

GROUND FAILURE DUE TO GYPSUM DISSOLUTION

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Abstract

Gypsum in Hellas and Cyprus occurs in three different types: (a) bedded (mainly of Messinian age in Cyprus and Crete), (b) domes (mainly western Hellas and Crete), and (c) as bodies, fragments and cementing material in Triassic conglomerate formations (western Hellas). Ground failure caused by void migration to the surface, resulting from gypsum dissolution, is a common phenomenon in such areas, which are also found in other European countries (e.g., Italy, Spain, Switzerland, U.K., Lithuania, Latvia, Poland, Romania, Turkey, Ukraine and Russia). In this paper three different case studies of ground failure are presented: Cyprus, Crete (Viannos) and Corfu. Engineering geological, stratigraphical, geophysical, hydrogeological and hydrogeochemical studies of these areas, revealed the direct relationship between surface runoff, and ground water circulation with the rate of gypsum dissolution, the subsequent development of karst hollows, and the associated ground failure in urban and suburban environments. Two main models were defined, according to different mechanisms of gypsum dissolution. The first model is associated with the erosion activity of surface runoff, the second with the dissolving capacity of ground water. Risks to the urban and suburban environments were assessed, and guidelines as well as mitigation measures were proposed.

Key words: ground failure, gypsum, Cyprus, Crete, Corfu

1. Introduction

Gypsum in Hellas and Cyprus occurs in three different types: (a) bedded (mainly of Messinian age in Cyprus and Crete), (b) domes (mainly western Hellas and Crete), and (c) as bodies, fragments and cementing material in Triassic conglomerate formations (western Hellas).

Gypsum affects many parts of Europe including Italy, Spain, Switzerland, U.K., Lithuania, Latvia, Poland, Romania, Turkey, Ukraine and Russia. Subsidence caused by gypsum dissolution has been recorded in Texas (Olive 1957), Canada (Wigley et al. 1973), Germany (Hundt 1950; Herrmann 1964; Strobel 1973), the Alps (Nicod 1977), Russia (Gorbunova 1977) and Newfoundland (Sweet 1977).

The presence of gypsum many times causes serious ground failure problems, especially when occurring in urban areas. Some of the towns and cities worldwide that are affected by gypsum geohazards are: Ripon and Darlington in the U.K. (Cooper 1995), the city of Zaragoza (Benito et al. 1995) and the town of Calatayud (Gutierrez et al. 2002) in Spain, the outskirts of Paris (Toulemont 1984) in France, Stuttgart and many towns peripheral to the Hartz Mountains in Germany (Pfeiffer and Hahn 1972; Strobel 1973), and the towns of Birzai and Pasvalys in Lithuania (Paukstys 1996).

Gypsum can also cause severe problems when it is situated beneath large engineering structures: at

least 14 examples of dams losing water or failing (James 1992) have been recorded in the USA, and at least two dams in China have been affected (Lu Yaoru and Cooper 1997). In the UK, at Ratcliffe, south-west of Nottingham, power station foundations have been affected by water leakage and dissolution of thin Triassic gypsum beds (Seedhouse and Sanders 1993).

There is a need for detailed site investigation and common methodology approaches for the mitigation of gypsum geohazards. In Hellas and Cyprus, several urban areas, mainly villages, are being affected by sinkholes due to gypsum dissolution. In the following, three distinctive case studies are presented.

2. Gypsum dissolution rates

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) dissolves in flowing water about one hundred times more rapidly than limestone, but at only about one thousandth the rate of halite. At Ripon Parks where Permian gypsum abuts the River Urea a large block (3m^3) of gypsum fell into the river and dissolved in 14 months. This occurrence was reported by James et al. (1981) who presented formulae from which the gypsum dissolution rates can be calculated (dissolution rates were estimated between 0.1 and 1.7 m per annum).

