Ground Fissures in the Area of Mavropigi Village (N. Greece): Seismotectonics or Mining Activity?

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Abstract

In the beginning of July 2010, a ground fissure was observed in the field near the village of Mavropigi (Northern Greece) and specifically in its NW side. Later on (early September), a second ground fissure was perceived, close and almost parallel to the first one and very close to the limits of the lignite exploitation mine (by the Public Power Corporation, PPC). It was observed that the village of Mavropigi slides away slowly towards the PPC lignite mine. Geological, seismological, as well as geotechnical survey in the field indicated that the phenomenon is related to the coal mining exploitation in the near vicinity of the village rather than to any seismotectonic activity in the surrounding area.

Key words: ground fissures, tectonics, earthquakes, lignite exploitation, Mavropigi.

1. INTRODUCTION

There are numerous studies in the literature, as well as real paradigms, of unusual ground behavior in the areas close to mines during their exploitations. According to Głowacka (1992), the induced seismicity observed in
mines is a result of rock deformation due to the excavation and the extraction of part of a deposit volume. Moreover, she proposed that these two quantities (deformation and volume of rock extraction) are proportional. A direct relation between mining-induced seismicity and interactions of mine excavations, as well as geotectonic structures with regional and local stress fields is suggested by Urbancic and Trifu (1997). They also pointed out that seismic energy is released when there is an occurrence of frictional instability at existing geotectonic structures or during the formation of new fractures. The spatial and temporal relation of micro-earthquakes in Greighton mine at Ontario, Canada, has been investigated by Marsan et al. (1999). They proposed a mechanism that caused stress diffusion and examined its effect on the occurrence of the stronger events.

Slope stability problems in coal mines have been described by Kayabasi and Gokceoglu (2012) for the Can pit mine in northwestern Turkey. The instability of slopes is a major problem for open mines and therefore the scientific community (Sonmez et al. 2003, Alejano et al. 2011, among others) made efforts in order to explore techniques for the elimination of this issue. Ruptures on ground surface, as well as at buildings, were also observed in another village, called Anargyroi, about 20 km away from Mavropigi. Lignite mine is still in operation in that region. This case was studied by Soulios et al. (2011), who concluded that land subsidence was directly related to the activity of a lignite mine in its vicinity. Land subsidence is the ground surface sinking and was observed in some parts of world, as a result of the heavy withdrawal water or the coal excavation during mining exploitation. Slides along a slope formation with very small content in marl were examined by Prountzopoulos et al. (2010) at another lignite mine, approximately 35 km from Mavropigi. They observed very low values of shear strength residuals during the sliding. For safety reasons they propose the reduction in the average slope inclination.

Mine-induced earthquakes are peculiar, given that their mechanism is based on different sources, such as rockburst, bump, cavity collapse, fault slip along weakened faults, etc. (Hasegawa et al. 1989). Mining operations that use blasting techniques often cause sliding problems in areas prone to this risk. Kijko et al. (2001) examined various seismic hazard distributions in two mines (copper mine in Poland and gold mine in South Africa) and declared that the non-parametric distribution of seismic hazard is considered as the most adequate for such studies, where the magnitude distribution could be very complex.

During the 1980’s, the Public Power Corporation (PPC) started the excavations in the lignite mine nearby the village of Mavropigi in Northern Greece. Up to July of 2010 no problems have been observed in the area (e.g., land subsidence, landslides, etc.) directly related with the mine exploitation.
On 7 July 2010, a first fissure was observed in the fields, in the NW side of the village. By early September 2010 another ground fissure was observed, close and almost parallel to the previous one, which was at a short distance (about 100 m) from the limits of the lignite mine. The phenomenon caused restiveness to the local community, as well as to the authorities, and gave the chance to a team of the Geology Department of the Aristotle University of Thessaloniki to study the problem.

The aim of this study is the investigation of the ground fissures observed close to Mavropigi village and their possible relation to the lignite mining excavations in a short distance. We firstly present the geological and structural setting of the region. Then, we comment on the seismicity of the area. Finally we discuss of the geotechnical investigations which have taken place in the area under investigation.

