Use of engineering geophysics to investigate a site for a building foundation

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Received 31 October 2006
Accepted for publication 16 January 2007
Published 28 February 2007
Online at stacks.iop.org/JGE/4/94

Abstract
The combination of geophysical data and geotechnical measurements may greatly improve the quality of buildings under construction in civil engineering. A case study is presented here at a vacant building site. Initially, boreholes indicated a complex geology. A dipole–dipole configuration was selected for electrical resistivity tomography (ERT) implementation and the data were processed and interpreted by applying 2D and 3D inversions. An electromagnetic survey was also carried out at different time periods and successfully used to verify the results of the resistivity measurements. It is demonstrated that engineering geophysics is able to provide solutions for determining subsurface properties and that different prospection techniques are necessary for developing a reasonable model of the subsurface structure.

Keywords: Geotechnical engineering, geoelectrical tomography, electromagnetic survey, engineering geophysics

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In the last decade, the involvement of geophysics in civil and environmental engineering has become a promising approach. Geophysical methods are implemented in a wide range of applications ranging from building ground investigations to the inspection of dams and dikes (Klimis et al. 1999, Luna and Jadi 2000, Othman 2005, Savvaidis et al. 1999, Soupios et al. 2005, 2006, Venkateswara et al. 2004), aiming towards the exploration of geological structures and the determination of the physical parameters of the rock formations. In engineering geophysics, the question of the quality of building foundations is frequently addressed in the very late stages, when earthquake damage is either observed or expected (Delgado et al. 2000a, 2000b, Seht Malte Ibs-von and Wohlenberg 1999, Parolai et al. 2001, 2002, Delgado et al. 2002). In the case of building construction, geophysics can be applied for exploration purposes to provide useful information regarding the early detection of potentially dangerous subsurface conditions. The sources of hazards in civil engineering disciplines result essentially from undetected near-surface structures, such as cavities and/or inhomogeneities in the foundation geomaterials. Information

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related to the local soil conditions is vital for risk assessment and mitigation.

The procedure for obtaining subsurface information is divided into two broad categories: indirect and direct methods. Indirect methods include aerial photography, topographic map interpretation and the study of existing geological reports, maps, and soil surveys. Direct methods are comprised of the following modules: (a) geologic field reconnaissance, including the examination of in situ materials, man-made structures, groundwater level and exploration of shafts, (b) application of modern geophysical techniques for mapping subsurface structures, (c) borings, test pits, trenches and shafts from which representative disturbed and/or undisturbed samples of the in situ materials may be obtained and analysed and (d) simple geotechnical field tests, such as the standard penetration test (SPT), which can be correlated with other engineering parameters.

The above methodologies were applied in our case study within the urban context of the city of Hania, on the island of Crete, Greece. Two different geophysical methods were applied, namely, electrical resistivity tomography (ERT) (Ward 1990) and electromagnetic terrain conductivity (ETC), using the Syscal Jr Switch 48 channels by IRIS and the EM31-MK2 instruments by Geonics Limited, respectively. Resistivity profiling and electromagnetic mapping have been carried out in grids of 8 × 20 and 20 × 20 m, respectively. The resulting measurements were combined with the available geological and geotechnical reports of the study area and were used to assess the structure of the near-surface geology. After the acquisition of the geophysical data, interpretation of the resistivity results was carried out using 2D and 3D algorithms (Loke and Barker 1996, Loke 1997) and confirmed by comparison to the corresponding electromagnetic map.

Excavations in the framework of the construction works that followed the geophysical survey confirmed that geophysical modelling could successfully approach the actual geological and geotechnical soil conditions. Moreover, the particular data obtained through indirect geophysical techniques contributed to the decision making process for choosing the appropriate footing of the structure based on the subsurface inhomogeneity of the site.

2. Area of investigation

2.1. Location

The study area is located almost 200 m away from the premises of the Technological Educational Institute (TEI) of Crete in the Halepa area, an eastern suburb of Hania city, in western Crete. The area is bounded to the north by the streambed and, in its vicinity, a man-made shaft (possibly a hand-dug well) was found (figure 1). Similar features exist in the surrounding area, suggesting a shallow water table which usually causes severe structural problems. The surveyed area is near a stream denoted by the dashed line in figure 1.