The rate of gypsum dissolution increases with temperature and the speed at which water passes the gypsum surface. The gypsum dissolution rates observed in the field agreed closely with those obtained from laboratory experiments by James and Kirkpatrick (1980), James and Lupton (1978) and by Kemper et al. (1975). These observations considered the dissolution of gypsum by pure water. In subsurface conditions where calcium carbonate is dissolved in the groundwater (waters rich in CaCO_3) the solubility of gypsum is increased; gypsum solubility may also be increased by the presence of other ions in solution such as chloride (Deer et al. 1962; Kempe 1972).

Water abstraction could affect gypsum-water systems. Calculations for a major water abstractor pumping from the Permian gypsum and limestone beds in Northern England show some alarming results. The water contains approximately 1200 ppm of SO_4 mainly as dissolved CaSO_4 ; the abstractor pumps 212 Ml of water per annum. This is equivalent to removing approximately 200 m^3 of gypsum a year from the area. It is likely that much of the dissolution represents the enlargement of joints over a wide area. (Cooper 1988). In places, such as at Ripon in North Yorkshire, the dissolution is so active that a new subsidence feature appears every year or two (Jones et al. 2005).

3. Case studies

3.1 Cyprus

Gypsum in Cyprus occurs in the form of strata layers created during Messinian Salinity Crisis in Mediterranean. These Messinian evaporates (“Kalavassos formation”) were deposited usually in fault controlled basins. (Koutsouveli et al. 2008). Gypsum layers are found between the Lower and the Upper Gypsiferous Marls.

Several ground failure problems were encountered in urban areas, mostly during the last decade, that resulted mainly by an increase of water abstraction (over-pumping). A two-year (2005-2006) project has been carried out by the Geological Survey Department of Cyprus in collaboration with the Institute of Geology and Mineral Exploration (IGME-Greece), and its external partners (Geoinvest-Cyprus, cbs - C. Stergiopoulos), for the study of sinkholes due to gypsum dissolution in Cyprus.

The target of the project was, a) the study of areas with known problems affecting urban environment and b) the definition of sinkhole prone areas and recommendation of appropriate mitigation measures.

The following works were conducted by a multi scientific team:

- Interpretation of airphotos and satellite images,
- Engineering Geological Studies,
- Geophysical Investigations,
- Hydrogeological – Geochemical studies,
- Underground stability analysis of cavities,
- Geotechnical Evaluation – Geological “Suitability” (using GIS).

Interpretation of airphotos and satellite images

The contribution of the interpretation-analysis of airphotos and satellite images to the current study was the definition of faults and its relation to karst structures and phenomena. Several geo-forms, such as sinkholes, lowlands, and cracks, were recognised and recorded.

Engineering Geological Studies

Detailed site investigation was carried out in areas formed by Kalavassos formations, with emphasis on two pilot areas (Pera Chorio – Nisou and Aradipou), leading to the following works:

- Engineering geological mapping,
- Palynological analysis,
- Surveillance – evaluation of geotechnical boreholes,
- Laboratory tests (soil and rock mechanics),
- GIS database,
- Correlation and interpretation of all data – design of engineering geological cross sections.

In the areas of Cyprus gypsum outcrops, engineering geological maps were produced in a scale of 1:5,000, using field data, palynological analysis, data from the interpretation of satellite images and airphotos, as well data from the boreholes.

In seven areas, twenty eight (28) geotechnical boreholes were drilled with total length 1,537.50 m.

Soil and Rock mechanic tests were carried out for the determination of natural and mechanical characteristics of the formations. Several specimens, representative of the various types of gypsum (marble, selenite, brecciated), were tested in uniaxial compression and then slake durability tests were performed on the “broken” samples.

The slake durability test examines mainly the mechanical corrosion of the rocks trying to simulate the climatic changes of dryness and wetness. The initial water used for the test was pure (distilled) water, while the used water at the end of the test was chemically analysed.

