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ОПРЕДЕЛЕНИЕ ГЕОТЕХНИЧЕСКИХ ПАРАМЕТРОВ СРЕДЫ С ПОМОЩЬЮ ДАННЫХ ЭЛЕКТРОМАГНИТНОГО МОНИТОРИНГА С КОНТРОЛИРУЕМЫМ ИСТОЧНИКОМ В РАЙОНЕ «15 МАЯ», КАИР, ЕГИПЕТ

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Аннотация. Изложены результаты геофизических исследований в районе «15 Мая» Каира, Египет. Целью настоящей работы было определить устойчивость верхней части среды, на которой находились дома и другие постройки. Была использована попланшетная электромагнитная методика с контролируемым источником в модификации широкого профиля, разработанная ранее в Институте геофизики УрО РАН и использованная для визуализации многоуровневой деформации в структуре горного массива. В рамках выбранной системы наблюдения измерялись модули трех компонент переменного магнитного поля на двух частотах. Четыре цикла наблюдений проводились в 2011–2014 гг. по одним и тем же профилям и тем же пикетам. Полученная база данных была обработана с целью определения изменений геотехнических параметров в течение четырех циклов измерения. В результате интерпретации наблюденных данных была получена новая информация о строении массива пород, степени его нарушенности, геотехнической неоднородности и потенциальной его устойчивости.

Электромагнитный мониторинг, попланшетная система наблюдений, обработка, интерпретация, геотехнические параметры, устойчивость массива.

ESTIMATING THE GEOTECHNICAL PARAMETERS FROM CSEM MONITORING DATA AT THE CITY OF 15TH MAY, EGYPT

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Abstract. The site of investigation, 15th May city, is a new suburb of Helwan, at about 35 km south of Cairo, Egypt. The work is aimed to investigate the rock massif stability at «Quarter 27» in 15th May City. A controlled source electromagnetic CSEM approach developed earlier by IGF UB RAS (Geophysical Institute, Ural Branch of Russian Academy of Science) is applied to image the ranked deformation levels in the massive structure. The wide profile system of observation has been used to monitor the three components of the alternating magnetic field along predefined measuring lines in the study area. Four cycles of observation have been carried out during 2011–2014 years. The acquired data sets have been subjected to analytical processing procedure to estimate the changes in the geotechnical parameters during the time of these four cycles of observation. The analytical treatments provided good information about the structure of the rock massive and its rank of degradation, the lateral distribution of the geotechnical heterogeneity, and finally a conclusive outcome about foundation stability. We conclude that the general dynamic state close to the destruction level within the investigation area is getting worse over the time; this is reflected in the crack's densities and positions, also on the changes in the lateral distribution of geoelectric heterogeneity as an indicator of the water saturation of the surface rock in the study area.

Electromagnetic monitoring, CSEM, processing, interpretation, geotechnical parameters, massif stability.

