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2 AUTHORS:


George Papathanassiou
Aristotle University of Thessaloniki


Spyros Pavlides
Aristotle University of Thessaloniki

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GIS-based database of historical liquefaction occurrences in the broader Aegean region, DALO v1.0

G. Papathanassiou*, Sp. Pavlides

Department of Geology, Aristotle University of Thessaloniki, Egnatia street, 54124 Thessaloniki, Greece

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A B S T R A C T

This paper presents the Database of historical Liquefaction Occurrences in the broader Aegean region (DALO). The database contains historical information regarding liquefaction manifestations, mainly in Greece and the broader Aegean region, that were collected during the last decade. In particular, descriptions of liquefaction manifestations triggered by 90 earthquakes since 1509 were collected and included into a database that was constructed using Ms-Access software. The database consists of six tables that are used for adding information into the database, while six forms have been created in order to present the dataset in a more suitable way. The outcome of this study is that 99% of liquefaction sites are located 0–100 m from a water body, and 94% consist of Holocene sediments and 6% of artificial fill. In addition, in order to present the data under a GIS environment, information in the database was exported into Google Earth kmz format. A web interface of DALO was developed and made available at the web site http://users.auth.gr/~gpapatha/dalo.htm where three maps are presented regarding historical liquefaction occurrences. Photos and figures of the ground or structural failures have been uploaded as well, mainly for the events that occurred after 1950. This GIS-based dataset can be helpful, especially to decision makers and urban planners, as it can be used as a screening guide of liquefaction hazard for avoiding in advance liquefaction prone areas.

1. Introduction

One of the preliminary studies that should be performed for the assessment of a natural – geological hazard within an area is the investigation of the past occurrence of relative ground failures. In order to achieve this goal, scientists search historical sources for reports describing effects induced by a natural event. Taking into account these historical reports, the delineation of areas prone to a geological hazard (soil liquefaction and slope instabillity phenomena) can be accomplished, because ground deformations have the tendency to re-occur in the same places. Therefore, inventory landslide maps are compiled in order to define zones prone to sliding while earthquake primary effects such as surface ruptures and secondary effects such as landslides, subsidence and liquefaction can be predicted using information published in seismic catalogues.

In particular, the collection of data concerning active faults and reports describing secondary effects generated by historical earthquakes has already been started in earthquake-prone countries. Characteristic examples of databases of faults and seismogenic sources have been developed in Italy; DISS by Basili et al. (2008), ITHACA by Michetti et al. (2000), in USA by USGS, in New Zealand by GNS and in Japan by AIST. Recently, a similar database was developed for active faults in Greece by Pavlides et al. (2010) using the structure proposed by DISS (Basili et al., 2008).

2. Soil liquefaction

Soil liquefaction is the transformation of saturated, unconsolidated granular material from a solid state to a liquid state as a consequence of increased pore pressures that reduce the effective strength of the material (Youd, 1973). The liquefaction of a subsoil layer may induced ground failures such as ground settlements, sand boils and lateral spreading and lead to structural damage of buildings, pipelines, and bridges. The generation of liquefaction manifestations is influenced by many factors such as the parameters of the earthquake, the depositional environment of the geological unit, the depth of the water table, and the density of the soil layer. These parameters can be evaluated based on seismic hazard analysis, in-situ tests and surficial geological mapping,

* Corresponding author.
E-mail address: gpapatha@auth.gr (G. Papathanassiou).

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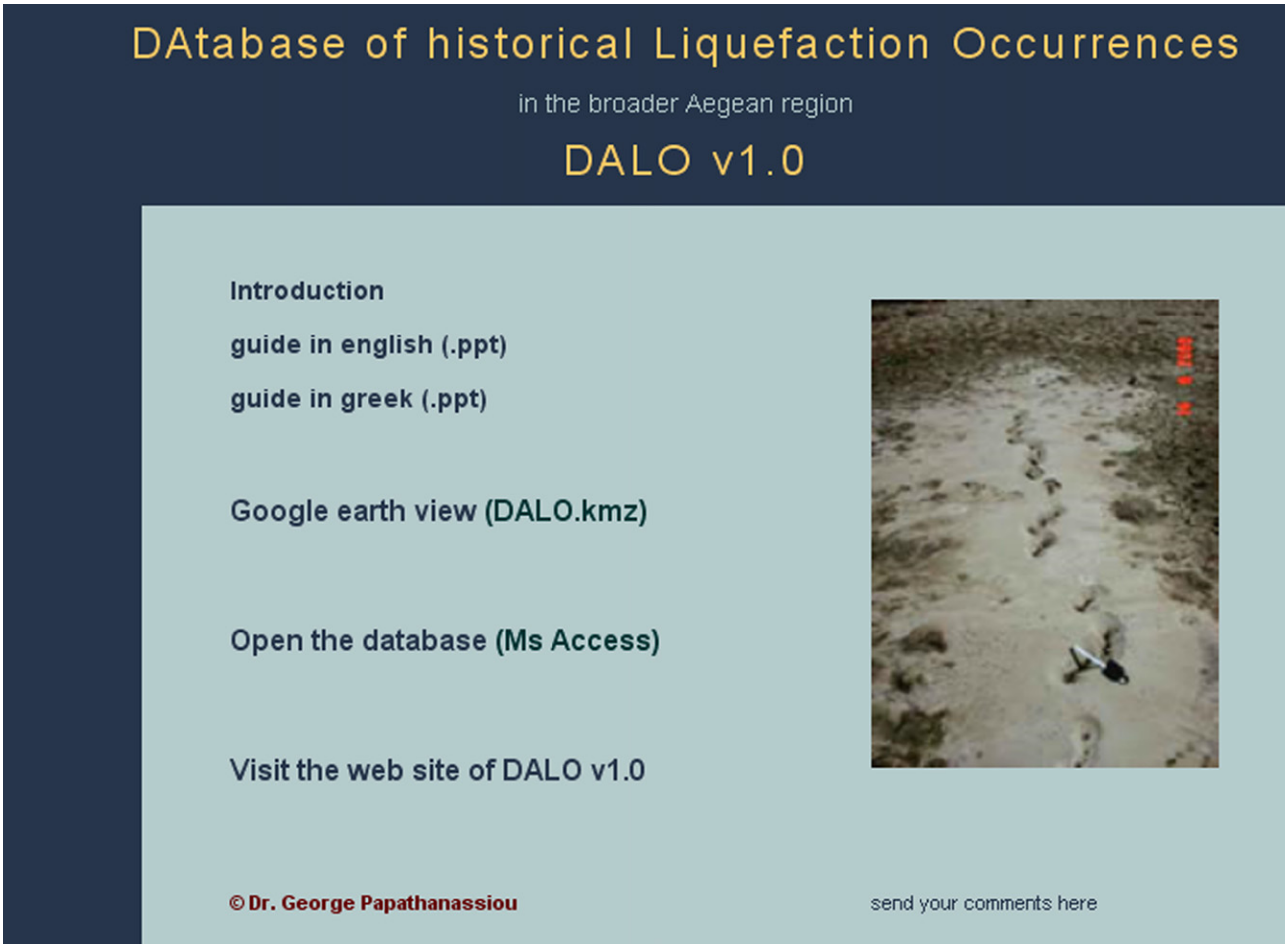