The following results were deduced from the correlation and interpretation of chemical analyses, slake durability index and the uniaxial compressive strength of the gypsum specimens:

- Gypsum of “marble” type present greater strength,
- Mechanical corrosion is not influenced by sample strength nor by the type of gypsum,
- Chemical analysis of the used water shows that all types of gypsum are soluble. The used water was found rich in Ca^{2+} and SO_4^{2-} , consequently the samples were supersaturated in gypsum,
- The values of the proportion $\text{Na}:\text{Cl} < 1.0$ show that gypsum samples present low relevant concentrations of Na explained by the way of gypsum genesis,
- The values of the slake durability index, which corresponds to the percentage of dry mass of the fragments retained by a drum of 2.0 mm (No 10) square-mesh after two cycles of oven drying and 10 min of mixing in water, vary between 76.2 and 95.6.

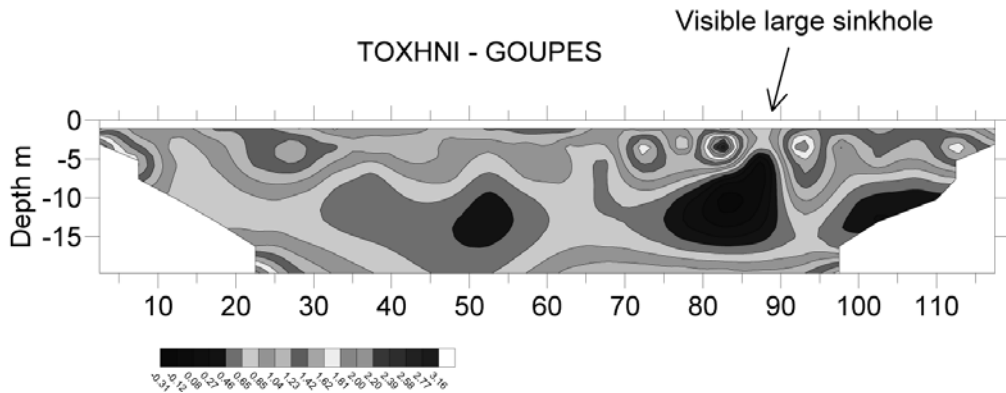


Fig. 1: Example of resistivity anomaly obtained over visible large sinkhole.

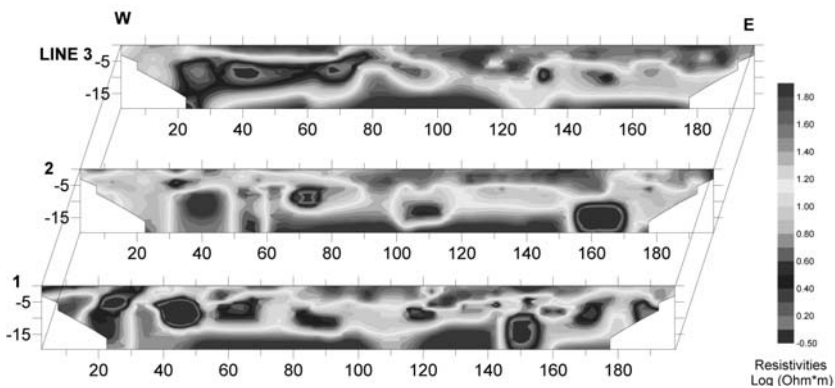


Fig. 2: Inverted resistivity sections of lines 1 to 3 at Pera Chorio, Cyprus.

Engineering geological cross sections were designed in all selected sites, which helped the better understanding of the geological structure. The data used for the design of engineering geological cross sections derived from morphological relief, field mapping, geophysical investigations and boreholes (195 boreholes with total length 6,132.60m were decoded and evaluated).

Geophysical Investigations

The Electrical Resistivity Tomography technique was utilized in the Cyprus study with good results. Targets tend to appear as conductive anomalies when filled with clay material and resistive anomalies when they are empty. The work was carried out using a 24-electrode system with a Pole Dipole array and an electrode spacing of 3 and 5 m.