Introduction

The site of investigation belongs to the new communities that had been established on the outer extensions of Helwan, at about 35 km south of Cairo, Egypt. This city had been built on Eocene limestone intercalated with thin beds of clay and very thin beds of salt (Morsi, Speijer, 2003). Generally, the Eocene limestone sediments in Egypt are characterized with karstification resulting in fractures, cracks, cavities, and land subsidence. Consequently, short after the city was constructed it started to suffer deformations that could be evidenced on the paved roads, the successive landfalls of the foundation grounds, the water accumulation through the fissures to form swamps, and the divergence of the blocks of the dwelling. Therefore; a cooperation work had been initiated between IGF UB RAS (Geophysical Institute of the Ural Branch of Russian Academy of Science) and NRIAG (National Research Institute of Astronomy and Geophysics) to investigate and monitor the state stability in a pilot area (Quarter 27). Four cycles of field observations (2011–2014) had been acquired along profiles crossing and intersecting the Quarter dwellings. The analytical screening and mapping of the rock massif structure approaches to critical trends with meaningful impacts to the factor «safe» in the engineering geophysics and mining. The present work proposed the rock massive at its optimum state at the top of ranged hierarchic structure model, and the rock massive at its present state represents a rank of disintegration or level of deformation. Investigating the rock mass stability requires well understanding of structural model and proposing a technical procedure to estimate the geotechnical and geoelectrical parameters as key information of dynamic state and stability of the massive structure (Panin et al., 1985; Sadovskiy et al., 1987; Goldin, 2002). In 2003, a new technique had been approached to reveal the disintegration zones in rocks of different content (Hachay et al., 2003; Hachay, 2007; 2008). It involves the application of controlled source electromagnetic method CSEM to image the ranked deformation levels in the massif structure. The new technique had been applied in a mutual work between the Russian IGF UB RAS and the Egyptian NRIAG using the device MFS-12 (A.I. Chelovechkov). The work had been devoted to monitoring a complicated engineering case at the city of 15th May, Helwan. The monitoring data had been acquired over 4 measuring cycles 2011–2014 years. The processing scheme was developed over several phases and conceptual proposals related to the site nature and the system of observation. The analysis of the data of all four cycles provided information about the geoelectrical section of the blocks structure and small disintegration zones using the data of lateral geoelectrical heterogeneity distribution, and finally a conclusive outcome about the foundation stability.

Surface Geology

The study area is a part of 15th May city and includes the Quarters 25–27. The geologic setting of the area is evaluated through constructing a new geological map based on a Land-Sat satellite image and an aerial photograph (scale 1:20,000) and describes the geological sections at more than 30 observation points distributed to cover the area of interest. For mapping accuracy, these observation points are controlled using a traditional survey. The constructed geological map reveals that most of the area consists of deposits of Pliocene, Upper, and Middle Eocene. The Pliocene deposits are represented by wadi deposits, which are composed of compacted sandstone of medium to coarse grains, these deposits occupy the southwestern part of the 15th May city. The Upper Eocene deposits are represented by Wadi Garawi and Qurn Formations, while the Middle Eocene deposits are represented by Observatory Formation. Wadi Garawi Formation distributes at the south and southwestern parts of 15th May city and consists of marl and marly limestone with clay intercalation at the upper part of the formation with thicknesses ranging from 50 to 80 m. The Qurn Formation belongs to the Upper Eocene and covers most of 15th May city and is composed of five units: the first unit (at the base) consists of massive crystalline limestone inter-bedded with argillaceous

limestone. This unit occupies the northeastern part of the area. The second unit includes argillaceous limestone, marl and shale and occupies the north, northwestern and central parts of the area. The third unit of the Qurn Formation outcrops at the northwestern, central and eastern parts of the area of interest and is made up mainly of marl and shale. The fourth unit is exposed in the northeastern and southwestern parts of the area and is represented by limestone with claystone bands. The fifth and last unit (at the top) of the Qurn Formation consists of limestone and shale and locates as small patches at the eastern, central and southwestern parts of the area. The Observatory Formation of Middle Eocene is characterized by highly fractured limestone and caves. This formation outcrops at the northeastern corner of the area.

Moustafa (Moustafa et al., 1985), Farag and Ismail (Farag, Ismail, 1954) investigated the surface structures at the whole city and stated that the area has been dissected by sets of faults trending NW-SE, E-W, and NE-SW. In the current study, the surface structures are characterized through detailed descriptions for the different observation points and confirmed by geophysical and geotechnical studies. They indicate that the area was dissected by two essential sets of faults trending NW-SE, therefore, they delineated secondary sets of faults trending NW-SE passing through Quarters 25–27 at the studied area.

Stratigraphy

The stratigraphic units at some localities of the study area were studied by Cuvillier (1924, 1930), Awad et al. (1953), Shukri (1953), Farag and Ismail (1955), Ismail and Farag (1957), Said (1962, 1971), Strougo (1979), and Moustafa et al. (1985). Middle Eocene, Upper Eocene, and Oligocene rocks crop out in the mapped area. Several classifications were proposed for the Eocene rocks in the different parts of the study area.