Fig. 1. View of the welcome page of the CD-ROM distribution of DALO v1.0, showing the available options.

realized by seismologists, engineers and geologists, in order to assess the liquefaction susceptibility and the potential to liquefaction in an area.

Reports describing liquefaction related phenomena in the broader Aegean region can be found in seismic catalogues and primary sources from 1509 A.D. (Papathanassiou et al., 2005a). Large-scale manifestations were reported and mapped by Schmidt (1867) for the Aeghio 1861 earthquake. The first event that occurred close to an urban environment and was studied in detail was the 1906 San Francisco earthquake. However, the most severe liquefaction-induced damages to civil infrastructure were triggered by the Niigata and Anchorage earthquakes in 1964, which helped to identify liquefaction as a major problem within an urban area (Idriss and Boulanger, 2008). Other major events that provided data regarding the occurrence of liquefaction were the 1989 Loma Prieta and the 1995 Kobe earthquakes. The latter event caused pervasive liquefaction throughout the reclaimed lands and the artificial islands in the Kobe region, causing extensive structural damages to quay walls around the port facilities and associated damage to the cranes and other supporting facilities (Idriss and Boulanger, 2008).

Several authors (e.g., Youd, 1984; Iwasaki, 1986) observe that liquefaction tends to recur at the same site. Thus, the identification of past liquefaction sites in an area could represent the first step for its classification as a liquefaction prone zone. Following this statement and in order to correlate the epicentral distance of the liquefaction sites with the earthquake magnitude, several researchers collected data and published preliminary databases of historical liquefaction occurrences. Particularly, Kuribayashi and Tatsuoka (1975) provided data from 32 historic Japanese earthquakes. Papadopoulos and Lefkopoulos (1993) updated the dataset, collected by Ambraseys (1988), with 30 new cases from Greece, and Wakamatsu (1993) supplemented the work of Kuribayashi and Tatsuoka (1975) with new data from 67 Japanese earthquakes. Galli (2000) and Aydan et al. (2000) re-evaluated seismic parameters of Italian and Turkish earthquakes, respectively, and a dataset consisting of 88 earthquake-induced liquefaction cases from the broader Aegean region was published by Papathanassiou et al. (2005a).

The parameters introduced in this published dataset were re-evaluated while new data of liquefaction case histories, generated by recent earthquakes were also added (June 8, 2008 event). In addition, the information included in the previous excel-version (Papathanassiou et al., 2005a) was introduced into a new database that was constructed under Ms-Access environment, creating the DALO v1.0. Into this new database, additional introduced information included the quantitative characteristics of the liquefaction sites. Moreover, the DAtabase of historical Liquefaction Occurrences, DALO v1.0, was linked to a GIS platform, using the free software of Google Earth. Both the Ms-Access file (.mdb) and the Google earth file (.kmz) of DALO v1.0 are open-access files and can be downloaded from the web site http://users.auth.gr/~gpapatha/dalo.htm. In addition, the Database of historical Liquefaction Occurrences was also released on CD-ROM, where several options are offered on the welcome page