2. GEOLOGICAL AND STRUCTURAL SETTING

The findings obtained through the geological inspection of the study area suggest a sedimentary sequence of lacustrine deposits, overlying the Palaeozoic and alpine bedrock (Fig. 1):

- The bedrock consists of the Pelagonian Palaeozoic metamorphic complex (gneisses and schists), which is overlain by Triassic-Jurassic carbonate platform rocks;
- The post-alpine sedimentary sequence that fills the neotectonic basin consists of lignite-bearing Middle-Upper Pliocene marls;
- Both the bedrock and the post-alpine rocks are unconformably and partially overlain by the Lower Villafranchian conglomerates of Proastion formation, alluvial and colluvial deposits, scree, thick soil or human deposits.

The village of Mavropigi is located on a NW-SE trending normal fault, dipping towards NE, which is one of the neotectonic faults that shaped the Ptolemais basin (Fig. 1). This normal fault had been formed during the first neotectonic extension stage of the Upper Miocene-Pliocene (Pavlides 1985, Pavlides and Mountrakis 1987), which was associated with the back-arc extensional regime of the Hellenides. As a result, the NW-SE trending basins were formed and sediments of the same age are traceable in the broader Western Macedonia region (i.e., Florina, Amyntaean–Ptolemais, Kozani–Serbia, Grevena basins). This stage was followed by the younger, and still active, Quaternary extensional stage, which caused the formation or reactivation of NE-SW and E-W trending normal faults. Although these faults were smaller than the NW-SE trending ones, they caused the separation of the initial larger basins into smaller ones in which Quaternary sediments were deposited. However, the contact between the bedrock and the sediments, in
Fig. 1. Simplified geological map, modified from the 1:50 000 geological map of Greece, Siatista sheet (IGME 1982). Explanations: sch – mica schists, T-J.k – limestone, Pt₁ – Proastio Formation, Pt₂ – Pleistocene deposits, al – alluvial deposits, af – alluvial fans (arrows showing direction of flow). The neotectonic fault is shown by the thick black line (solid for visible trace and dashed for covered), while the surface ruptures are marked in red. Ticks show downthrown block in both cases. The approximate extend of Mavropigi village is shown in grey. The location of the study area is shown as a solid rectangle in the inset map of Greece. Colour version of this figure is available in electronic edition only.

the area where the surface ruptures have been observed, coincides with the strike of the aforementioned NW-SE fault. Given that the latter had been formed during the first neotectonic stage, which was superseded by the second Quaternary stage, it has been considered as inactive.
To better understand whether the observed surface ruptures were caused by a possible reactivation of the NW-SE fault, we have performed a fault kinematic analysis by analysing the striation data and defining the paleostresses. The results were obtained using Win-Tensor, a software developed by Dr. Damien Delvaux of the Royal Museum for Central Africa, Tervuren, Belgium. The calculated P-T axes are consistent with the first neotectonic stage, which is now inactive (Fig. 2). The surface ruptures were formed along the NW-SE direction, similar to the direction of the neotectonic fault. However, the strike of the ruptures is 130-140° and 110° (Fig. 3b, c, respectively), whereas the strike of the fault is about 150°. Therefore, it is suggested that the surface ruptures could not be directly associated to the existing neotectonic fault. Figure 3a shows the location of the surface ruptures around the basement promontory NW of Mavropigi village. Along these fractures the slip vector, *i.e.*, the direction towards the hangingwall moved during the deformation, was measured and it is shown with blue arrows. The slip vector direction was measured in the field by measuring the azimuth of displaced markers along the fracture line. Strike and vector analysis showed that there is a clear differentiation between the northern and the southern line. It was clear that the southern line exhibited slip vectors mostly perpendicular to the strike, while the northern one showed a left-lateral component.

As a conclusion, it can be argued that the observed fissures are not associated to the fault (see Fig. 1) nearby Mavropigi.

![Fig. 2. Paleostress analysis of the fault striations. Faults have been plotted as great circles and their respective striations as blue arrows. The orientation of the T axis, corresponding to the minimum stress (*i.e.*, extensional) direction corresponds to the Upper Miocene-Pliocene stress field (NW-SE). Colour version of this figure is available in electronic edition only.](image-url)
3. SEISMICITY OF THE AREA

In general the investigated area is characterized by low seismicity (Drakatos et al. 2005). No strong earthquakes were reported or recorded in the vicinity of Mavropigi during the historic or recent times.

