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Editors
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O. HUNGR
The University of British Columbia, Department of Earth and Ocean Sciences, Vancouver, British Columbia, Canada

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Is it safe to build on fault surfaces in a seismically active area? The case of Eleohori village (Southwestern Peloponnessos, Greece)

I. Mariolakos & I. Fountoulis

Department of Geology, Division of Dynamic Tectonic Applied Geology, University of Athens, Greece

ABSTRACT: The study of the damage distribution caused by the Kalamata earthquake (Sep. 13, 1986, Ms=6.0) at Eleohori village (SW Peloponnessos, Greece), pointed out that the damages were mainly due fault and fracture reactivation as well as to the creation of new features. These faults and fractures were the main active factors for causing damages, in contrast to other ones (non active discontinuities, morphological gradient, etc.), which played a secondary passive role. The density, the geometrical and kinematic characteristics of these active tectonic discontinuities define the behavior of the rock-mass during an earthquake. As a result, the distinction of the rock-mass into loose or compact structural rock-mass unit is necessary.

RESUME: La distribution des degats seismiques, dans le village de Elaiochori, pendant les seismes de Kalamata, a montre que ceux-ci ont ete principalement controles par la reactivation des failles et des ruptures qui ont joue un role actif. Au contraire le role des autres facteurs, (discontinuites inactives, pentes morphologiques etc.), fut passif. La frequence, ainsi que les caracteres geometriques et cinematiques de ces discontinuites actives determinent le comportement de la masse rocheuse, durant un seisme, rendant ainsi necessaire sa distinction a des unites tectonorocheuses “coherentes” et “non coherentes”

1 INTRODUCTION

The Messinia province is one of the most seismically active areas of Greece due to its neighboring to the Hellenic Trench. Eleohori is a small village located eastern of Kalamata (Fig. 1A) and it is one of the most damaged areas, as almost all buildings were collapsed or suffered severe damages. Very few buildings were safe while two of them were among the oldest houses of the village.

During the detailed mapping of the village destruction, the damage distribution in this specific area was tried to be understood. Hence, the target of this paper is to describe the crucial characteristics which define the quality of the carbonate rock-mass occurring in the narrow as well as the wider Eleohori area.

Eleohori village has been built on the higher part of an elongated hilly area striking E-W at an altitude of 530m. Along the watershed the morphological gradient is very low and in any case no more than 15%. On the contrary, at the slopes of the hilly area the morphological gradient is very high and in some locations is more than 120%.

Almost all the houses had been founded on the thick-bedded or non-bedded neritic Cretaceous-Eocene carbonates of Tripolis geotectonic unit, the thickness of which is more than 1.000m (Mariolakos *et al.,* 1986). Generally, the carbonate rocks in case they are not fractured are very cohesive with physico-mecanical properties indicating good behavior in the seismic loading, as these rocks react with bigger elastic and remained deformation (Koukis, 1981).

Concerning the study area (and other areas) the “expected” behavior is totally theoretical, because the carbonate rock-mass is crossed by a big number of different types of discontinuities, with very high density. The properties are such as, the rock-mass behaves as loose breccia with very low strength and very bad behavior under the seismic loading.

2 FAULT ZONES – FAULTS - DISCONTINUITIES

The study area is located at the eastern margin of the Kalamata – Kyparissia graben (1st order neotectonic macrostructure) and constitutes the northwards prolongation of the Gulf of Messinia (Fig. 1A). Big and composite fault zones define the margins of the 1st order neotectonic macrostructure. Within as well as at the margins of the graben there are 2nd order macrostructures, that are smaller grabens and horsts (Fig. 1A). The kinematic evolution of these fault zones is very complicated and differentiated in each fault zone. The most intensive kinematic activity is focused mainly along these fault zones, outlining the rock mass properties in these areas.

Eleohori has been founded on the transition fault zone between the Kalathion Mt. horst to the south and the Dimiova - Perivolakia graben to the north (Xerilas fault zone) (Fig. 1B). A number of parallel big faults in en echelon arrangement striking E-W constitute the fault zone. It is a typical scissor fault zone and the vertical throw is zero at the eastern part and increases towards west. At the western part of the fault zone the total throw is more than 2.000m (Mariolakos *et al.*, 1986, 1989).