2.2. Geological features

The city of Hania is laid over a complex geological structure, due to dense faulting of the whole area. Old faulting with E–W orientation has resulted in the creation of a small dipping basin, where nowadays the centre of the city is located. This basin is filled with Quaternary deposits covering most of the centre of the city and the southern part of it. Alluvial deposits, sand and anthropogenic deposits are evident in the northern part. As we move towards the south, marls appear at a few metres depth, covering most of the area in the south and east parts of the city. In the south-east part, massive Triassic limestone appears, which is considered the basement for the whole urban area. The limestone is dipping towards the north and the west at a few hundred metres depth.

Specifically, in the area under investigation, the geological formations are formed by alluvial, Quaternary and neogenic clay sediments, sands and roundstones. The sediments cover...
the biggest part of the stream banks but an olistolith (cohesive marly limestone conglomerates) has also been found in the south bank and in the study site. The stream in this area enters into an autochthonous alpine marly and dolomitic limestone overlain by alluvium, with an average thickness of 10 m, reaching 20 m in a few places. The drainage pattern of the area is closely related to the structural lines, with a general directional trend almost from east to west. Topographically, the area is in a mature stage as far as the fluvial erosion cycle is concerned.

From a hydrogeological point of view, the free underground water level is located 5 to 10 m below the surface (due to the adjacent stream), varying seasonally. The pore water pressure is hydrostatic from this level.

2.3. Preliminary explorations

The depth, thickness and the extent of all major soil and rock strata that will be affected by future construction must be determined in reasonable detail. The primary objective of these explorations is to obtain sufficient subsurface data to permit the reliable determination of the types, locations and principal dimensions of all major structures. Disturbed and undisturbed samples of the foundation and buried materials must be obtained for laboratory testing to provide a basic knowledge of their engineering properties. Thus, the research procedure requires a few reconnaissance drill holes that will verify the initial assumptions as to the type of geomaterial present, and the depth and thickness of the deposit. Then it will be possible to design a suitable framework including the prospecting depth.

The geotechnical properties of the ground were investigated by continuous core sampling of four boreholes drilled to depths of up to 16 m. The samples were obtained throughout the entire length of the hole and SPTs (standard penetration tests) were made at every change of geomaterial. The generalized soil profiles and geotechnical properties at these four boreholes, called B3, B3E, B1 and B2 respectively, are shown in figure 2.

The geological profile indicates stiff to hard silty sand, sand–silt mixtures (SM) up to a depth of 2 m, inorganic clays of low to medium plasticity, sandy clays, silty clays, lean clays, inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity at depths from 2 to 4 m, inorganic silts and very fine gravels and sands (CL-ML) at depths from 4 to 8 m and finally inorganic silts and very fine gravels and sands, rock fragments and olistolith (ML) at depths from 8 to 16 m. The samples have been characterized...
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The observed horizontal and vertical discontinuities of these strata are remarkable, which may be attributed to reworking by earlier streams. In order to resolve the ambiguities raised by irregularities in geological/geotechnical profiles and to achieve well-defined upper subsurface geological conditions, two geophysical methods were suggested as necessary additional explorations.

It should be mentioned that every geotechnical in situ survey gives only discontinuous one-dimensional information for the subsurface conditions. In contrast, the application of engineering geophysics can provide either 2D or 3D subsurface images of the study area.

3. Geophysical exploration

Both ERT and ETC have repeatedly fulfilled the expectations for obtaining rapid and cost-effective subsurface information and are thus indispensable supplements to borings in exploratory surveys for civil engineering purposes (ASCE 1996, Sharma 1997). These geophysical engineering tools provide valid information for bedrock profiles and yield a definite determination of the general subsurface structure including the depth of aquifers. Ideally, the resulting geophysical model should be combined with the results from borings and/or other direct methods of geotechnical and geological exploration in order to refine the interpretation of the geophysical measurements, which in some cases have limited success under specific soil conditions.