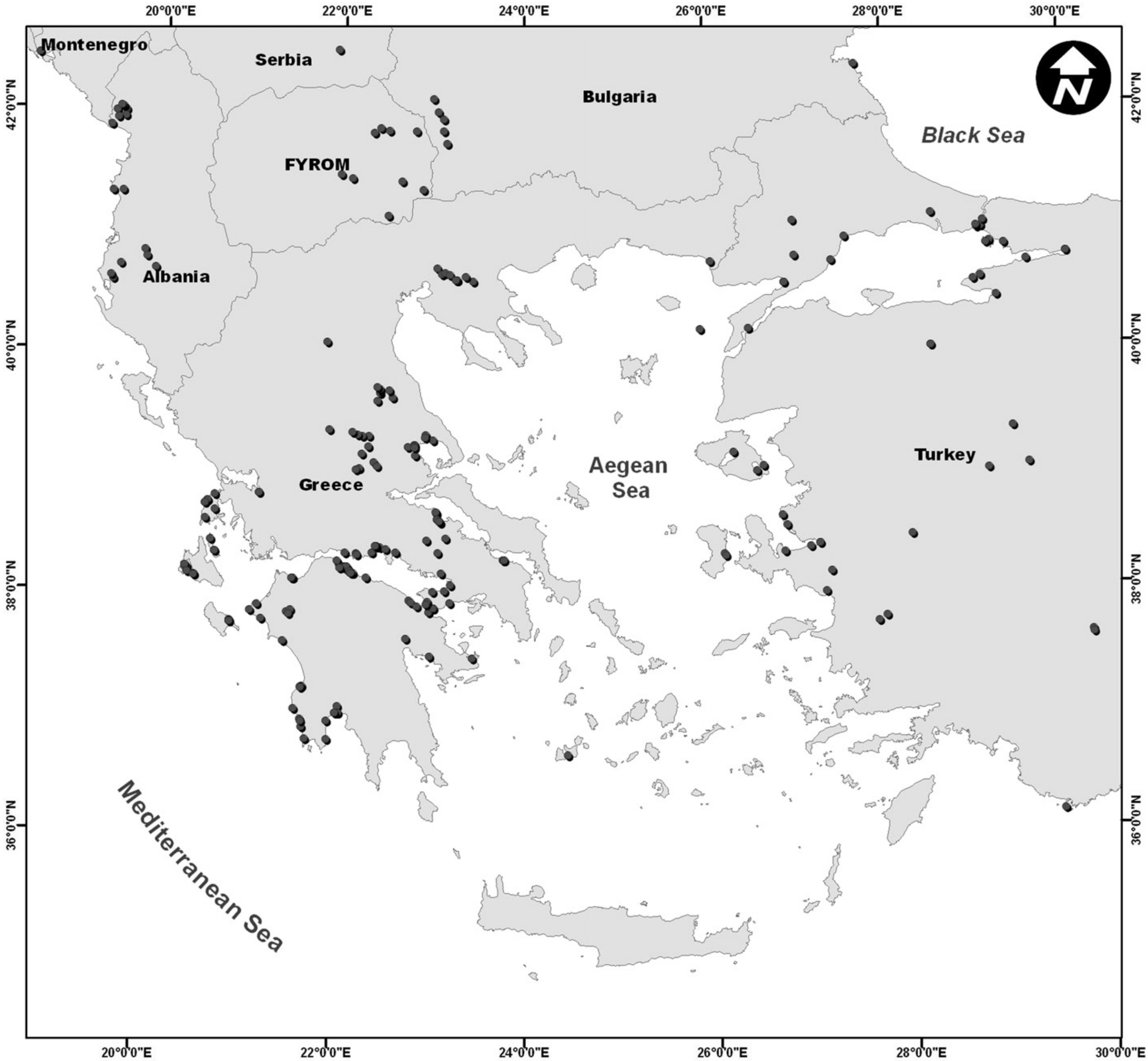

Fig. 2. Map showing the distribution of historical liquefaction occurrences in the broader Aegean region (from Papathanassiou et al., 2005a).

(index.html). In particular, the files DALO.mdb, the DALO.kmz and a guide (Power Point file) explaining the navigation into the database can be downloaded (Fig. 1).

3. Development of the database

DALO v1.0 is an open-access database where information regarding liquefaction-induced ground and/or structural deformations is provided. The first entry in the dataset dates from the 16th century AD while the most recent entry for this project is provided by the earthquake-induced liquefaction of June 8, 2008 in NW Peloponnesus, Greece. However, the oldest events that are mentioned in the seismic catalogues and were correlated to liquefaction-induced failures are the Eliki (Helike) 373 B.C. and Sistos 478 A.D. earthquakes.

An issue that is crucial for researchers is the completeness of a database. In this case, DALO v1.0, the majority of collected data are related to events that occurred in the 20th century since almost all the earthquake-induced secondary effects were reported and studied in detail. Therefore, the catalogue of liquefaction-induced failures in Greece for that period, included in DALO v1.0, can be considered as complete. However, more data including photos of the failures or geotechnical information regarding the liquefaction sites are mainly available for earthquakes occurred after 1950. In addition, the instrumental period of seismicity in Greece began in 1911, and thus, reliable and accurate evaluation of the earthquake parameters (location of epicenter and magnitude) was achieved after that date. Obviously, the small number of historical descriptions of liquefaction phenomena in the earlier centuries is generally due to the fact that most of the events were not reported in detail.

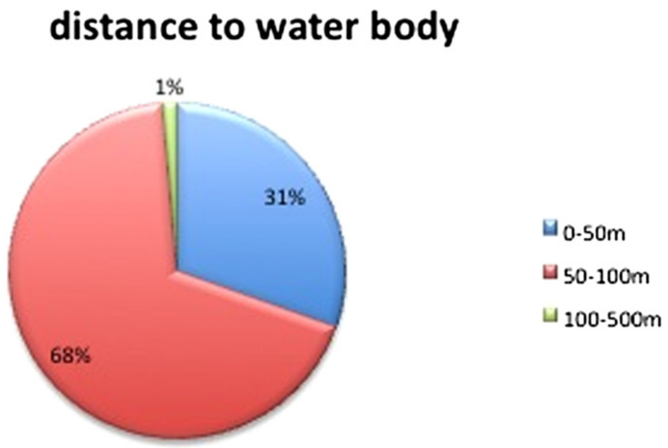

Fig. 3. Chart showing the distribution of liquefaction-induced failures regarding the distance to a water body.

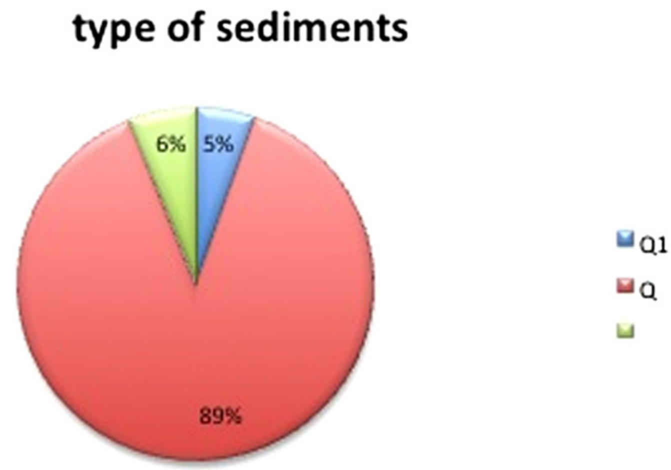

Fig. 4. Chart showing the distribution of liquefaction-induced failures regarding the geology of the liquefaction sites.

The majority of the data (55 cases) that have been introduced in the database, triggered by earthquakes occurred in Greece. Furthermore, 25 introduced cases of earthquake-induced liquefaction reported in Turkey, 5 cases in Albania and 1 case in Bulgaria and Montenegro, respectively. The outcome of this study was that liquefaction manifestations were reported a total of 321 times. In Greece, liquefaction phenomena were repeatedly triggered mainly towards the Gulf of Corinth and towards the islands of the Ionian Sea. In the surrounding region, liquefaction phenomena were mainly reported at the coastal zone of the Sea of Marmara (Turkey) and on river deposits in Bulgaria and in Turkey (Fig. 2).

The proximity of the liquefaction sites to a water body (river network, seashore and lakes) and the presence of geologically

Fig. 5. Chart of the database showing the relations among the introduced elements.