Concepts and Models

Understanding the rock massive structure as a conceptual ranged hierarchic structure model is the key point to investigate the inner state dynamics and the self organized system associated to the massive structure; this could be achieved by geophysical methods considering the model proposed by (Hachay, 2005; 2007; 2008), (Hachay, Khachay, 2010), (Hachay et al., 2012). A modern conceptual geological medium model is introduced by Panin (Panin et al., 1985), Sadovskiy (Sadovskiy et al., 1987), Nikolis (Nikolis, 1989), Goldin (Goldin, 2002); the block-hierarchic structure is the result of the destruction processes. Applying an external mechanical stress will influence the initial inner structure forming the hierarchic structural deformation levels, which can be indicated by geophysical fields. The embedded heterogeneities of the smaller rank and the block dimensions in the discrete piece-heterogeneous block medium model are named as heterogeneities of the second rank (heterogeneities can be named as heterogeneities of the next rank depending upon research scale). Applying external induction electromagnetic field with many frequencies and arrays using a controlled source and the elaborated processing and interpretation technologies (Hachay, 1997; 2007), (Hachay et al., 2003) allows revealing the disintegration zones, which indicate the rock stability (Hachay, 2008). The objects of electromagnetic monitoring of geological medium state are heterogeneities of the second rank, which appear and change during the variations of external influence. In the Institute of Geophysics UB RAS, a new method was established to monitor the massive state, which allows classifying the massive by its degree of stability (Hachay, 2008). In the frame of natural research we can identify the geoelectrical heterogeneities of the second rank and achieve the objective of monitoring. They are defined by interpretation of the ratio of two horizontal components of the measured modulus of the alternating magnetic field on fixed frequencies ω at different positions in space points, i. e.:

$$\bar{\delta}(x_l,\omega)=\frac{1}{k}\sum_{n=1}^{k}\frac{\left|H_{\varphi}(x_l,\omega)\right|}{\left|H_{\rho}(x_l,\omega)\right|}\cdot 100\ \%\ , \qquad (1)$$

where $\bar{\delta}(x_l,\omega)$ is the average parameter of

horizontal heterogeneities; $H_{\rho}(x_l,\omega)$ – horizontal magnetic component directed to the source of excitation; $H_{\phi}(x_l,\omega)$ – horizontal magnetic component directed perpendicular to $H_{\rho}(x_l,\omega)$; k – number of arrays, which content the same x_l.

Applying the approaches interpreting the space-frequency distribution of the average parameter (1) we approximate the disintegration zones by small current lines located into the block geoelectrical section. The moment $\tilde{M}_0$ of these current lines is identified and named as intensity of disintegration zones observed on the whole profile. These zones are located on different depths of the cross section, therefore we divide the depth on some intervals: (1) 0–2 m, (2) 2–4 m, (3) 4–6 m, (4) 6–8 m, (5) 8–10 m, (6) 10–15 m, (7) 15–20 m, (8) 20–25 m, and so on. Then we suggested two elaborated integral parameters; the distribution of the summed intensity of the disintegration zones for each interval along the profile ($S_{l,\,\text{interval}}$), and integral distribution of the intensity of the disintegration zones for all intervals (S_{integral}) along the profile. The first parameter provides information about the activity of crack's which in turn indicates qualitatively the stability level of the rock massive, and the second parameter helps to classify the massive stability in terms of numerical criterions using the synergetic theory approaches (Hachay, 2008). The following equation is used to estimate the parameters:

$$S_{l,\text{interval}}(N_l,T,\omega)=\sum_{i=1}^{N_l}\tilde{M}_0^{\,i}(\omega,T); \qquad (2)$$

$$S_{l,\text{integral}}(L_l,T,\omega)=\sum_{1}^{L}S_{l,\text{interval}}(N_l,T,\omega) \qquad (3)$$