In Figure 1 an example is presented of the typical anomaly pattern of ERT obtained over an open sinkhole. The cavity is filled with clayey material with resistivity values smaller than 2 Ohm*m.

The method was applied on grids with parallel lines at a distance of 10 m. In Figure 2 the results of 3 parallel lines are presented. The lines were located within the banks of a river and this resulted to a large number of anomalies possibly associated with sinkholes.

A layer of coarse grained sediments is shown near surface to a depth of 3 to 5 m with resistivity val-

ues between 20 and 60 Ohm*m (1.25 to 1.8 in log scale). The layer of gypsum marl is detected at that depth, with resistivity values in the range of 5 to 12 Ohm*m (0.6 – 1.2 log scale). The presence of possible sinkholes is identified by the characteristic circular or funnel shale conductive anomalies with values between 1 to 3 Ohm*m.

In certain cases, the presence of a sinkhole is been evidenced by a conductive lineament migrating and reaching the surface.

“Anomalies” with characteristics of cavities were detected in all sites except Aradippou because the cavities there are found in great depths, greater that the max depth where geophysical investigation can reach.

Hydrogeological – Geochemical studies

In the frame of the hydrogeological, hydrochemical and geochemical investigations, a network of hydro-points was established in two reference sites (Aradippou and Pera Chorio Nisou) and water table measurements and sampling of underground water were carried out. The frequency of measurements for year 2005 was every six months and for year 2006 every month. Moreover, hydrochemical and geochemical analyses were carried out on selected soil and rock samples from the drill cores.

The physicochemical parameters evaluated were pH, Ca, SO_4^{2-} , HCO_3^- and electrical conductivity (E.C.). The physicochemical “trends” were correlated to the hydraulic characteristics of the underground water flow.

The karst forms observed in the drill cores allowed the introduction of the reference sites into the following four categories of karst types:

“young”,
“active”,
“mature” and
“inactive”.

The main conclusions referring to genetic mechanism of gypsum karst were the following:

- An important factor of gypsiferous formations solubility is the groundwater. This is confirmed by the tracing of “active” or “young” karst cavities in great depths under impermeable overburden formations with thickness ≥ 60 m. Within these conditions, surface water cannot act mechanically.
- Karst processes are natural phenomena that are under development. The progress of karst formation depends on the local engineering geological conditions. Consequently, the time occurrence and magnitude of sinkholes varies in every location.
- Finally, “saturation” conditions, namely equilibrium state and pausing of solution processes, cannot be reached as both groundwater systems, Aradippou and Pera Chorio – Nisou, are not “closed”. Thus, the whole process of karst development is a natural phenomenon in progress and cannot be stopped.

Underground stability analysis of cavities

Underground stability analysis was performed for the determination of the geological suitability of a village called Maroni (Poyiadji et al. 2009). The stability analysis was carried out for karst cavities under the central area of the village with a hypothetical geometry. According to the results of the stability analysis and the calculations of safety factors for the examined wedges it was concluded that there is a stability problem of a tetrahedral wedge falling from the roof, but the expected ground failure on the surface should be very small.