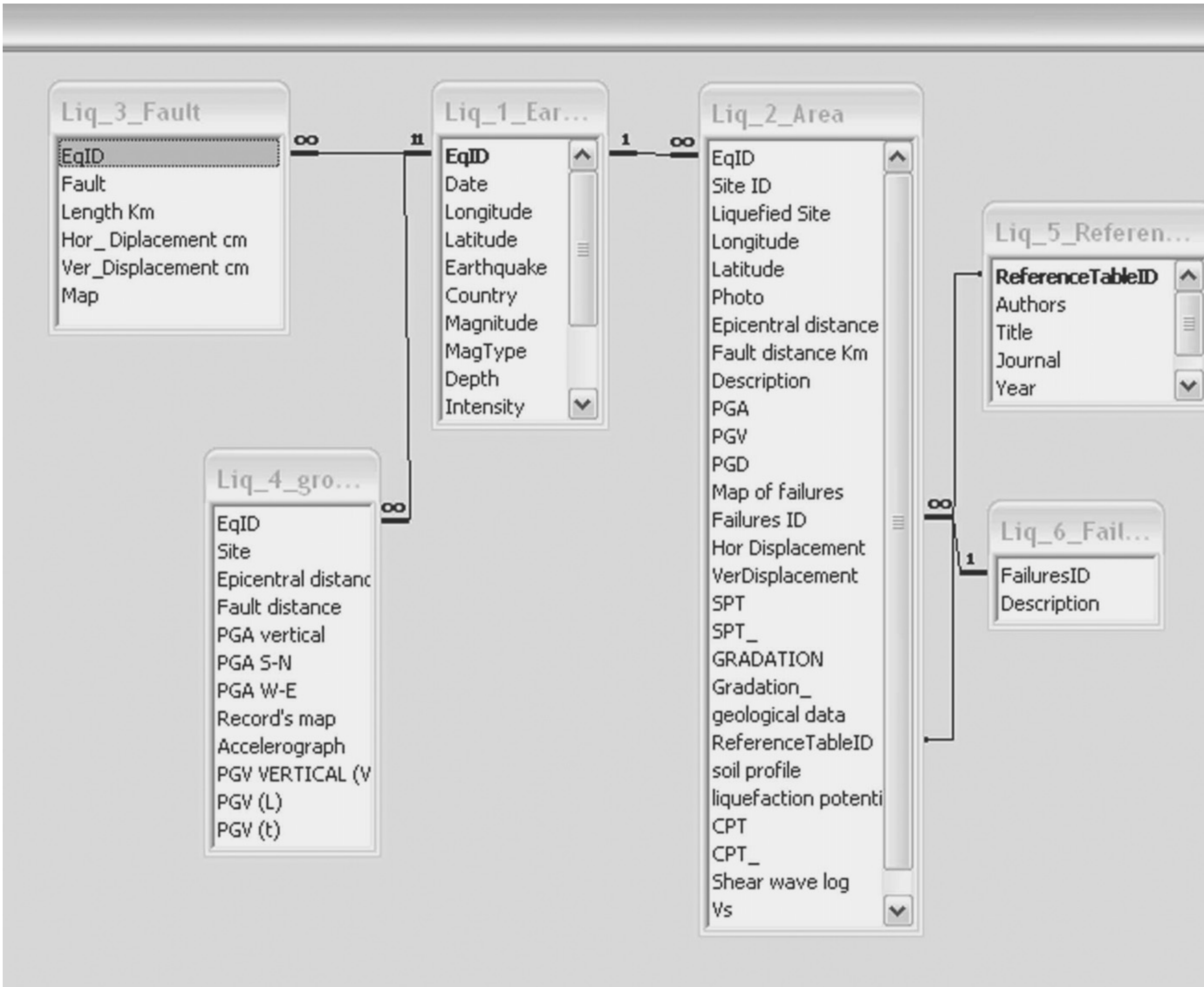

Fig. 6. Relationships among the constructed tables of DALO v1.0.

youthful deposits or artificial fill materials was investigated, taking into account the classification suggested by Knudsen et al. (2009). In particular, the proximity of liquefaction sites to a water body was examined for a distance of 50 m, 100 m and 500 m. The age and the type of sediments were evaluated using the geological map of Greece, at 1:500,000 scale (IGME, 1989). As shown in Fig. 3, 68% of liquefaction sites were induced 0–50 m from a water body, 31% between 50 and 100 m and only 1% farther than 100 m. Regarding the type of material that was liquefied, 94% consist of Holocene sediments and 6% of artificial fill (Fig. 4).

In particular, 89% of liquefaction occurrences were observed in recent to present formations (Q) that mainly consisted of alluvial and fluvial deposits, and dunes: sands, clays, sandy or silty clays usually without a surficial water layer, Liquefaction manifestations observed in coastal, fluvial, deltaic, marsh deposits, usually fine-grained and loose (Q_1), represented 5%.

One of the basic goals of this database is to provide information regarding past liquefaction occurrences, helping delineate areas prone to liquefaction. An example showing the usefulness of DALO v1.0 is the Lefkada, 2003 earthquake ($Mw = 6.2$) that triggered both liquefaction-induced ground deformation and structural damage. As reported by Papathanassiou et al. (2005b), soil liquefaction phenomena were triggered in the town of Lefkada and the villages of Nydri and Vassiliki causing structural damage to port facilities. From a search into the database, more than one event induced similar phenomena at the same sites, such as the 1914 and 1948 earthquakes that caused ground fissures along the coastal road at the town of Lefkada.

3.1. Tables and forms

The database was constructed under Ms-Access software and consists of six tables that are used for adding information. Data presentation is realized using six forms. Fig. 5 shows the chart of DALO v1.0 and the links among the forms that were created.

The six tables are cross-linked by keys using elements that are common to several tables, such as the earthquake ID, the failure ID, site ID and reference ID. Fig. 6 displays the relationships among the independent tables which are based on these primary keys. The independent tables include information regarding the earthquake, the liquefied site, the causative fault, the type of failure, the

Liq_6_Failures : Πίνακας

FailuresID	Description
A1	ground fissures with ejection of mud
A2	Sand boils
A3	local Settlement
A4	Lateral spreading
A5	Settlement of the coast
B1	Settlement of building
B2	Tilting of building
B2,B3	damages to buildings and roads at the port.
B3	Settlement of quay/pier
B4	Lateral spreading of quay/pier
B5	Failure of railway embankments
B6	Settlement of bridge
B7	Failure of river banks
B8	Damage in the lifelines system
C	evidense/no subscription

Fig. 7. Codification of the liquefaction-induced failures.