where $\tilde{M}_0^{\,i}$ is the intensity of the disintegration zone, N_l is the number of disintegration zones inside one interval l, L is the total number of intervals, ω is circle frequency of observation, and T is the time in years of a cycle of monitoring, ($S_{l,\,\text{interval}}$), (S_{integral}) (2, 3), $\tilde{M}_0^{\,i}$ are in conventional units. This technique had been provided in the deep mines of bauxite and magnetite (up to 800 m depth); in which, the prediction and defining of the instable localities inside the mines and the forecasting of the energetic dynamic events were definitely right and approved (Hachay et al., 2012). Furthermore, this procedure had been applied to estimate the geoelectrical and geomechanical state in inhabited area of Cairo with multilevel appearances of instable features. The system of observation, method of processing and interpretation had been detailed in (Attya et al., 2010).

Results and Discussions

The monitoring data has been analyzed after each survey cycle. For each profile, two images have been constructed; the first image represents the distribution of the average parameter of geoelectrical heterogeneities. The second image represents the geoelectrical cross section along the profile for each frequency. Such sections include indications for the 2D distributions of resistivity and indications for the existence, depths and densities of cracks (Atya et al., 2010). Here, we will provide an analytical estimation of the information of the geoelectrical parameters for all depth intervals in the whole block layered half space of the rock mass for all profiles over the four cycles of CSEM monitoring. The distributions of the geomechanical and the geotechnical parameters ($S_{l,\,\text{interval}}$) and (S_{integral}) have been constructed and correlated. Two images representing two kinds of output of such analysis are introduced; the first image (Fig. 1a, b) shows the distribution of integral intensity of the cracks in some wide profiles at the block layered half space for all the sub parallel wide profiles, CSEM monitoring data. It shows that profiles 6 and 3 suffer the most changes in the intensity of cracks occur in the mass which is visible at two frequencies (40 and 20 kHz). This could lead to geomechanical instability of their mass. The most intensity of the cracks stays in the massif of profile 3 (Fig. 1). The most stable (in time) state of the massif is observed along profiles 6, 7 and 1. Correlating that information with the geologic map, we find that the most changes in the geotechnical parameters correspond to location of the two major faults crossing the area; at the north along profile 6 and at the south profile 1; they represent two stable banks around the zone of possible damage represented between the two faults.

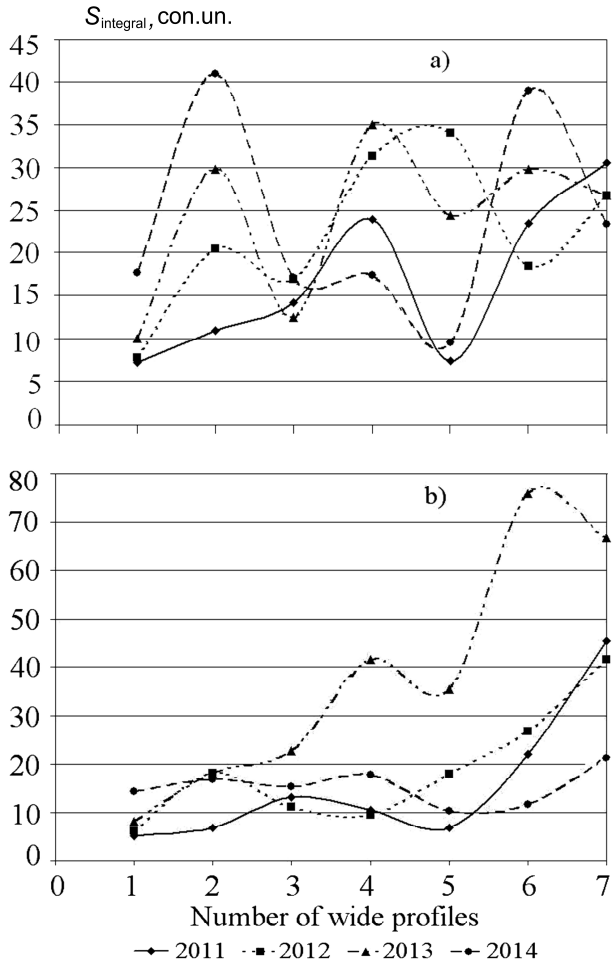

Fig. 1. Distribution of integral intensity of cracks of the block layered half space for sub parallel wide profiles, CSEM monitoring data. Symbols:

The most changes occur in the values of the parameter ($S_{integral}$) in the massif of profiles 4–7 during the year 2013 for the frequency 20 kHz. The reason of that effect was not defined.