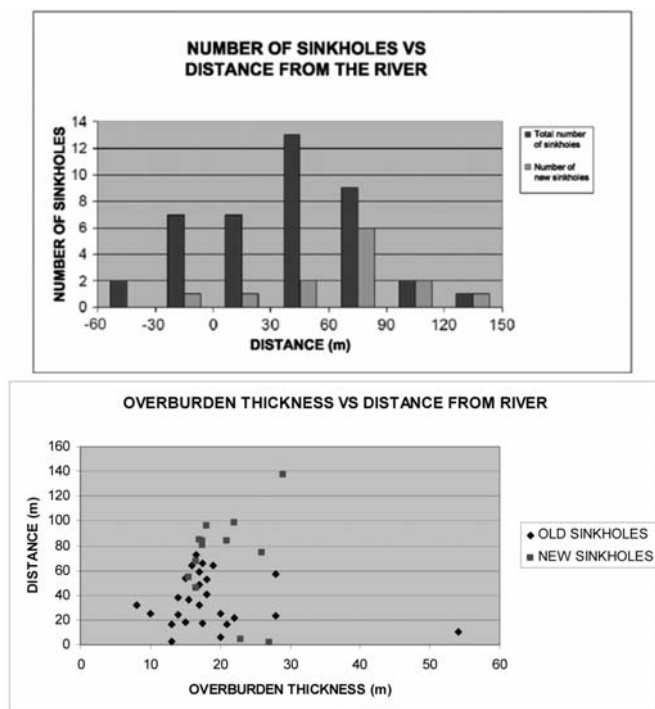


Fig. 3: a) left – Number of sinkholes versus distance from the river, b) right – Overburden thickness versus distance from the river

Geotechnical Evaluation – Geological “Suitability” (using GIS)

In the frame of the geotechnical evaluation, the distribution and magnitude of sinkholes in a selected area were statistically evaluated. Every sinkhole was numbered and for each one several characteristics were recorded (time of occurrence, distance from the river, thickness of overburden loose materials, thickness of cohesive overburden material, max diameter and surface area).

The greater number of sinkholes occurs in the zone of 30-60 m, an area that coincides with the riverbed (Fig. 3a). The distance from the river of younger sinkholes, tend to increase (Fig. 3b). This can be explained by the theory that the mechanical action of the water washes out filling materials and progressively can reach more remote areas.

The distance from the river is determinative factor while the overburden thickness also affects the development of sinkholes. Another controlling factor for the development of sinkholes is the depth of groundwater table as the mechanical action of river water decreases when entering in the regional water table because of the reduction of its velocity.

The greater recorded distance of a sinkhole from the river was 137 m (Fig. 3a) and the greater overburden thickness 54m (Fig. 4a).

The study of sinkholes due to gypsum dissolution revealed that in Cyprus two are the most significant genetic models (Table 1).

One of the main targets of the study was the estimation of ground failure consequences on urban en-

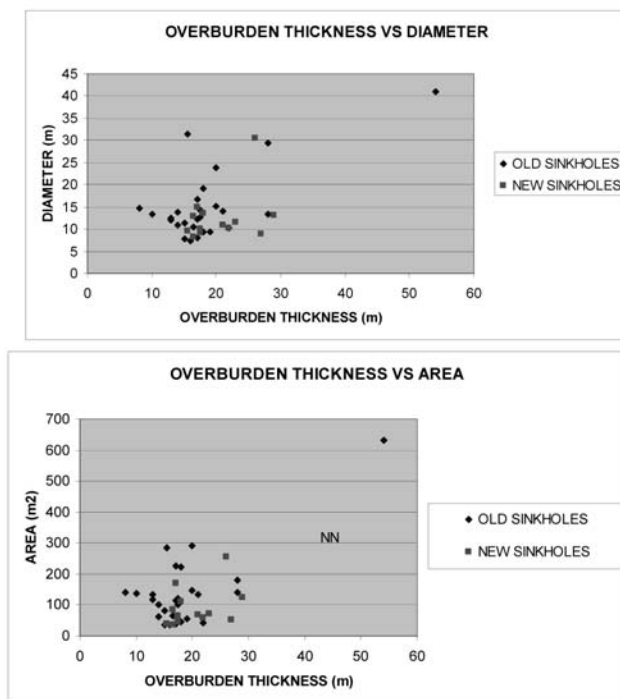


Fig. 4: a) left – Overburden thickness versus diameter of sinkholes, b) right – Overburden thickness versus area of the sinkholes

Table 1.