Between these big faults there are other smaller faults striking transverse to the bigger ones (Fig. 1B) cutting the area in smaller faulted blocks which are structures of smaller order. Eleohori has been built on such a macrostructure that constitutes an active half graben of 3rd order. The margins of this neotectonic structure are defined by two sets of parallel faults. Within this half graben there is a big number of smaller faults.

The detailed study of the fault pattern in all scales of observation, gave us information about the "behavior" of the different types of faults and fractures during a seismic event and consequently about the "seismo-geological" behavior of the carbonate rocks. By this way within the carbonate rock mass, areas can be distinguished that are intensively fractured and other that are much less fractured. In the study area somebody can easily understand the difference in the grade (frequency + density) of fracturing, as well as in neighboring areas.

- Fault size differs from place to place, and a local classification as 1st, 2nd, and 3rd, etc, order may be made (Fig. 2). In many cases, genetic relationship between faults of a greater order and those of lesser order is apparent.
- These faults show an en echelon arrangement.
- From the kinematic point of view, these faults should be considered as oblique slip faults, with movement normal and /or reverse. Generally, the normal or reverse character of these faults is not apparent because of the complex shape of the fault surface.

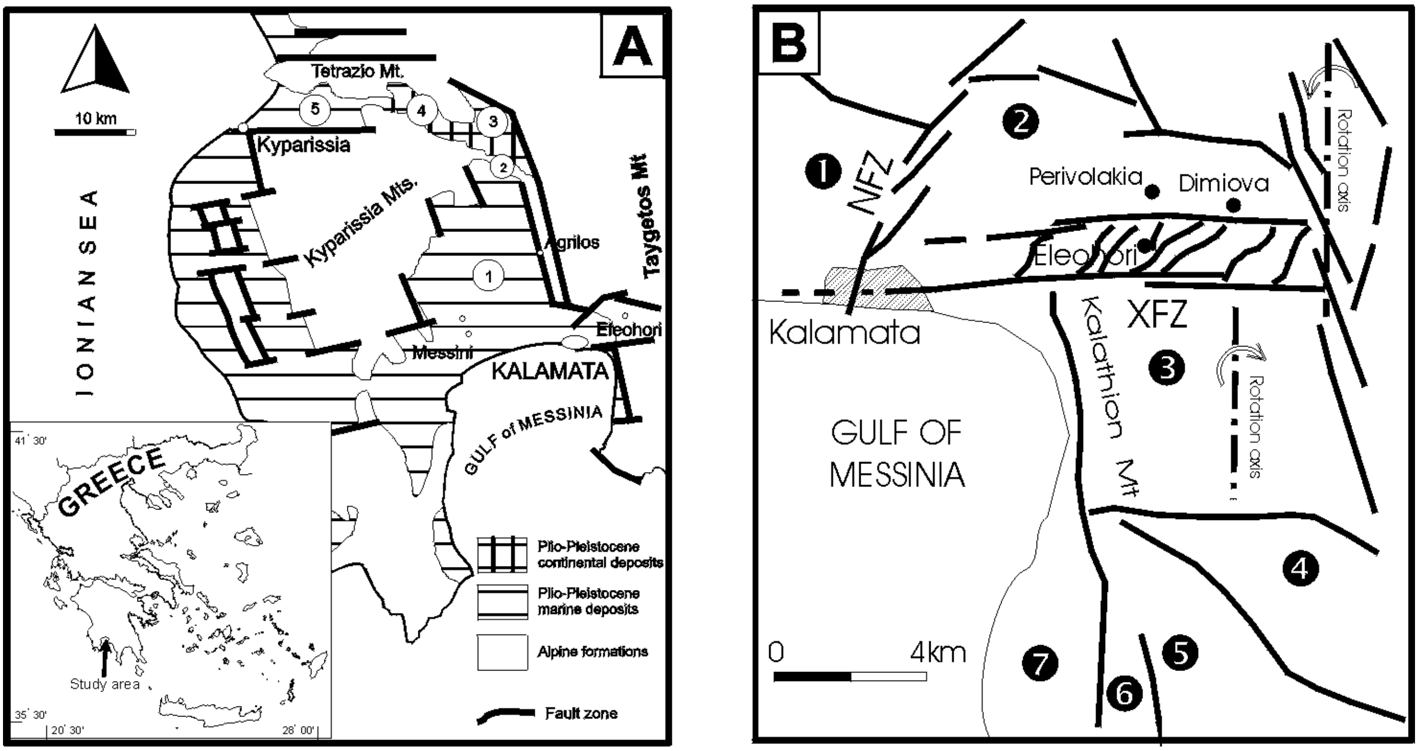

Figure 1 (A) The 2nd order neotectonic macrostructures within the 1st order neotectonic macrostructure of Kalamata-Kyparissia graben. The numbers correspond to the following 2nd order neotectonic macrostructures: 1:Kato Messinia sub-graben, 2:Meligalas horst, 3:Ano Messinia graben, 4:Dorion basin, 5:Kyparissia-Kalo Nero graben. (B) Sketch map of smaller order neotectonic