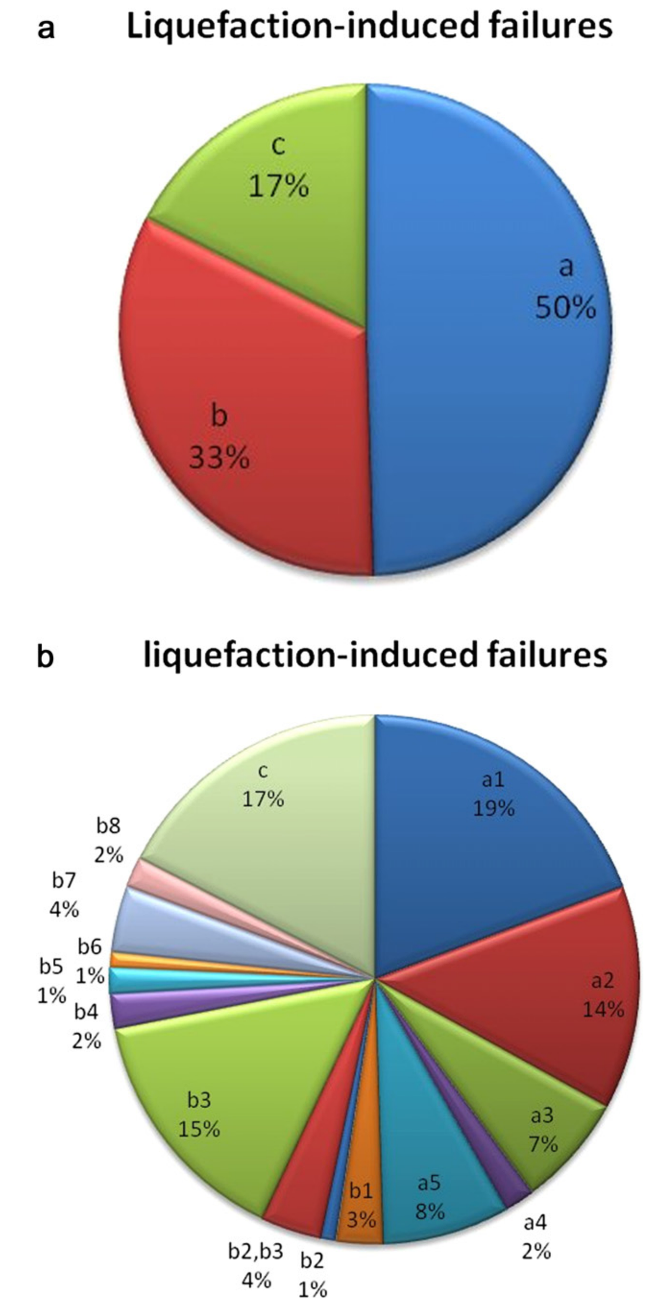

Fig. 8. a. Chart showing the distribution of liquefaction-induced failures regarding the type of failure (a: ground failures, b: structural damages, c: descriptions of liquefaction occurrences where no details concerning either the type of failure or the location of the liquefaction sites were provided). b. Chart showing in detail the distribution of liquefaction-induced failures regarding the type of failure. Codification of the type of failures is presented in Fig. 7.

recorded ground motion and the historical source where the liquefaction-induced failures were described.

In particular, table *Earthquake* defines the earthquake characteristics such as magnitude, epicenter coordinates (latitude, longitude), the focal depth of the event, date of occurrence, country, and maximum intensity. Information regarding the site where liquefaction phenomena were reported is provided by the table *Area* which includes data regarding the epicentral and fault distance, information about the surficial geology of the area, the coordinates of the liquefied site, description and quantitative parameters of the liquefaction-induced failure, map of failures, data provided by boreholes with in-situ tests (SPT, CPT, Vs) and the recorded values of ground motion. Table *Fault* provides information regarding the causative fault such as the type of fault (normal, reverse, strike-slip), length (km), the average of the horizontal and vertical displacement and in few cases a map of the surface ruptures is included. Table *Ground motion* includes the recorded ground motion, providing the values of peak ground acceleration, peak ground velocity and peak ground displacement as they were recorded by accelerometers and the relative time-histories. The table *Reference* includes information regarding the source (report) from where the description of liquefaction manifestation was collected such as the author's name, title of paper, journal and year of publication. Finally, the table *Failures* provides the coding of the description of the liquefaction-induced ground and/or structural deformation (Fig. 7). In particular, the cases of liquefaction-induced failures have been initially grouped into three categories: ground failures/deformation (A group) and structural damages (B group), while a third group was also created including cases of liquefaction for which details concerning either the type of failure or the location of the liquefaction sites were not provided (C group). Afterwards, sub-categories were developed corresponding to the primary description of failure as derived from the historical seismicity catalogues and recent published reports and articles. As shown in Fig. 8a, 50% of the cases of liquefaction that were included in this database deals with ground failures while 17% grouped in the C group due to the lack of accuracy of the provided data. In addition, descriptions of ground fissures with ejection of mud and sand blows consist of 19% and 14%, respectively of the cases grouped in group A (Fig. 8b), probably due to the fact that the formation of these type of failures is the most common surface evidence of soil liquefaction which is easily detected during post earthquake reconnaissance reports.

The presentation of the collected data is accomplished using forms grouped in two main categories. The first group provides information of earthquake-induced liquefaction characteristics, and the second one includes data regarding the liquefaction site. Navigation into the database is accomplished by the welcome form (Fig. 9) which gives the opportunity to select one of these two groups for browsing through its contents. Moreover, searching for a specific liquefied site or an earthquake that triggered liquefaction