<i>MAIN CHARACTERISTICS</i>	<i>MAIN INFLUENCING FACTORS</i>
TYPE I (Pera Chorio – Nisou) the dissolution of gypsum and associated problems occur in the vicinity of rivers	
<ul style="list-style-type: none"> • Mature karst environment • Direct inflow of runoff water • Washout of filled karst • Low dissolving capacity of groundwater 	<ul style="list-style-type: none"> • Distance from watercourse • Thickness and lithological overburden type • Groundwater table depth
TYPE II (Aradippou), the dissolving capacity of groundwater is high, there is no direct flow of runoff water and the associated problems at the surface are controlled mainly by the fault systems.	
<ul style="list-style-type: none"> • Young karst • Overburden formations of low permeability • Widening of underground voids • High dissolving capacity of groundwater 	<ul style="list-style-type: none"> • Thickness and lithological overburden type • Overburden formations of low permeability • Dissolving capacity of groundwater • Fault systems

vironment and the design of geological housing “suitability” maps for the selected areas. The main target of a geological “suitability” study is to define zones with same characteristics in respect to safe



Fig. 5: a) left – An old sinkhole in a riverbed , b) right – Linear ground cracks.

housing. The term “safe” refers to any kind of geo-problem and its consequences; thus any geological condition that can affect people, buildings and infrastructure. In the case of this study, the main geo-problem is the development of sinkholes and so the zones correspond to different degree of sinkhole prone areas but also are related to the set of respective measures or directives that can be applied for every zone.

Geological “suitability” can be determined provided that the genetic model is defined together with the determination of the local engineering geological conditions. Geotechnical maps of 1:2,000 scale were designed for this purpose in six (6) areas mostly effected by gypsum geo-problems.

The general criteria that were used for the determination suitability zones were the following:

- Gypsum thickness,
- Presence or not of karst forms, type, magnitude, distribution and depth,
- Gypsum depth (overburden thickness),
- Lithological type and geomechanical characteristics of overburden formations,
- Type of groundwater and fluctuations of water table,
- Solubility,
- General engineering geological conditions.

3.2 Crete - Viannos

In May 2000 a large sinkhole developed in an agriculture area south of Ano Viannos village in Crete, causing the collapse of a local road. The sinkhole had a conical shape with 50m diameter and depth (Fig. 6).

IGME conducted a preliminary site investigation, which included engineering geological mapping in 1:5,000 scale, hydrogeological and geophysical works.

The sinkhole occurred in the edge of a small internal basin consisting by alluvial and Neogene deposits. The surrounding cliffs are formed by alpine formations (mainly limestones and flysch) belonging to two geotectonic zones: Olonos – Pindos and Gavrovo – Tripolis. Oligocene gypsum domes were also recorded as intrusions in flysch and limestone of Pindos zone.

The site investigation revealed that there were several old sinkholes in the greater area. The possible formations that could be connected with such phenomena were limestones and gypsum. Gypsum

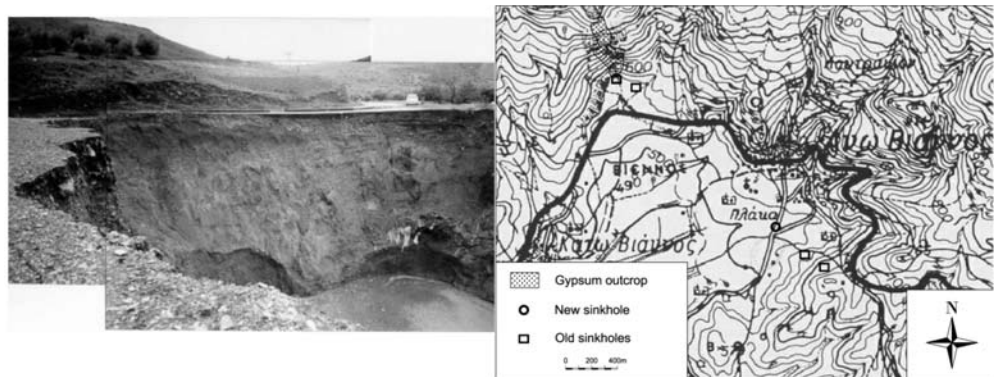


Fig. 6: a) left – A sinkhole in Viannos village (May 2000), Crete , b) Topographical map of Viannos village area.