The second image is given in Fig. (2, 3) showing the distribution of integral intensity of cracks of the block layered half space for all wide profiles, over the four cycles of CSEM monitoring data; the given profile represents an active «instable» zone (Fig. 2b, Fig. 3 f–g) located corresponding to a major faults, the given image refers to the grade of the changes in the state of the rock mass over the measuring cycles. Because the value of the intensity of cracks is defined from electromagnetic induction data, therefore it is linked with the conductivity of the cracks matter. If the matter is water saturated the conductivity will be higher and therefore the intensity will be larger. Thus it could be easily evidenced that the cracks within the first cycle (2011) are less dense and less water saturated, then in the year 2014 (fourth cycle), the intensity of the cracks became greater which could be directly linked with water dynamics and saturation. It could be also noticed that the grade of changes is basically big over all previous cycles of observation (except cycle 3); which is considered as a direct indicator for massive destruction in the structure along the profile 6 and 7 (the southern major fault). On figures 2 and 3 we can see the interval intensity of cracks distribution along the axis OZ inside the massif. That information is very significant for estimation the position of unstable rock or migration of rock unstability in a frame of two hierarchic model interpretation.

Summary & Conclusions

The present work provides a technical procedure to estimate the geomechanical and geoelectrical parameters as key information of the dynamic state and stability of the rock mass structures. It involves the application of Control Source Electromagnetic CSEM approach developed by IGF UB RAS to image the ranked deformation levels in the massive structure. The Wide Profile System of Observation had been used to monitor the three component electromagnetic field along predefined measuring lines at «Quarter 27» in the City of 15th of May, Helwan, Egypt. Four cycles of observation had been carried out in 2011–2014. The acquired data set had been subjected to analytical processing procedure to estimate the changes in the geotechnical parameters over time of observation. Interpreting the measured data concluded that the general dynamic state at the area is getting worse over the time, this is reflected in the intensities and positions of crack's, also on the changes in the distribution of the parameter of horizontal geoelectrical heterogeneity as indicator for water saturation. method of processing and interpretation had been detailed in (Attya, 2010).