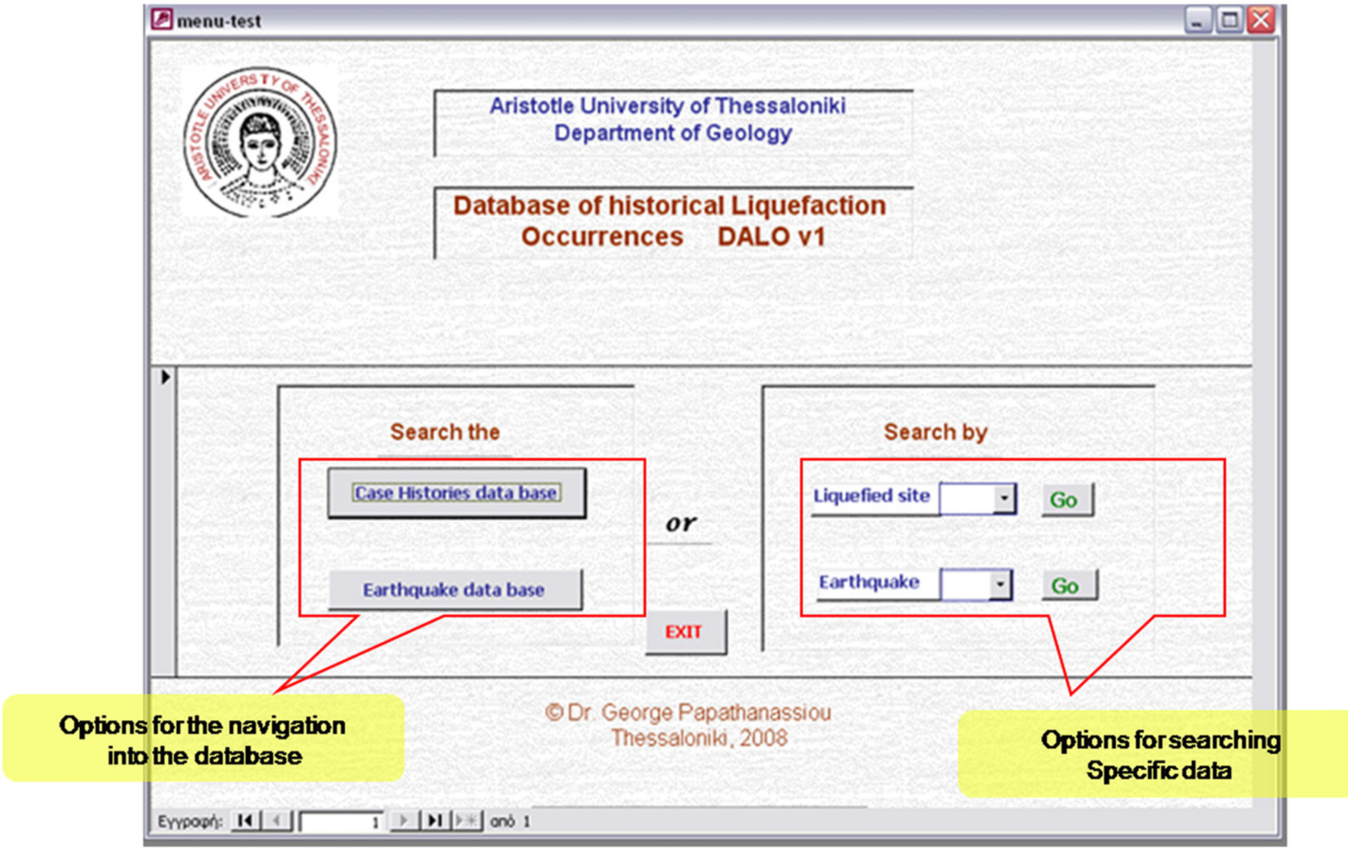

Fig. 9. Top-level form of DALO v1.0.

phenomena is now possible and can be achieved by selecting the corresponding options, appearing in the menu at the right side of the introductive form. Searching is accomplished using the primary keys of Eq ID and site ID, respectively and the user can select either an earthquake based on the date of occurrence or a liquefied site based on its location.

The buttons located on the form (Fig. 9), lead to the basic forms of DALO v1.0, Area and Earthquake, respectively, where information in the tables *Earthquake* and *Area* is presented. As can be observed on the form in Fig. 10a, hyper-links were used for introducing photos of the failure and profiles provided by in-situ tests in order to minimize the size of the database. These elements were uploaded to the server of the Aristotle University of Thessaloniki, AUTh, and can be viewed as an html page. Moreover, the type of liquefaction-induced failure has been introduced using a failure ID. For a detailed description of the failure, the user should select the button *damage* presented in the menu located at the bottom of the *Area* form. The button *earthquake* leads to a form where the earthquake parameters are presented, the button *reference* leads to the Reference form, and the button *fault data* leads to the Fault form. In addition, fields presenting the recorded values of ground motion at the liquefaction site have been created, despite the fact that in the broader Aegean region such type of data/recordings are rare. Fig. 10b shows the *Earthquake* form where the seismic parameters of the event are presented. Moreover, a brief description of the secondary effects that were triggered by the event and a map showing the spatial distribution of the failures is provided. The buttons *site*, *fault* and *ground motion*, located at the bottom of the form, are used to link the earthquake form with the forms where information regarding the liquefied site, the fault and the recorded ground motion were introduced.

4. Connecting DALO v1.0 to a GIS platform

The next step of the project was the development of a user-friendly web interface, where the information included in the database DALO v1.0 is presented. In particular, the goal of the project was to present the distribution of the liquefied site in conjunction with basic information regarding the liquefaction case histories. In order to achieve this goal, Google Earth software was selected due to the fact that it is a free application and it can be easily downloaded from the web site http://earth.google.com/index.html and because it provides the opportunity to compile maps accessible via Internet.

The liquefaction case histories in the DALO v1.0 were initially separated into two groups depending on their location; sites in Greece and in surrounding countries, respectively, and two corresponding maps were developed. In addition, a map was compiled showing the epicenters of the earthquakes that induced the liquefaction cases in the database. These, three maps were created using the Google Earth software and organized as layers in a file of kmz format (Dalo.kmz). This file is included on the CD-ROM while the three compiled maps can be viewed (Fig. 11) as separate elements at the web site of DALO v1.0 (http://users.auth.gr/~gpapatha/dalo.htm).

The icons on these maps represent either liquefied sites or epicenters of earthquake-induced liquefaction. Information regarding the liquefaction manifestations is accessed by clicking on the icons. In particular, every icon of a liquefied site includes data regarding the date of occurrence, the location and a short description of the liquefaction-induced failures. Moreover, in some case histories, mainly after 1950, a photo of the failure is also included, as is shown in the example of the June 8, 2008 event in