macrostructures of the Kato Messinia sub-graben 1:Asprochoma-Koutalas horst, 2:Dimiova-Perivolakia graben, 3:Kalathion Mt. horst, 4:Altomyra semi-graben, 5:Kambos graben, 6:Vardia-Koka horst, 7:Kitries-Mantinia sub-graben, XFZ:Xerilas Fault zone, NFZ:Nedon Fault Zone

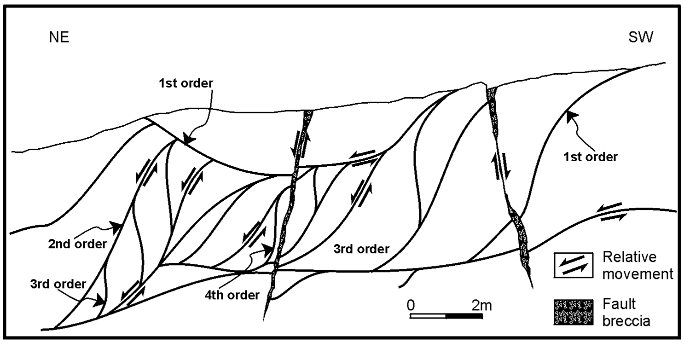

Figure 2 Schematic depiction of older (inactive) neotectonic faults of various order intersected by younger active faults

- The smaller order fault surfaces are limited (bounded) by greater order faults, they usually have an "s" shape and occur in en echelon arrangement. This is an evidence of the dynamic and kinematic dependence of the smaller order fault surfaces to the greater ones (Fig. 2).
- Usually the fault surfaces are polished and more than one slickenside generation occurs on the surfaces. They are characterized by the absence of tectonic breccia or looseness zone along the fault zone.
- These surfaces have been created in the latest alpine orogenic stages or in the very early stages of the neotectonic period, hence, they are considered as inactive (Mariolakos et al., 1986, Mariolakos et al., 1989, Mariolakos, 1991).

On the contrary, the active fault surfaces intersect the inactive ones. They usually dip with more than 70^0 and they usually form conjugate set of fault surfaces in the shape of Ypsilon (Y), that is fault surfaces with the same strike but with opposite dip direction, well known as antithetic faults (Fig. 2). These faults are characterized by the presence of tectonic breccia forming a looseness zone or zones with remarkable thickness. Locally, and parallel to these fault surfaces intensive karstification is developed. Some of these fault surfaces were reactivated due to the main shock and others due to the main aftershock. This fact indicates that during different seismic events probably different set of active faults may be reactivated. These active faults create on the ground surface locally small or large surface fractures (discontinuities).