3.1. Electrical resistivity tomography (ERT)

Electrical resistivity tomography data are collected along a line as a combined sounding–profiling survey, using a multi-electrode resistivity measurement system. This data set can be inverted for the true subsurface resistivity by using 2D or 3D inversion algorithms and the resulting estimated models can be interpreted accordingly (Papadopoulos et al 2006). Electrical resistivity tomography is a method adapted to the recognition and study of 2D structures perpendicular to the profile and to the identification of the various geological layers, including the surface cover, but is more expensive and time consuming than the electromagnetic survey.

3.2. Electromagnetic terrain conductivity (ETC)

ETC surveys are especially adapted to map lateral variations of resistivity or conductivity distribution. Possible geological targets are steep dipping structures, such as faults and fracture zones. In particular, EM31 instrumentation features a large effective prospection depth (~4–6 m), depending on the geoelectrical properties of the subsoil. The EM31 induces currents to the ground by emitting a 9.8 kHz electromagnetic field. The basic operation principles of the EM31 are outlined by McNeill (1980, 1990) and Nobes (1999), which discuss the role of the orientation of the EM31 relative to certain targets. Analysis of the measured quadrature mode permits the estimation of the soil conductivity, whereas the analysis of the measured real mode estimates the magnetic susceptibility of the soil. It is emphasized that the vertical orientation of the coils is characterized by a greater penetration depth than the horizontal orientation.

4. Geophysical measurements

4.1. Data acquisition and processing

The geoelectrical data were collected using an IRIS-Syscal Jr Switch 48 instrument with an accuracy of 0.1 mV. The system features 48 electrodes, enabling fully automated measurements of the shallow subsurface apparent resistivity using the dipole–dipole configuration. This technique has the advantage of very good horizontal resolution, but its main disadvantage is the relatively low signal strength (Sasaki 1992). Five geoelectrical profiles were carried out forming a grid with 2 m profile spacing (figure 3, lines 1–5). Two additional profiles (lines 6 and 7), perpendicular to the previous ones, were conducted in order to verify the results. The dipole–dipole spacing (a) was 1 m, providing the possibility of detecting small bodies and/or structures up to 3 m depth, which may be considered satisfactory for the detection of near-surface geotechnical anomalies in the study area.

A Geonics Limited EM31-MK2 instrument was used for the ETC survey. The prospection mode was set to carry out measurements in parallel profiles utilizing a 20 m × 20 m measuring grid. Readings were taken at 1 m intervals along
parallel profiles also with 1 m spacings, achieving high-resolution mapping. The measurement layout is depicted in figure 3 (see the dashed line grid). Due to the existence of buildings in the investigated area, a limited number of choices were available concerning the location and orientation of the measuring grid. Furthermore, de-spiking algorithms were applied to filter out extreme values that aggravated the identification of interesting anomalies. Line equalization techniques in both dimensions \((X, Y)\) were implemented for the rectification of the data to the mean-level base line. Application of filtering was crucial in cases where data suffered from instrumental and/or geological noise.

The resistivity cross section data were processed and inverted using the commercial packages RES2DINV (Loke 1997) and RES3DINV (Loke and Barker 1996). These programs use an implementation of the smoothness-constrained least-squares method (Sasaki 1989) based on the Gauss–Newton optimization technique. The 2D and 3D electrical responses are calculated either with the finite-difference or the finite-element method.

Each resistivity cross section was processed independently. Identical inversion parameters were used to process all the cross sections in order to reduce the misfit as much as possible. The good quality of the collected data resulted in quite low RMS errors for the inverted resistivity sections (below 7%).

The independent five parallel 2D lines were then combined into a single data set and the commercial software RES3DINV (Loke and Barker 1996) was used to produce the horizontal depth slices through the earth. The 3D model consisted of 643 model parameters. The inversion process converged to an acceptable solution after six iterations, while the resulting model had a percentage RMS error equal to 5.95%.

The presentation of the modelling results was made by means of the Surfer\textsuperscript{TM} software that produced a plan-view image of the site’s conductivity based on the analysis of the collected data.

