upper diagram) and modelled data (lower diagram)

4. Conclusions and Recommendations

This paper describes the geophysical surveying carried out to detect subsurface anomalies (e.g. cavities) within an industrial plant located on an island in the Arabian Gulf. A combination of three methods (GPR, MASW, ERT) was applied, with a focus on GPR and MASW. Both, GPR and MASW together were cross-validated on more than 90 % of the total surveyed area.

Anomalies were found at several locations having different depth and size. The signal pattern or the effect of an anomaly shows up with different strength and clearness in the geophysical data. Thus, a ranking of the anomaly according to the proposed categorization scheme was made based on the pattern and scale of the anomaly.

There are two potential scenarios of the effect of a cavity on a building or plant facility. Within the first scenario a sudden collapse of a cavity causes an immediate effect on a facility. Those damages cannot be foreseen and there are only short-term indications for such an event. As there is no reaction time left precautions in terms of underground investigations by drilling and geophysical investigations have to be made.

The second scenario describes medium to long-term processes caused by settlement and subsidence. In this case there will be early indications which could be recognized not only by instrument installations for monitoring settlement or deformations. Both types of anomalies could have a different impact to structures built on the surface.

A total of 96 anomalies were identified by the geophysical methods. Anomalies were ranked into four categories each having a different probability of a cavity risk. Anomalies with a potentially high cavity risk were found at shallower depth by GPR whereas MASW located deeper anomalies related to potentially loose sediments. 11 anomalies out of the 96 were identified to belong to the highest category. Many of these are related to single and isolated subsurface features where the signal pattern caused in the geophysical data strongly point to a cavity or other feature/body with a strong petrophysical contrast.

General recommendations have been drawn from the available geological information and geophysical data. Anomalies with a potentially high cavity risk should be verified by drillings. Short-termed hazards should be inspected by geophysical surveying and drillings immediate following to map the extent of the hazard zone. Medium to long-term hazards should be documented by regular visual inspection of roads and facilities. Regular levelling of critical structures as well as the installation of settlement observation sensors shall be made.

Future action for site investigation shall be taken into account especially on those areas where karstic rocks are known to be present.

5. Literature

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