3.1 Background seismicity

Figure 4 represents the background seismicity of the broader area together with the faults. The faults in the area are also illustrated. The data set used is extracted from the earthquake catalogues of the National Observatory of Athens, as well as from the databank of the Geophysical Laboratory of the Aristotle University of Thessaloniki. The earthquake magnitudes are in moment-magnitude scale following up the determination made by Papazachos...
Fig. 4. The seismotectonics of the broader area of Mavoropigi. The cities are presented by red triangle, while towns are indicated by red circle. The Proastio–Asvestopetra fault, which is depicted by blue line, is in close distance to Mavoropigi, while white lines illustrated some large normal faults of the broader area. Shallow earthquakes of various magnitudes are observed, as well. Colour version of this figure is available in electronic edition only.

et al. (1997). The examined earthquakes are restricted to shallow depth. The figure declares that the majority of earthquakes occur up to 20 km with a mean depth at 9 km.

As it is illustrated in Fig. 4, there are two large faults (in white) in the area. Despite the existence of these faults, no strong earthquake was reported, as a result of the activation of the fault. The potential of these faults, expressed as earthquake magnitude, is in good agreement with the empirical relations (length of fault-earthquake magnitude) introduced by Wells and Coppersmith (1994), Ambraseys and Jackson (1998), Drakatos and
Latoussakis (2001), Papazachos and Papazachou (2003), and Pavlides and Caputo (2004). For earthquakes in Greece Papazachos and Papazachou (2003) introduced the following relationship between the moment magnitude $M_w$ and the faults rupture $L$ (in km):

$$\log L = 0.51M_w - 1.85 .$$

(1)

This means a theoretical earthquake occurrence of magnitude $M = 6.5$, which is “equivalent” to a fault length of 30 km. Therefore, we examined the seismicity in the area included within a circle of radius 30 km around Mavropigi and as mentioned earlier, the background seismicity (1900-2010) is generally low (Fig. 4). Specifically, 67% of the earthquakes are of magnitude ranging from 2.0 to 2.9, 29% ranging from 3.0 to 3.9, and only the 4% of them are in the magnitude interval 4.0-4.9. Only one earthquake with magnitude 5.2 occurred in 1984, but its epicentre was relatively far ($\approx 25$ km) from Mavropigi, so it did not affect the region of the village. The magnitude-frequency relation was applied to this sample and the obtained parameters are: $\alpha = 3.76$ and $b = -0.95$.

Also during May 1995 the area experienced a strong earthquake (south of Mavropigi, see Fig. 4) with magnitude $M = 6.6$, which caused severe damages in the area of Kozani and Grevena (Papazachos and Papazachou 1997, Pavlou et al. 2013). The earthquake did not affect the village of Mavropigi, because its epicentre was also far from the region (almost 35 km).

Another fault (Proastio–Asvestopetra fault – the blue fault in Fig. 4), which could cause serious troubles to Mavropigi, is about 9 km long (Xanthopoulou 2006) and is very close to the village. The point of the middle of this fault is approximately 7 km away from Mavropigi. According to this length, an earthquake of $M = 6.2$ could have occurred (Wells and Coppersmith 1994, Ambraseys and Jackson 1998, Pavlides and Caputo 2004), but this is not the case until now.

### 3.2 Worst case scenario

The seismicity of the area is low. However, the faults (30 km in length) of the area could be considered of special interest since, potentially, they can produce earthquake of magnitude close to 6.5. In order to estimate the “worst case scenario” for the investigated area, one has to estimate the maximum regional earthquake magnitude $m_{\text{max}}$. It was done by applying the procedure developed by Kijko and Sellevoll (1989), and Kijko (2004). The procedure allows the utilization of all available seismicity information, as it makes use of an earthquake catalogue containing both incomplete historical observations and more congruous and complete instrumental data. In addi-
tion, the Kijko–Sellevoll’s approach accepts division of the complete data set into some sub-catalogues, each of them being complete starting from its own level of completeness. Errors of the assessed quantities are also estimated. A brief description of the method is given below.