The density of the neotectonic faults of all orders is generally very high. It is observed in many sites of the Hellenic territory and is related to the local dynamic and kinematic regime of the neotectonic deformation of each area. The high density of the active neotectonic faults by itself is very difficult to transform the massive rock mass into loose one (soft rock). The transformation of the mechanical properties of the rock mass is a more complicated phenomenon related to the kind of movement along the surfaces of the active faults and to their geometry. If there are some presuppositions some inactive blocks may be displaced due to passive reactivation of inactive faults. These small passive displacements cause new displacements to other minor blocks etc. Due to the geometry of the inactive fault surfaces even a very small displacement causes locally sites of compression, and tension, which in their turn cause reactivation of other inactive blocks. Following this way and because the reactivation has taken place many times in the past, mountainous areas can be fractured in various size blocks with various degree of looseness. Hence, areas that have suffered such a type of deformation, they are transformed to a huge size tectonic macro-breccia. Within this loose rock-mass there are some parts of various size which can be still remain massive. All the described processes take place mainly in the transition zones between the positive and negative neotectonic structures (horsts, grabens).

Regarding active faults the following must be noted:

- Generally, they are the result of reactivation of older neotectonic faults. However, in one case, (in the area of the small village Diassello), a totally new fault was created.
- Reactivated faults strike in different directions.
- The throw of the faults due to the reactivation is generally small (maximum 20cm) and of normal character. The maximum throw has been observed at the seismic fault caused by the main aftershock (Ms=5.6 R).
- Seismic faults have been observed in all kinds of formations, alpine and post alpine.
- Most reactivated faults occurred during the main shock; only one (west of Eleohori) occurred during the main aftershock.

Regarding the seismic fractures (ruptures without visible throw)the following must be noted:

- Most of the fractures are relatively small (4-5 meters in length); however, some may be longer (10-50 meters).

- The seismic fractures form zone or zones. The arrangement of the seismic fractures within the zones is typical en echelon. In some areas these fracture zones are of right lateral and in some other areas of left lateral character.
- Seismic fractures were created during both the main shock and the main aftershock. In some cases two separate fractures that were created by the main shock were intersected by a new fracture created during the main aftershock.
- Some fractures created by the main shock were enlarged in width and length by the main aftershock.
- The density of the fracture zones containing large fractures varies from place to place. In one area the density was ten fracture zone per 100 meters.

3 CORRELATION BETWEEN ROCK MASS AND DESTRUCTION

Based on the detail study of the tectonic characteristics of the rock-mass at Eleohori, the following observations could be done concerning its behavior as a foundation material during an earthquake:

i. Apart of the modern constructions of reinforced beton those generally have shown a relative good behavior, it seems that there is not any direct connection between the destructions and the type as well as the art of the buildings. Older and new houses of the village have been destructed. Actually only two old small houses build in the traditional way, that is stones with mortar, remained untouched.

ii. The distribution of the damages at Eleohori shows a very little dependence on the morphological gradient. Heavy damages and/or a great number of total destruction have been observed, even on almost horizontal areas of the village, whereas the two untouched buildings (an old and a relative new) are founded on slope with relative high morphological gradient.

iii. The frequency, as well as the density of the tectonic discontinuities, can be correlated to the distribution of the damages. Most of the damages were observed in buildings founded on multi fractured rock mass, although there were some exceptions.

iv. The most important factor for the damage distribution is the presence of active faults and fractures, which have been reactivated during the seismic activity (seismic faults and fractures). The more intensive damages have been observed on the cross points of two sets of seismic fractures. The most characteristic case is that of the small square of the village, where all buildings around it have been totally destructed, although the foundation conditions were favorable. The morphological gradient was not higher than 5%, whereas the quality of the rock mass would be good enough if it was not crossed by a great number of discontinuities. The detail mapping of the area after the main shock as well as after the aftershock has shown that the area is crossed by many seismic fractures (Fig. 3).

v. Another important factor which supports the direct connection of the behavior of the rock mass and the seismic fractures is the fact that some of the buildings have been destructed during the main shock, whereas some others during the main aftershock. The detail study during the time interval between the main shock and the aftershock, showed that in both cases another fracture set has been reactivated, that is the reactivated fractures by the main shock caused damages which were different to those of the aftershock that reactivated another set of fractures.

vi. One of the two houses that remained untouched was founded on an area with very low morphological gradient, whereas the other one was founded on steep slopes (≅100%). In both cases a great number of discontinuities crossed the rock-mass but none of them is active and consequently the earthquakes have not reactivated them.