4.2. Data interpretation

4.2.1. 2D-inversion geoelectrical modelling. The geoelectrical measurements were carried out along five parallel profiles spaced 2 m apart (figure 4). It must be stressed here (and will be commented on in a following section) that the geoelectrical survey was conducted during a separate field season (the summer of 2004). These profiles (so called lines 1 to 5) can be considered to be located at points 9.58, 7.58, 5.58, 3.58 and 1.58 m along the \(y\)-axis, while the measurements were conducted along the \(x\)-axis, where the \(xy\)-coordinate system is that of the electromagnetic survey.

The resistivity cross sections resulting from the inversion analysis of the geoelectrical data exhibit significant variations of resistivity values especially at shallow depths, as figure 4 depicts. We draw attention to an important underground anomaly characterized by low resistivity values (between 20 to 40 Ω m), which is recognizable in all sections at a distance ranging from 7.5 to 9.5 m on the \(x\)-axis and, moreover, at a distance ranging from 4 to 7 m on the \(y\)-axis. Based on the shape of this feature and the existence of similar structures in the broader area, this body could be reasonably identified as a possible hand dug well which has since filled with clay. Usually, clays exhibit low resistivities that range from 3 to 50 Ω m and sandy clays range from 10 to 100 Ω m.

Two additional geoelectrical profiles were carried out in perpendicular directions (which are indicated with dashed lines in figure 4 and shown in detail in the lower part of the figure) to verify the results from the first cross sections. The final inversion model for the latter two profiles reveals the same anomaly at 4 m and 13.5 m, respectively. Furthermore, between 20 m and 23 m on the \(y\)-axis, a linear high resistivity anomaly is detected which is interpreted as a stone wall foundation, shown as a dashed ellipse in figure 4.

4.2.2. 3D-inversion geoelectrical modelling. The dipole–dipole electrical resistivity pseudosection data sets collected along five parallel lines are inverted by using the 3D commercial inversion software RES3DINV (Loke and Barker 1996). The estimated model is represented as six different depth slices (figure 5). Their depths are 0.00–0.35 m, 0.35–0.75 m, 0.75–1.22 m, 1.22–1.75 m, 1.75–2.36 m and 2.36–3.06 m, respectively. The two upper (shallow) slices (see figure 5) indicate strong variations in resistivity values (20 to 800 Ω m) attributable to the shallow inhomogeneities of the soil and rock material present, as depicted in figure 2. The remaining deeper slices reveal a low resistivity anomaly with coordinates of 9 m on the \(x\)-axis and 7 m on the \(y\)-axis, which could be safely correlated with the man-made shaft as mentioned above.

4.2.3. Electromagnetic survey results. The electromagnetic survey was carried out in autumn 2004. Both geophysical measurements should be acquired in the same time period in order to have comparable results. Unfortunately, the EM equipment was not available in the summer period and additionally, during the autumn period (when the EM measurements were carried out) limited access to the site was available since construction work at the site had been initiated.

The composite map image (figure 6) is a 2D-colour scale map of the shallow subsurface apparent conductivity in mS m\(^{-1}\) from the EM31 quadrature data. It should be reported that very significant interference was experienced in the beginning (first 5 m along the \(x\)-axis) of all the electromagnetic profiles due to the various buildings and spoil metal fragments present at this side of the study site. The circular shaped low conductivity anomaly, located at \(x = 9\ m\), \(y = 6.5\ m\), is closely correlated with the low resistivity anomaly which had been determined by the electrical resistivity tomographies after their 2D and 3D interpretation.

The dimensions of the particular anomaly is \(4 \times 3\) square metres, consisting of low conductivity values reaching a minimum of 24.3 mS m\(^{-1}\), surrounded by a background conductivity of 25.0–25.5 mS m\(^{-1}\). Although the particular anomalous conductivity measurements are close to the threshold accuracy (±0.5 mS m\(^{-1}\) of the instrument at
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Figure 4. Inversion model results inferred from electrical resistivity tomography profiles. RMS error fluctuates between 1.34% and 7.3%. Electrode spacing was 1 m. Black dashed lines, across the five parallel cross sections, indicate the position and direction of the two additional geoelectrical profiles conducted and the two resulting cross sections, as shown in the lower part of the figure.

20 mS m$^{-1}$ level, the number of measurements that define the particular anomaly (more than 9) increase the confidence level of delineating the particular feature.