The estimation of the maximum regional earthquake $\hat{m}_{\text{max}}$ is based on the condition that the largest “observed” magnitude $m_{\text{max}}^{\text{obs}}$ is equal to the maximum “expected” magnitude $E(m_{\text{max}}/T)$ in the span of a catalogue of earthquakes and this condition provides a quite satisfactory estimate of $\hat{m}_{\text{max}}$ (Kijko 1988). If this equation is applied to the G-R magnitude distribution, the estimator of maximum magnitude $m_{\text{max}}$ is obtained (Kijko and Graham 1998):

$$\hat{m}_{\text{max}} = m_{\text{max}}^{\text{obs}} + \frac{E_1(TZ_2) - E_1(TZ_1)}{\beta \exp(-TZ_2)} + m_{\text{min}} \exp(-\lambda T).$$

(2)

The quantities in the above relationship are assessed as:

$$Z_1 = \lambda A_1 / (A_1 - A_2), \quad Z_2 = \lambda A_2 / (A_1 - A_2),$$

$$A_1 = \exp(-\beta m_{\text{max}}), \quad A_2 = \exp(-\beta m_{\text{max}}^{\text{obs}}),$$

while $E_1(Z)$ indicates an exponential integral function (Abramowitz and Stegun 1970):

$$E_1(Z) = \int_Z^\infty \exp(-\zeta)/\zeta \, d\zeta.$$  

(3)

It is easy to show that the approximate variance of the maximum regional magnitude $\hat{m}_{\text{max}}$ is equal to the one introduced by Kijko and Graham (1998):

$$\text{var}(\hat{m}_{\text{max}}) = \sigma_m^2 + \left[ \frac{E_1(TZ_2) - E_1(TZ_1)}{\beta \exp(-TZ_2)} + m_{\text{max}} \exp(-\lambda T) \right]^2,$$

(4)

where we supposed that the observed (apparent) magnitude is distorted by an observational error, which is normally distributed with a known standard deviation $\sigma_m$, following in the applied procedure provided by Tinti and Mulargia (1985). The approximate standard deviation of $\hat{m}_{\text{max}}$ is derived through Kijko and Dessokey (1987) process:

$$\sigma_{m_{\text{max}}} = T(\hat{\Theta}) \sigma_x,$$

(5)

where

$$T(\Theta) = ABS \left[ \xi \exp(\xi) E_1(\xi) \right]^{-1}$$

(6)
with $\xi = T_2 Z_2$ and $\sigma_\xi$ is the standard deviation of $m_{\text{max}}^{\text{obs}}$. One the other hand, $T_c(\Theta)$ can be considered as a “transmission coefficient” which transmits the uncertainty in $m_{\text{max}}^{\text{obs}}$ into uncertainties of $\hat{m}_{\text{max}}$.

The parameters $\beta$ and $\lambda$ for a given region are estimated by the maximum likelihood procedure described by Kijko and Sellevoll (1989). These are given by

$$11\frac{1}{\lambda} = \varphi_1^E + \varphi_1^C \quad (7)$$

and

$$12\frac{1}{\beta} = \langle X \rangle - \varphi_2^E - \varphi_2^C + \lambda \left( \varphi_3^E + \varphi_3^C \right), \quad (8)$$

where $\langle X \rangle$ is equal to the mean earthquake magnitude for both historical (if existed) and recent earthquake files. The indices $E$ and $C$ denote the different sources of function $\phi$. When they are derived from extreme part of the catalogue, they are marked with the letter $E$, while they are marked as $C$ when they follow the complete part (recent earthquakes).

Based on the knowledge how our seismic event catalogue was compiled, it was assumed that for the standard error of the maximum observed magnitude, $m_{\text{max}}^{\text{obs}}$, is $\sigma m_{\text{max}}^{\text{obs}} = 0.25$.

The largest magnitude recorded in the area is $m_{\text{max}}^{\text{obs}} = 5.2$. The application of the Kijko–Sellevoll formalism results in the estimation of $\hat{m}_{\text{max}} = 5.33 \pm 0.28$, activity rate $\lambda = 12.27 \pm 0.53$ and the Gutenberg–Richter parameter $\beta = 1.71 \pm 0.09$. Clearly, the estimated value of $\hat{m}_{\text{max}} = 5.33 \pm 0.28$ cannot be considered as the maximum possible regional magnitude because it was calculated only on the records of very local seismicity, with the radius of 30 km from Mavropigi area.