vii. The two old houses of the village that remained untouched are the best example to study the crucial role of the reactivation of specific faults and/or fractures on the distribution of the damages (Fig. 3). Both have been built on a fault surface striking E-W, which constitutes the contact of the neritic carbonates and the flysch sediments of the Tripolis geotectonic unit. This fact is very impressive and can be explained (interpreted) if somebody takes into account the kind of the fault surface, as it is a typical alpine inactive fault surface and the building has been founded on the massive rock-mass. So, in spite the fact that (a) the two houses were among the oldest ones, and (b) the morphological gradient in this site is relatively high, none of these houses suffered any damage (Fig. 4).

viii. Worth to note is the case of the remnants of a very old wall from the antiquity period occurring at the westernmost part of the village. This wall remained untouched although a great number of seismic fractures were observed on the ground surface and in spite of that the buildings next to it were totally destructed. This behavior most likely is connected to the type of construction and mainly to the polygonal shape of the stones (building material). Obviously, the seismic energy was absorbed through micro-displacements between these polygonal building elements (stones) allowing in this way small deformation to the construction but not to its catastrophe.

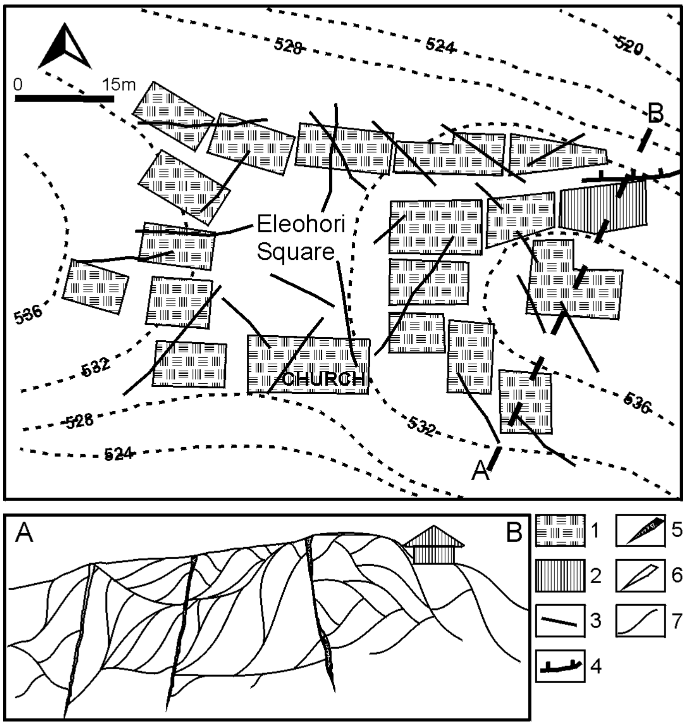

Figure 3 Correlation between the type of fractures (active – inactive) and the damages in Eleohori. 1:Damaged houses, 2:non-damaged house, 3:seismic faults and fractures, 4:inactive fault, 5:active fault reactivated by the Kalamata earthquake, 6:active fault non activated by the Kalamata earthquake, 7:inactive curved fault surfaces

3 STRUCTURAL ROCK UNITS IN ACTIVE AREAS

From the above mentioned it is apparent that the evaluation and classification of the rock-mass according to its expected behavior as a foundation soil in seismic active areas, and apparent of the well known factors which affect more or less their fitness, a great attention should be given to the localization of the active tectonic structures, either of great scale of fault zones in the order of some kilometers in length or to small active faults and fractures in scale of some tens of meters or smaller.

The distinction and mapping of the structural rock units should be done in all scales of observation, from the large-scale maps (1/100.000 or 1/50.000) when it is for basic planning and then to smaller scale maps (1/5.000, 1/1.000 etc). In smaller scale maps the mapping of the rock-mass will be done in a favorable scale representing the special demands of the construction. This work should include the following stages.