outcrops were mapped in the greater area and two old sinkholes were directly related to them (Fig. 6b). The geophysical investigation in the vicinity of the sinkhole confirmed the existence of gypsum in the form of dome, exactly under the sinkhole. The estimated depth of the gypsum dome roof was about 130 m. The projection of the gypsum dome on the surface had an elongated shape with max diameter of approximately 180 m in a NNE-SSW direction and min, which fluctuated between 30 and 90 m.

This preliminary study suggested that the investigations (mainly geophysical surveys and geotechnical drillings) should expand in a wider area to cover the whole region where old sinkholes were recorded.

The local road should be abandoned and a diversion constructed, away from the sinkhole. Moreover, instructions were given for the filling of the sinkhole under examination:

- The filling must consist of large rocks at the base of the sinkhole, fragmented and earth materials on top of them,
- After a logical time when any settlements should be eliminated by adding more earth materials, concrete should be introduced in the hole,
- The final stage should be the construction of a reinforced concrete plate, which will cover the hole plus a ring with 15m thickness.

According to information received from the local authorities the road was diverted but the sinkhole is still open, gradually filling from river materials.

3.3 Corfu

Near the town of Corfu (Temploni area) a large sinkhole was developed in May 2008 (Fig. 7). IGME conducted a hydrogeological, engineering geological and geophysical survey for the study of the phenomenon. The region is a typical karstic area from the dissolution of gypsum with characteristic morphological features like dolines, karstic shafts and generally karstic geo-forms. Geologically the area consists of Triassic breccia (limestone fragments with gypsum as cemented material) and Triassic gypsum.

The tectonic structure of the area affects the geographical distribution of failures as the circulation of water and its dissolving action act much easier along the faults and discontinuities in general.



Fig. 7: The sinkhole in Temploni are.

The sinkhole under study has a symmetrical cylindrical form, inclined towards North, with 11m diameter. The depth of it was estimated 40m, using stratigraphic and hydrogeological data. The area of this ground failure geologically consists from Triassic breccia covered by clayey marly material with thickness at least 7m.

The Electrical Resistivity Tomography technique was also utilized in Corfu study with excellent results. A number of 15 lines were surveyed at 2 orthogonal orientations and spacing of 5 and 10m. As can be seen in Figure 8 a large resistivity anomaly is recorded over the void, with a characteristic funnel shape. The gypsum is easily distinguished from the overlying breccias sediments, with high resistivity values in the range of 500 to 700 Ohm*m. The effect of 3D geometry is evident in the interpreted 2D sections. The void which is easily detected on line SV1 is not seen on lines S10 and S11. A large resistive layer is seen instead and the resolution is lost. The large number of available data enabled the 3D processing and interpretation of the surveys. This was effected with the use of the program DC_3Dpro by Junh-Ho Kim and Mywong-Jong Yi of the Korean Institute of Geosciences and Mineral resources. In conclusion the application of ERT has proved the effectiveness of the method and the relative merits of using 3D interpretation schemes. Sinkholes are 3D targets and they require 3D processing and interpretation approach.

The under study phenomenon of ground failure and the development of the sinkhole was studied in detail and the geophysical achieved to determine the geometry of the underground cavity, while the hydro-geological and engineering geological findings clarify completely the genetic mechanism.