Therefore, it was assumed that the maximum regional earthquake magnitude is controlled by the fault of ca. 30 km length, which is capable to produce earthquake magnitude $\hat{m}_{\text{max}} = 6.71 \pm 0.32$. Such maximum regional magnitude is considered as the “worst case scenario” for the area under investigation. It is interesting to mention that the value $\hat{m}_{\text{max}} = 6.71 \pm 0.32$ is very close to the earthquake magnitude $M_w = 6.6$, occurred in 1995, ca. 37 km from Mavropigi. The earthquake was the largest ever recorded in the whole territory of Western Macedonia, Northern Greece. The results were computed by using the HN-code provided by Kijko (personal communication).

One has to emphasize very strongly that the local seismicity observed in the area does not represent the seismicity of the region.
3.3 Recorded seismicity of the area

In order to validate the presented results and to examine in details the seismic activity of the area, five digital (Reftek 72A07) seismic stations were installed, with broadband seismometers (Gural CMG40T) around the village (Fig. 5). The time and the site of the installation were accurately evaluated by a GPS device, which is a part of the equipment. The sampling rate was 125 samples/s.
Three of the stations that were installed (with codes PAND, DHMS, and CHAI) are located around the village, while the two others (with codes ANAN and APOT) are located in the countryside of Mavropigi (Fig. 5). In the same figure, the lignite mines (4 mines in the surroundings indicated with arrows in the same figure) at the north (Mavropigi mine-open pit 1) and at the southeastern (Kardia mine-open pit 2) sides of the village are also shown. We want to notice that open pit 3 (Fig. 5) was during our investigation not under full exploitation. It is also noteworthy that the observed mines’ boundaries are those existing (Fig. 5) during our investigation and they are moving towards (open pits 1, 2, and 3) Mavropigi. The spacing between the stations was selected to be too short because our interest was to define any connection of the surface ruptures with seismic activity, even with very weak events. For the accurate location of all the earthquakes recorded by the network and occurred in the surrounding area, they were compared with the recordings of the permanent stations of the Hellenic Unified Seismological Network (HUSN). By this way, ninety three events were located in the broader area of the local network. Thirty-three of them were explosions, and this was verified by the information provided by PPC.

Figure 6a is the vertical component of a ground tremor recorded at one of the local seismological stations. The time is measured in seconds after the beginning of a ten (10) minute file and amplitudes show velocity in m/s. It is observed that this waveform, which is a representative of several recordings, starts with higher frequencies and after some seconds longer periods are dominant. For the estimation of dominant frequencies in each of the above mentioned parts of the waveform, Fast Fourier Transform was applied.

Figure 6b shows the spectrum of the first part of the recording (251.8-253 s). Corner frequency was found to attain a value of about 30 Hz. Then, for higher frequencies, a continuous attenuation of the amplitudes is observed. Figure 6c shows the spectrum of the second part of this recording (255-286.2). The amplitude attenuation starts at the frequency of 3 Hz and then it becomes higher, in the value of 30 Hz. For comparison with these data, Fast Fourier Transform was applied in different parts of the waveform (Fig. 7a) of local earthquakes (s-p ~3 s). Independently of the part of the seismogram, the corner frequency was found in the range of 20-30 Hz (Fig. 7b).

In addition, after a thorough check it was found that all the recordings, as this one of Figure 6a, have been registered by the local network only. In Fig. 8 the epicenters of these recordings are illustrated. There is no record at stations of the permanent seismological network in the broader area. From all the above data, it is derived that the recording as in Fig. 6a have local origin but they are not local earthquakes. Taking into account their frequency content we interpreted them as explosions for mining purposes. Informa-
Fig. 6: (a) Waveform of an explosion vertical component with body waves at the beginning followed by surface waves; (b) Fourier Transform of the first part of the waveform (body waves) with corner frequency to ~30 Hz; and (c) the same process is also applied for the next part of the waveform, where both body and surface waves that have arrived, is characterised by a corner frequency in the interval 4-30 Hz.

tion given by PPC, reporting the explosions’ time supports our interpretation. The high-frequency first part of the recordings corresponds to the compressional waves. The lower-frequency second part of the waveforms corresponds to the surface waves.