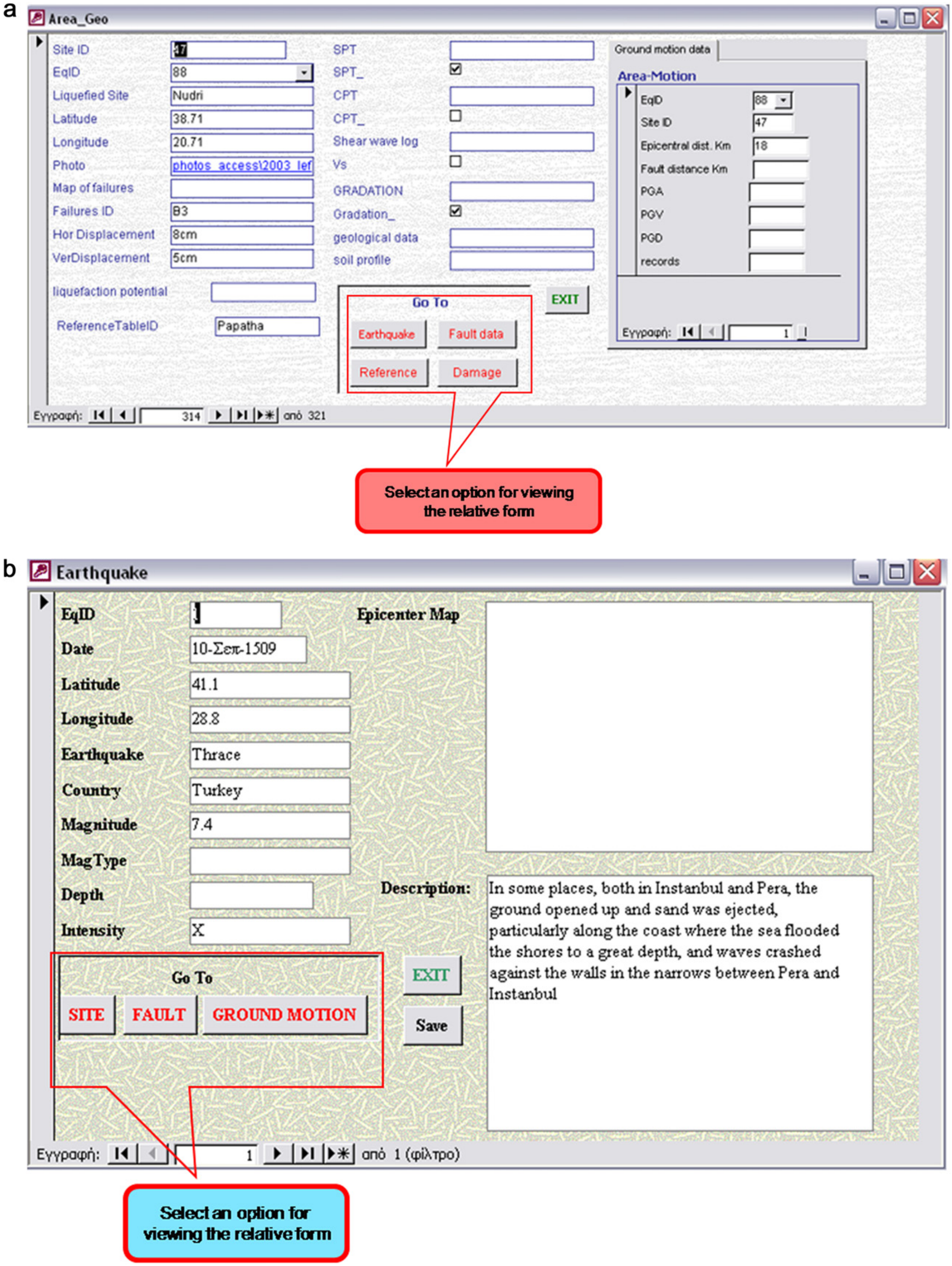

Fig. 10. The two basic forms of liquefaction sites (10a) and earthquake (10b) that are used for browsing through the contents of the database.

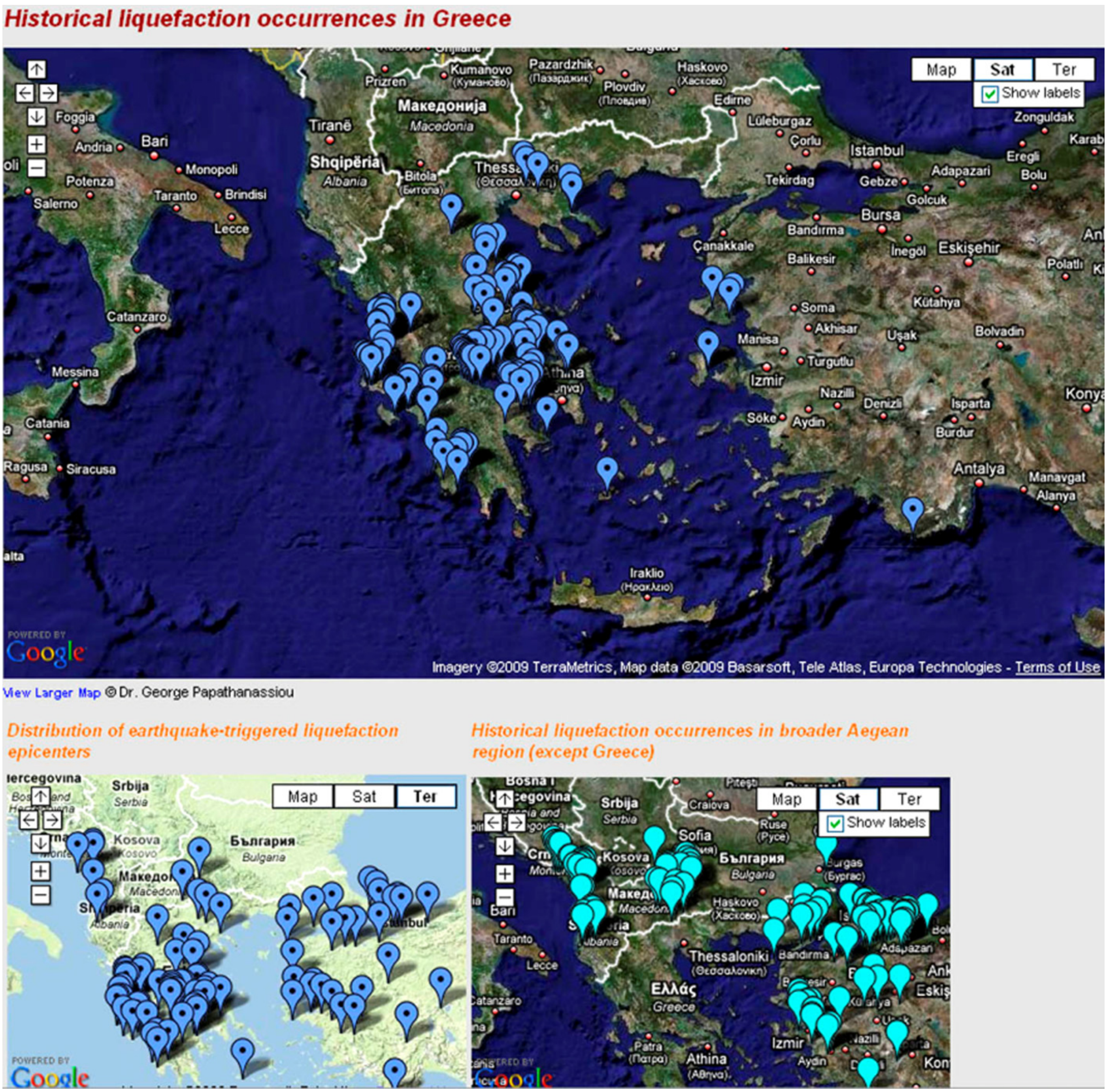

Fig. 11. Home page of DALO v1.0 showing the three compiled maps of liquefaction sites in Greece, liquefaction sites in surrounding countries and of the epicenters of earthquakes that caused.