The apparent contradiction (low conductivity–low resistivity) for the same place is fully discussed and clarified in a following section below. Furthermore, another low conductivity zone is identified in the lower right part of the composite map image (figure 6), probably associated with the foundation of a stone wall, the surficial appearance of which is located at the bottom-right margin of the EM grid.

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5. Effect of clay on resistivity/conductivity measurements

The apparent ambiguity, called low resistivity–low conductivity (LRLC), produced by the implementation of the two different geophysical methodologies and related to the above-mentioned detected geophysical anomaly, could be resolved in the context of the time difference between the conducted surveys. As mentioned in the sections above, the ERT measurements were carried out in summer of 2004, whereas EM data were collected in autumn of the same year. This inconformity drove the experimental work to examine the temporal stability of the results and their relative independence of the environmental conditions, by taking into account that the near-surface geological structure was studied.

To study the effect of clay (LRLC behaviour) on resistivity/conductivity measurements, soil and rock samples from the study area (clay and marly limestone) were collected and resistivity measurements were carried out by means of a high-resolution broadband dielectric spectrometer (Novocontrol Alpha-N analyser), in conjunction with a BDS1200 sample holder. The specimens were mounted in appropriate sample cells between two parallel electrodes forming a sample capacitor. Conductivity $\sigma^*$ (resistivity$^{-1}$) was calculated from the dielectric permittivity $\varepsilon^*$ of the sample through the relation

$$\sigma^* = \frac{i\omega\varepsilon_0(\varepsilon^* - 1)}{(1)$$

where $\varepsilon_0$ is the permittivity of the vacuum and $\omega = 2\pi f$ is the frequency of the measurement.

The samples were measured at both high (8 kHz, similar to EM31 emitted electromagnetic field) and dc-like (1 Hz) frequencies, in order to test that resistivity variations of the measured samples for various water contents exhibit similar behaviour at different frequencies.

Marly limestone samples of cylindrical shape (40 mm diameter and 8 mm thickness) remained in deionized water for a few days, resulting in a water saturation of approximately 2% ww. Clay samples were measured in powder form at low water contents, in order to correlate their resistivity values with those of marly limestone samples. All the samples were dried

Figure 5. 3D inversion model of the electrical resistivity tomography profiles. Iteration: 6 and RMS error: 5.95%.

Figure 6. 2D contour image of the soil conductivity resulting from the synthesis of the parallel EM transects. Measurements of conductivity in mS m$^{-1}$. 

$\sigma^*$
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at 105 °C for sufficient time and the resistivity measurements were repeated again.

In order to associate the measured resistivity values with the effect of clay on resistivity/conductivity and the influence of water, it is useful to refer to the general climatic trends that exist in the study area. Specifically, the climatological conditions in Crete during summer are very dry with almost no precipitation, and intense irrigation lowers significantly the aquifer. Thus, during this period subsurface clay remains much more humid (because of the remaining pore water) from the surrounding gravels and marly limestones. Contextually, the detected anomaly is expected to exhibit much lower resistivity compared to the surrounding geology.

On the other hand, during autumn the rainy season begins, thus the soil becomes much more homogeneously conductive relative to its summer condition as the aquifer also rises. This is evident from the inspection of the conductivity values and their dispersion observed with EM measurements. However, the clay, due to its low plasticity, granularity and porosity, is only slowly moistened compared to the surrounding gravels and marly limestones, and thus appears less conductive.

The LRLC behaviour of the clay and the surrounding rocks is in agreement with the measured resistivities and the literature (Butler and Knight 1998). Dried clay is less resistive than marly limestone at zero water content (summer period), as is shown in figure 7. As the water content in both samples increases (transition period from summer to autumn), the clay becomes more resistive than the marly limestone (see figure 7). This could be explained by the different amount of adsorbed water in each sample, as mentioned previously.

Summarizing, from the laboratory measurements above, it is clear that the difference between the two data sets (geoelectrical and electromagnetic) is due to the partial and overall seasonal change in resistivity of the clay material and its surrounding geology, being on average over twice as resistive in summer than in autumn. A small change in the amount of pore water (e.g. increased precipitation in autumn) can have a significant effect on the overall conductivity (McNeill 1990).