For the location of the local explosions, only the $P$ arrivals, which were picked manually, were taken into account. The epicentral distances are some
Fig. 7: (a) A small local earthquake (waveform) for comparison reasons; the $s$-$p$ value is about 2 s, the arrival of $S$ waves (taking in mind the horizontal components) is on 288 s; and (b) the fast Fourier Transforms for the initial or the late part of the waveform are similar, with the same corner frequency \(~30\) Hz, as the body waves in the explosion.
GROUND FISSURES IN THE AREA OF MAVROPIGI VILLAGE

Fig. 8. The recorded events in the broader area of Mavropigi are indicated by red circles. There are also depicted the portable network installed in Mavropigi (in yellow), as well as the 3 main seismic stations FNA (Florina), KZN (Kozani), and PENT (Pentalofos) which can provided additional information for the epicentres determination. Sketches of the Mavropigi and the Kardia mines are illustrated as well. Colour version of this figure is available in electronic edition only.

hundreds of meters and therefore the maximum depths of ray paths are very shallow. Thus, explosion sources were located using a half space with velocity of compressional waves equal to \( V_p = 0.4 \) km/s. This value was adopted using the results of the geophysical prospecting in the study area, and is almost the same as the velocity model proposed by Walter and Joswing (2008) for the ground shaking (based on landslides) at the Vorarlberg area in Alps.
For the location of the few local earthquakes observed, we used not only the recordings of the local network but also the recordings at stations of the HUSN, which are in operation close to the study area. Both $P$ and $S$ arrivals picked manually were used for the location. Among various local models (e.g., Hatzfeld et al. 1996) we preferred a model proposed by Rigo et al. (1996), who used the recordings of a very dense local network in Central Greece. This is a model of ten layers over a half space. The velocities of the $P$ waves and the thicknesses of the layers are given in Table 1. Time residuals for each seismological station were calculated to correct any model uncertainties and lateral variations of the structure following a procedure proposed by Karakostas et al. (2012, 2014). Applying the Wadati method, the $V_p/V_s$ ratio was calculated equal to 1.85. For the location of the data the HYPOINVERSE program (Klein 2002) was used.

<table>
<thead>
<tr>
<th>$V$ [km/s]</th>
<th>$d$ [km]</th>
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<tbody>
<tr>
<td>0.40</td>
<td>0.1</td>
</tr>
<tr>
<td>0.50</td>
<td>0.2</td>
</tr>
<tr>
<td>1.20</td>
<td>0.3</td>
</tr>
<tr>
<td>3.00</td>
<td>0.7</td>
</tr>
<tr>
<td>5.20</td>
<td>4.0</td>
</tr>
<tr>
<td>5.80</td>
<td>7.2</td>
</tr>
<tr>
<td>6.10</td>
<td>8.2</td>
</tr>
<tr>
<td>6.30</td>
<td>10.4</td>
</tr>
<tr>
<td>6.50</td>
<td>15.0</td>
</tr>
<tr>
<td>7.00</td>
<td>30.0</td>
</tr>
</tbody>
</table>

It is suggested, therefore, that the causative of the ground fissures is most probably due to mine activity rather than background seismicity.

4. GEOTECHNICAL INVESTIGATION IN THE AREA

In this work, we have studied and analyzed the induced displacements and slide failures around the open excavations at a lignite mine in Ptolemais basin of the Public Power Corporation S.A. in Western Macedonia, Greece. Deformations, if any, around these pits usually disappear in a distance of 200-250 m. However, significant ruptures and horizontal as well as vertical displacements were observed 600 m westwards from the open pit, where the village of Mavropigi is located. A significant number of houses in the village have sustained damages and the relocation of the village has been decided.
The open pit slopes have a maximum height of 165 m with benches and dips from 45° to 70°. The principal characteristics that caused the excessive stress relief phenomena and thus the ground rupture and large displacements, involve the initial stress field, its changes after the excavation, the geological particularities in the site specific, the groundwater, and the mechanical properties of the discrete engineering geological units. These units involve the Quaternary deposits, the weathered and sound marl, the bedding and the fault zones.