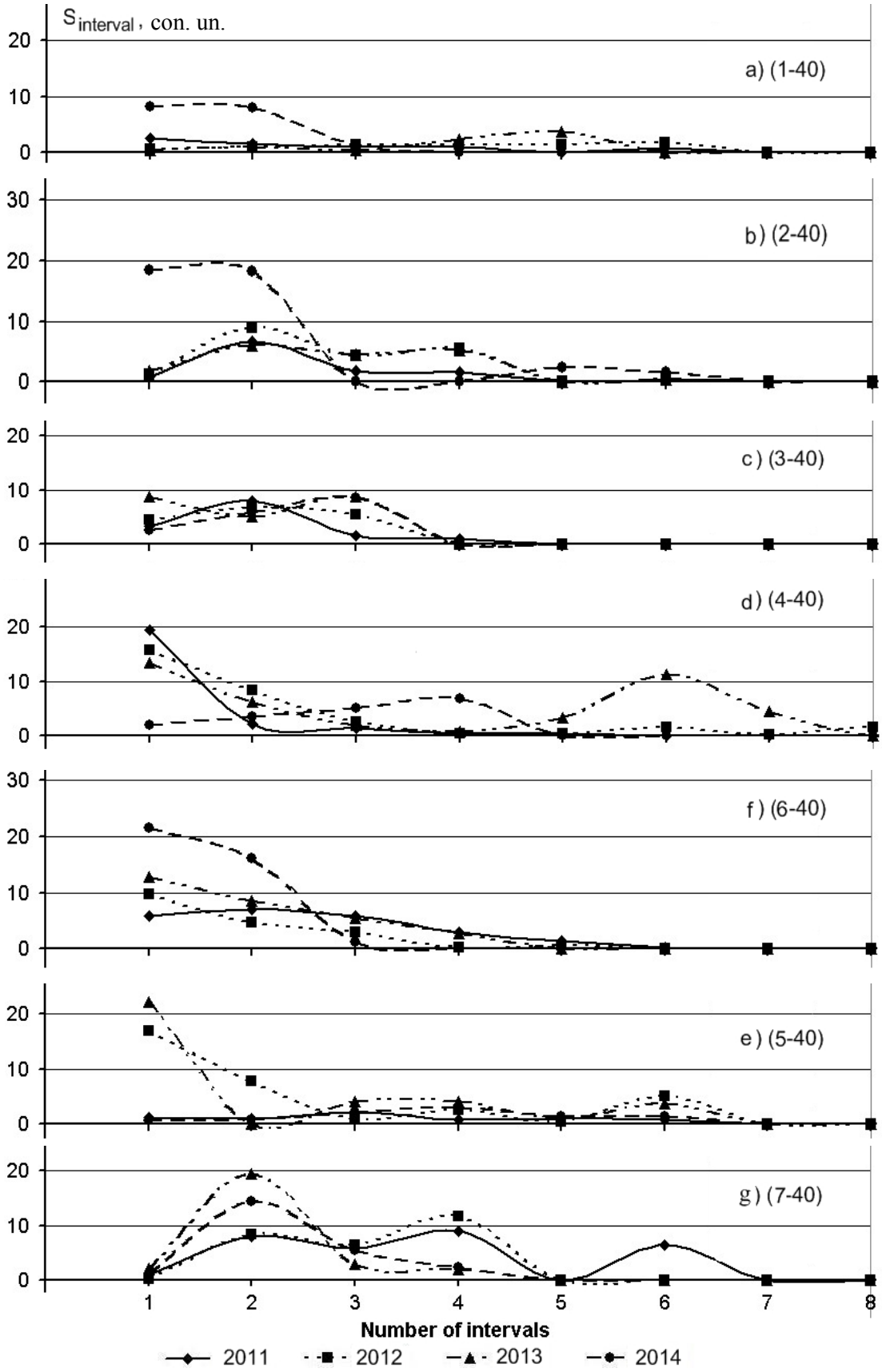

Fig. 2. Distribution of interval intensity of cracks of the block layered half space for sub parallel wide profiles, CSEM monitoring data during 2011–2014 years, frequency 40 kHz.
Symbols: a – wide profile 1, b – wide profile 2, c – wide profile 3, d – wide profile 4, e – wide profile 5, f – wide profile 6, g – wide profile 7