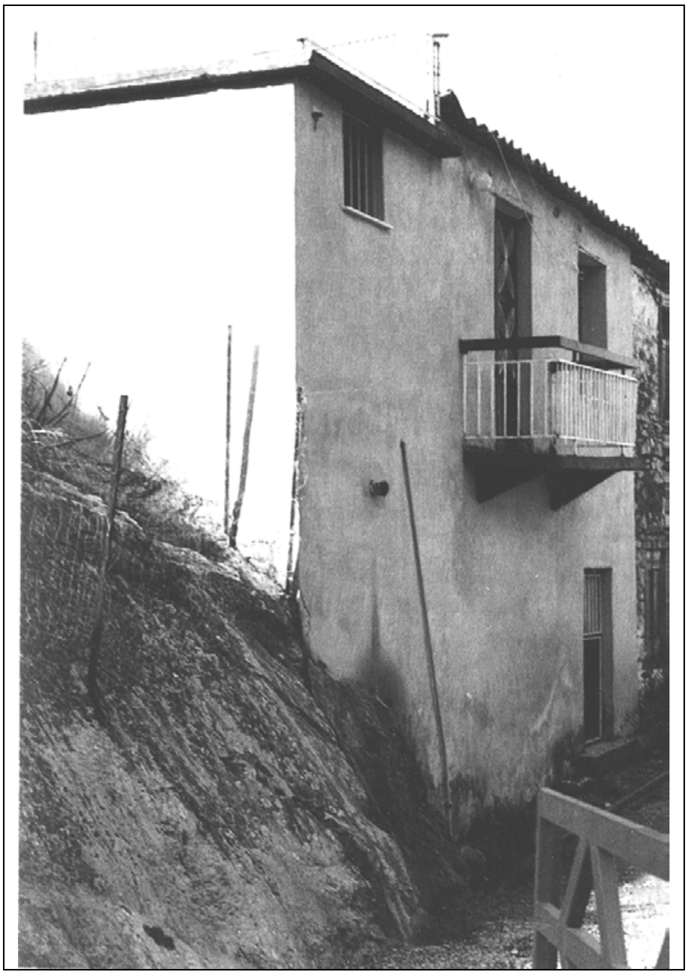

Figure 4 Two old houses remained untouched after the earthquake, although they have been built on an old inactive fault surface but on a massive rock body (neritic carbonates)

i. Localization, mapping and tectonic analysis of the neotectonic macro-structures and mainly the great active fault zones which define their margins. Areas belonging in such zones are not favorable for construction foundation as the frequency and the density of the tectonic discontinuities should be great compared to other areas. They change (influence) greatly the (primary) original characteristic of the rock-mass and the most of them have the characteristics of the active ones and it is most likely expected to be reactivated by a future earthquake. Eleohori village for example has been built on such big fault zone named Xerilas fault zone, which bounds the southern margin of an active neotectonic graben the Dimiova – Perivolakia graben. The Kalamata earthquake reactivated this graben. The city of Kalamata has been built on the cross point of the prolongation of two such big fault zones, namely the Xerilas (XFZ) and the Nedon (NFZ) (Fig. 1B).

ii. In the second stage mapping and detail tectonic analysis of the smaller fault systems and structures that have all the characteristics of active ones and therefore is expected to be reactivated by a future seismic event. In the same mapping the compact rock-mass units that are not crossed by active discontinuities should be also distinguished (Fig. 2). In the parts that the frequency of the active discontinuities is very high, the rock-mass is multi-fractured and behaves with the same characteristics as a loose breccia (loose rock-mass unit). This kind of rock-mass unit is a completely unfavorable ground for structures foundation purposes. In Eleohori for example, the whole rock-mass presents such characteristics and the cohesive rock-mass units which are bounded by active fault zones are very small, and that is the reason of almost total catastrophe of the houses.

iii. In the third stage in the areas that have been characterized as cohesive, the rock-mass unit is definitely evaluated taking into account the rest characteristics as the geometry, the frequency, the density of the inactive discontinuities, the mechanical properties of the cohesive rock-mass, the karstification if it is carbonate rock, the hydrogeological regime, the morphological gradient, etc. The goal is the classification of the rock-mass in various categories according to the expected behavior as foundation ground.

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