The Neogene marly deposits lie on bedrock of schists and limestones. A thin cover of recent Quaternary deposits of reddish clays is also present. The slide phenomena, within the marl formation, concern both the weathered and the non-weathered zone. Bedding planes with a sub-horizontal geometry towards the main basin and the open pit are also present. The faults in the area have a NNW-SSE and NE-SW direction. These faults have played a role to the overall stability of the area and the mechanism of failure since they present lower mechanical characteristics and are located parallel with the main excavation face of the pit. The exact location of these faults was retrieved through a geophysical survey. As far as the hydrogeological conditions are concerned, groundwater is within limestones, while some confined groundwater can be found in the marly deposits around 30 m depth. Groundwater flow is towards the open pit, while the water table is lowered after every excavation step.

In order to analyse and model the excavation of the pit and its subsequent failures, an engineering geological and geotechnical study was to be performed. A fundamental step before going into analysis was to define the specific geotechnical properties of the encountered engineering geological units. These properties were concluded after a site specific engineering geological field work and from back analysis performed in very similar cases (Steiakakis and Agioutantis 2010, Prountzopoulos et al. 2010) close to the area of the open pit area. The engineering geological units of the studied area are: (a) the clayey Quaternary deposits, (b) the loose Neogenic weathered marls, (c) the fresh more competent Neogenic marls with lignitic horizons, (d) the fault zones, and (e) the bedrock of limestones or schists. The mechanism of failure and horizontal deformations initiated from shearing along the marly bedding planes, while the tensile failures with the development of fractures in the surface (Fig. 9) were presented along the fault planes. However, the amphitheatric geometry of the later scarps shows that the failure has probably evolved to a more isotropic failure of the marly rock mass.

A numerical analysis, with the software Phase 2 ver. 6 of Rocscience Inc., was performed to simulate the deformations and the shear and tensile failures and to evaluate the exact mechanism of failure. The geotechnical parameters were based on investigations performed in the past (Steiakakis and
Agioutantis 2010, Prountzopoulos et al. 2010) in similar formations, and on in situ observations. The geotechnical properties used for the analysis are presented in Table 2.

Some assumptions, based on geotechnical judgment, have been made about the geotechnical properties of the fault zones and the change of deformation modulus of the marl deposits from the crest of the excavation pit. This geotechnical judgment was verified through analysis, the results showed a clear tendency between the open pit excavations, the ground movements and fissures, beyond any limit of the assumptions taken. The geotechnical properties of limestones that are found in the perimeters of the ba-
Table 2

Geotechnical properties and geometrical information as input for the model used for analysis with the software Phase (Rocscience Inc.)

<table>
<thead>
<tr>
<th>Geometrical data</th>
<th>Excavation depth [m]</th>
<th>Dip of excavated cuts</th>
<th>Dip of natural ground (towards the village)</th>
<th>Up to 160</th>
<th>45°-70°</th>
<th>4.5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary deposits</td>
<td>Unit weight $\gamma$ [MN/m$^3$]</td>
<td>0.018</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Friction angle $\varphi$ [°]</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Cohesion [MPa]</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deformation Modulus $E$ [MPa]</td>
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<td></td>
<td></td>
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<td>Neogenic deposits</td>
<td>Unit weight $\gamma$ [MN/m$^3$]</td>
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<td>Limestones</td>
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<td>Constant $m_i$</td>
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sin have been estimated through the Hoek & Brown failure criteria (Hoek et al. 2002) and the use of the Geological Strength Index (GSI) (Marinos and Hoek 2000). It is noted that the overall good slope stability of the marls around the open pit guided to the assumption of higher geotechnical properties (angle of internal friction $\varphi = 33°$ and cohesion $c = 200$ KPa, Young’s Modulus $E = 350-1000$ MPa) based on the investigation program and range of properties from the work of Steiakakis and Agioutantis (2010) and Prountzopoulos et al. (2010) in similar formations.

Analyses were performed in two different series, depending on the distance between the open pit excavations and the village, the modified deformation modulus of the marl, after the excavation disturbance and marl’s expansion, around the open pit and the geometry (dip from 45° to 70°) of the
open pit cuts. For the calculation of the factor of safety of the analysed slopes the SRF (Stress Reduction Factor) coefficient was considered. For all the analyses, this coefficient was calculated to be from 1.15 to 1.25, which is consistent with the overall stability of the excavated slopes.