As it was described in the aforementioned paragraphs the geophysical investigations revealed the existence of an underground cavity under the sinkhole. The cavity is unfilled and was formed in gypsum formations. The elevation of upper part of cavity is estimated at absolute altitude +55 with overburden thickness 10m of rock formations (gypsum and Triassic breccias) and 13m of soil materials (clayey marly materials). The creation of the sinkhole derived from the partial failure of the roof of the cavity, which created a passage for the overburden loose soil materials.

The existence of the underground unfilled cavity complicates the rehabilitation of the sinkhole by filling it, while there is a risk of total collapse of the cavity which would result in the creation of a larger ground failure. Dissolution of gypsum is a continuous and relatively rapid process leading to the widening of cavities and the induced seismicity of the region increases the probability of a total collapse.

The study focused on the consequences of a total collapse. The best approach to the specific problem was the delimitation of a high risk zone, where it was proposed that building should be prohib-

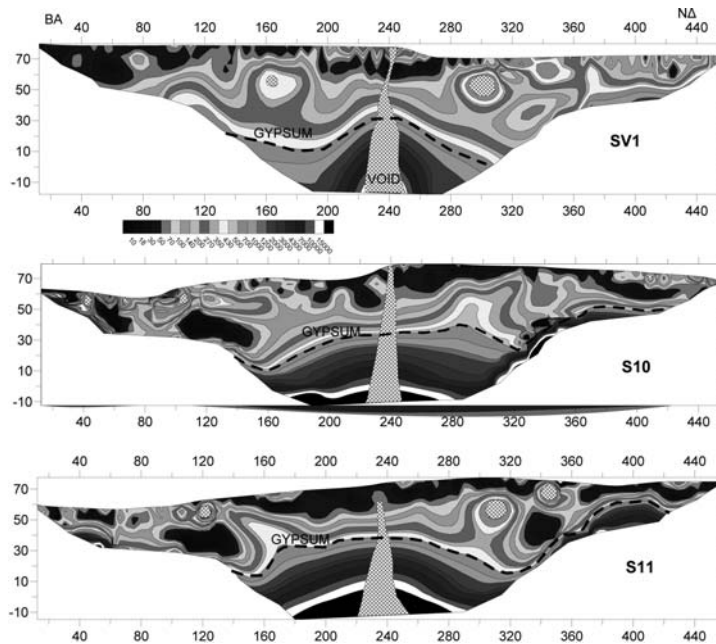


Fig. 8: 2D Inversion results of lines SV, S10, S11. Line SV1 is running over the sinkhole.

ited and the existing buildings should be abandoned. The determination of high risk zone resulted from the greater diameter of the cavity, the average thickness and the angle of friction of overburden loose soil materials ($13\text{m} - 45^\circ$). The resulted zone outside the sinkhole had a width of 13m.

The whole area is at a stage of development and as it was already mentioned similar engineering geological and hydro-geological conditions exist. The possible impacts on built environment as well as on humans should be investigated. For this reason the following were proposed:

- Determination of investigation zones according to engineering geological and urban planning criteria,
- Detailed engineering geological and hydro-geological investigations,
- Geophysical surveys,
- Geotechnical evaluation and determination of hazard zones.

In addition to aforementioned and until their implementation, geological, geophysical and geotechnical investigations should be conducted locally prior to any new construction of buildings or any other structures.

4. Conclusions - Discussion

The presence of gypsum and associated karst formation many times cause serious ground failure problems, especially when occurring in urban areas. Karst processes are natural phenomena that are continuous and the rate and type of karst development depend on the local geological conditions (tectonism, type of gypsum, overall geological structure).

Experience gained through aforementioned studies shows that there is a need for detailed site investigations (engineering geological, hydrogeological, geophysical and geotechnical surveys) with

target the good understanding of the genetic mechanism and local conditions, before applying any mitigation measures.

For large areas geological suitability maps help the determination of “safe” zones. A first logical approach would be to avoid the problematic areas by relocating structures to an area not affected. In the case that this is not possible mitigation measures depend mainly on the size of ground failures and the importance of structures under risk.

5. Acknowledgments

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