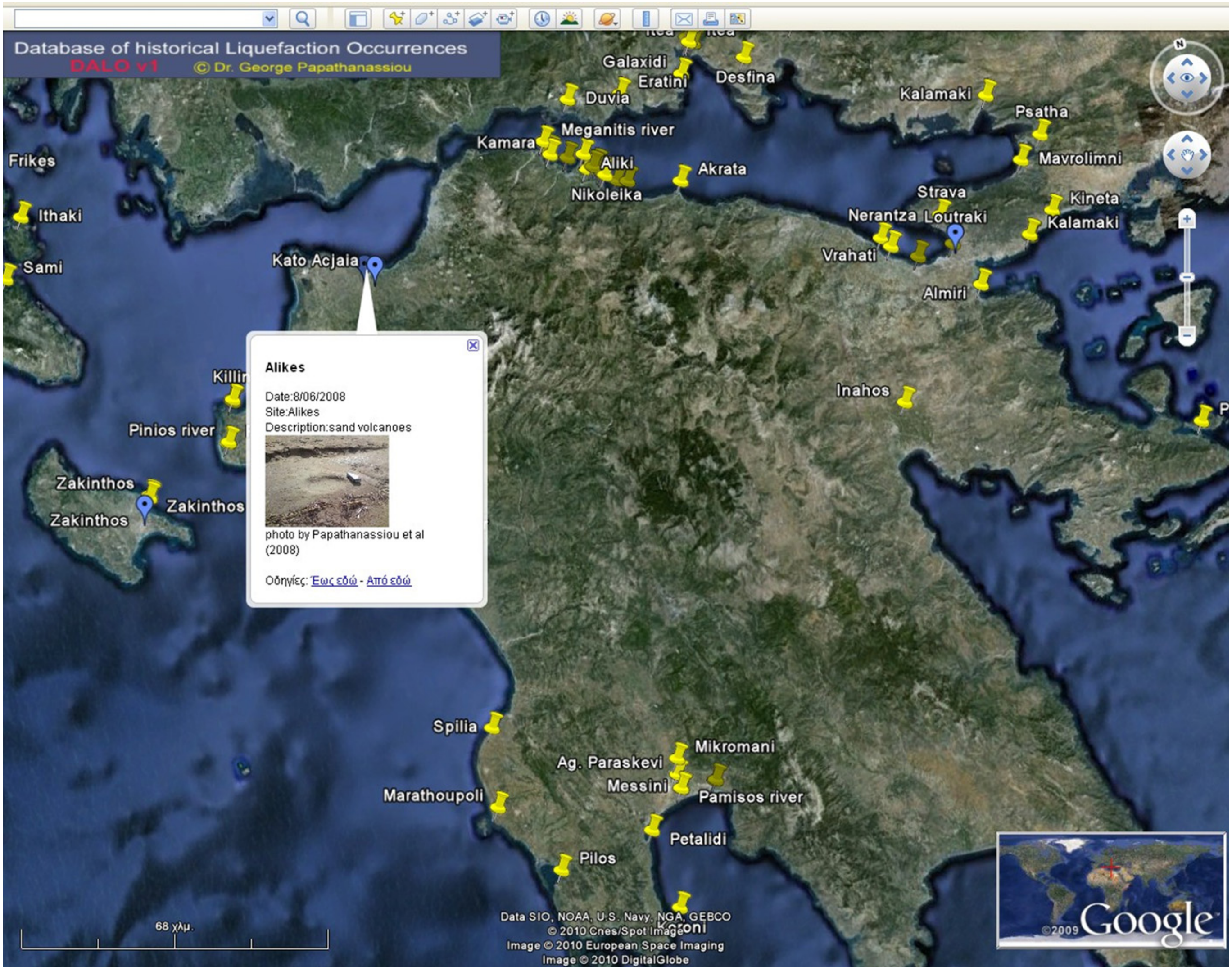

Fig. 12. Example of the information accessible through the icons on the Google Earth map of historical liquefaction occurrences in Greece.

NW Peloponnesus, Greece (Fig. 12). The icons on the map of earthquake epicenters include information regarding the date of occurrence, the primary source and a brief description of the secondary effects that were generated by the event. In addition, the option *See details* leads to an html page presenting all data in the database for the particular earthquake.

5. Conclusions

This paper presents the structure and the contents of the Database of historical Liquefaction Occurrences (DALO v1.0) in the broader Aegean region. The database was developed in the frame of a project that was accomplished the last decade at the Department of Geology at the Aristotle University of Thessaloniki, Greece. The basic aim of this project was the development of a database of historical liquefaction occurrences and the linkage of the collected information to a GIS environment. This goal was achieved using the Ms-Access and the Google Earth softwares, respectively. Initially, a digital version of the database published by Papathanassiou et al. (2005a) was created where information regarding liquefaction sites and parameters of earthquake-induced liquefaction was introduced. Subsequently, basic parameters were linked to a GIS environment using Google Earth and three maps were compiled, two maps showing the distribution of liquefaction sites in Greece and in the broader Aegean region, respectively, and a third map showing the distribution of the epicenters of earthquakes that induced liquefaction. These maps, available at the web address of DALO v1.0, http://users.auth.gr/~gpapatha/dalo.htm include data that were further used for the compilation of the preliminary susceptibility map of Greece (Papathanassiou et al., 2010) in conjunction with a map of the distribution of the Quaternary deposits and the seismic hazard map published by IGME (1989) and EAK (2000), respectively.

Statistical analyses were performed correlating the occurrence of liquefaction manifestations with the proximity to a water body and the surface geology, respectively. The outcome of these analyses indicate that 99% of liquefaction surface evidence was observed at a distance of 0–100 m from a water body and 89% in recent to modern formations.

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