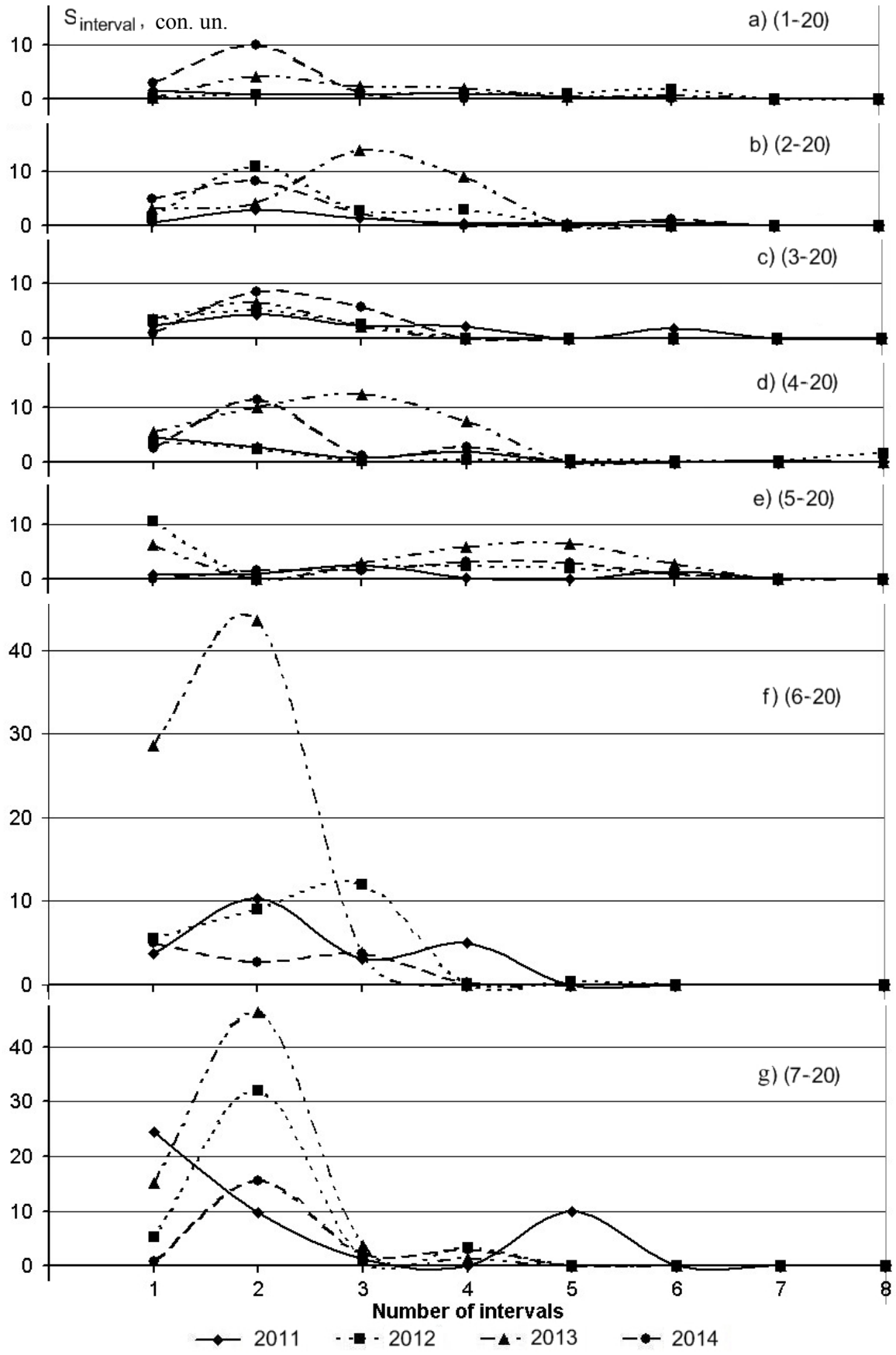

Fig. 3. Distribution of interval intensity of cracks of the block layered half space for sub parallel wide profiles, CSEM monitoring data during 2011–2014 years, frequency 20 kHz.
Symbols are the same as in Fig. 2

Analyzing the geomechanical and geotechnical parameters could clearly evidence that the profiles 6 and 3 (which correspond to the pass of two major faults in the site), enclose a zone of high change in the geotechnical parameters; this in turn could be interpreted as the fault's passage points to a general deformation case of instability close to destruction level where the northern flank at profile 5 and the southern flank at profile1 show relative stability. We conclude that the general dynamic state close to the destruction level within the investigation area is getting worse over the time; this is reflected in the crack's densities and positions, also on the changes in the lateral distribution of geoelectric heterogeneity as an indicator of the water saturation of the surface rock in the study area. Thus, the estimated parameters helped to understand the geodynamic state of the massif along the observed profiles and monitor it over the observation cycles. The study yielded powerful dications for the destruction probability within the site.

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