6. Combinative geophysical interpretation

Geoelectrical resistivity 2D and 3D inversion modelling of the ERT data together with shallow subsurface apparent terrain conductivity contours from the EM survey were combined to enable a complementary and cross-validated interpretation. Both geophysical engineering methods indicate the presence of two major and consequently important geophysical anomalies (A1 and A2). The first one ‘low resistivity–high conductivity’ (A1) is denoted with a dotted ellipse in figure 8 and was determined from the ERT prospection. At almost the same position, the EM exploration defined a circular low conductivity–high resistivity anomaly.

The second identified anomaly (A2) is a high resistivity body that is depicted in the lower right corner of figure 8 (in the area of building F4). This anomaly seems to be continued as it is inferred from the results of the EM survey and the high resistivity anomalies depicted in the perpendicular inversion models (around location 22–26 m along lines 6 and 7, figure 4).

7. Real geological setting—comparison with geophysical results

In October 2004, excavation commenced in the area, initiating the building construction. It was a great opportunity to verify the geophysical modelling results by comparing them with the actual geological conditions.

A 3 m thick discontinuity in marly limestone filled with clay was detected at the location of anomaly A1, by the end of the excavation works (figure 9). The geometrical regularity
of this structure (e.g. vertical borders, invariant thickness) suggested that it was a hand dig well.

It is emphasized that the structure was found at the exact location indicated by the geophysical measurements, and its geometrical characteristics were in agreement with the determined circular geophysical anomaly.

8. Discussion—effect of clay on the foundation

The dissimilarity which was observed in the geotechnical boreholes through the typical SPT approach required the complementary use of geophysical investigations in order to clarify the image of soil morphology and explain adequately the variance of the geotechnical rates. The main problem discovered from the geotechnical measurements and the later detailed geophysical study was the existence of clay in specific places.

The clay soils, even those which are not pre-stressed, i.e. when they are not under a long-term process of compression and stiffening (gradual reduction in pore fluid pressure and increase of the effective stress), are more susceptible to subsidence and they are also affected by environmental conditions (besides others), particularly temperature and moisture, which vary irregularly throughout the year. The results of the geotechnical boreholes showed that the specific type of clay, which was found in lenticular form, is very neogenic and soft (easy penetration: Nspt = 15–18), supporting our considerations about the nature of the clay in the site.

Likewise, it is recommended that continuous foundation footings should not be placed on soils comprised of clay alternating with stiffer soils. In such a case, the rate of the elastic ground coefficient, $K_s$, is not stable lengthwise and for this reason it is harder to support properly the entire foundation, with obvious consequences for the bearing structure. When this appearance of clay is restricted and has a very local nature, as it is here, then it is preferable to place the building elsewhere.

9. Conclusions

Engineering geophysics combined with geotechnical engineering focuses on the behaviour and performance of soils and rocks in the design and construction of civil, environmental and mining engineering structures.

Often, existing buildings are located over anomalous subsurface zones which are inappropriate for bearing the load of a structure. Moreover, building foundations may not have been built properly. Recent and present damage, such as terrain subsidence and cracks in houses, call for attention and for further investigation using some non-destructive geophysical methods to guide additional exploratory drilling and trenching.

Based on the above, geophysical surveys could contribute significantly in major construction projects in which subsurface structural problems are possible. The approach outlined in this paper allows for the rapid characterization of subsurface formations that can help to guide site investigations through the advancement of soil borings or test pits. Anomalous areas, as defined by the results of the geophysical surveys (such as electrical resistivity tomography and shallow electromagnetic terrain conductivity) in the early stage of construction work, can be used to prepare construction bid documents and estimate potential costs for in situ material handling and the possible reinforcement of the local complex geological structure for safe construction.

All this information is vital to the successful completion of construction projects where development costs can be significant if site characterization does not adequately address the geological formation types and geotechnical parameters observed during the actual construction process.

Acknowledgments

The authors would like to thank the Skouloudis & Xaritakis Construction Company and D Diamantakis Technical Office for making available geotechnical data from the study area and for providing the license to measure in the area. We are also grateful to the students involved in the survey work: Giuseppe Mastrolorenzo, Evi Seferou and Maria Mixalaki.

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