The finite element model with the different geomaterials is illustrated in Fig. 10. The mesh is determined assuming that the affected area due to the excavation is limited to a distance less than 1000 m while the depth from the floor of the excavation to the lower boundary is equal to 300 m. The boundary conditions of the model are determined as followed: constraint-restriction of the horizontal and vertical displacements at the lower boundary (Hinge), while at the side (vertical) boundaries only the horizontal displacement is constrained (Roller). Finally, the discretization of the mesh is done using three-node, triangular finite elements, with the level of refinement of the mesh increasing (smaller finite elements are employed) close to the area of interest and towards the Mavropigi village. By performing this particular analysis, the horizontal displacement of the ground over the excavation area is simulated more accurately. The analysis of the excavation is performed in four stages and not abruptly in a single stage.

Fig. 10. Finite element model at the geostatic phase (with all the excavation stages). Different colours correspond to different geomaterial and geotechnical properties: red – quaternary deposits, yellow – highly disturbed marl with low deformation modulus after the excavation, light orange – less disturbed marl with higher deformation modulus, light grey – competent marl with high deformation modulus in order not to heave, and dark grey – limestones, orange line – fault zone (see Table 2 for properties). Colour version of this figure is available in electronic edition only.
The results from the analyses showed that these displacements and local slide failures are clearly connected with the exploitation of the open pit lignite mine (Fig. 10). These displacements are not limited close to the excavation surface (decades of meters) but may exceed 600 m, where the village of Mavropigi is located. This is an ongoing phenomenon since the main displacement started on 2010 with few mm to 20 cm (around the fault zones) but has been constantly increasing and has recently reached few meters with a length of the fracture of several hundred meters. An example of the analysis results, illustrating the horizontal deformation and the tension failures (open fissures in the ground), is presented in Fig. 11.

The macroscopic observations and the inclinometer measurements verified the analyses results (displacements and surface failures). The main movement is located in a depth around 40 m and the added displacements were 20 cm (October 2010 data).

5. DISCUSSION AND CONCLUSIONS

This paper studies and analyses the induced displacements and slide failures around the open excavations in a lignite mine in Ptolemais basin, of the Public Power Corporation, near the village of Mavropigi (northern Greece).

Significant ruptures and horizontal and vertical displacements, rather than deformations, were observed 600 m westwards from the open pit, where the village of Mavropigi is located. These phenomena caused sustained damages in a number of houses in the village and the relocation of the village has been decided. The open pit slopes have a maximum height of 165 m with benches and dips from 45° to 70°.

Geological survey in field indicated that the village of Mavropigi is located on a NW-SE trending normal fault, dipping towards NE, which is one of the neotectonic faults that shaped the Ptolemais basin. This survey
evinced that: (i) although similar in strike, surface fissures and the existing neotectonic fault, it is obvious that these tectonic structures are not directly associated, so, it was concluded that the neotectonic faults did not involve at all in the whole phenomenon (ground fissures appearance); (ii) the aforementioned fissures moved in a slightly different way, though it was considered that they operated together based on the same causative.

Seismicity study of the area shows that the investigated area did not experience any high seismic activity, during the last decade. The background seismicity, in a 30 km radius around Mavropigi, also demonstrated that the seismicity level is a normal one. A portable seismological network was installed around Mavropigi and 93 events were recorded around the broader area. Careful inspection on the records revealed that the observed events very close to Mavropigi are explosions inside the Kardia mine, rather than earthquakes. The help of the PPC is considerable and, based on the information provided, it was verified that these events are blasts, and they numbered almost 1/3 of the total recorded events. All of them lead to a safe conclusion that the ground fissures are not a product of any intense seismic activity in the examined area.

A finite element analysis was performed to simulate the deformations, the shear and tensile failures and to evaluate the exact mechanism of failure. The analysis results showed a clear connection between the open pit excavations and the ground movements. These displacements are not limited close to the excavation surface (decades of meters) but exceed to the 600 m, where the village is located. This is an ongoing phenomenon since the main displacement started in 2010 with few mm to 40 cm (around the fault zones) but has been constantly increasing and has recently reached few meters at the surface. The macroscopic observations and the inclinometer measurements verified the displacements and surface failures from the performed analyses. The main conclusion is that the ground fissures close to Mavropigi are caused from the open lignite mine exploitation, while there was not an obvious connection with any other activity around the examined area. As a result, the local authorities decided to move the Mavropigi village to another place.

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