

Implementation of the damage index approach for the rapid evaluation of earthquake resistant buildings

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Received: 21 August 2014 / Accepted: 23 December 2014 / Published online: 15 January 2015
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Abstract This paper presents a promising approach to modeling the building resistance in the seismic rehabilitation process. The damage index model (DIM) can be interactively utilized into the Geographical Information Systems (GIS) in order to compute parameters and to analyze data for a quality management purpose. It can perform an easy accessibility of the data to evaluate buildings for earthquake mitigation and preparedness. This research article intended to introduce a software program by using an integration system to design and to dissect the data for evaluating a building resistance against earthquakes. This paper promises a new integrated system for rapid evaluation of buildings, further a city planning by combination of GIS, civil engineering and industrial engineering upon the Federal Emergency Management Agency (FEMA) accompanied by seismic data, structure, parcel, material type, foundation, ceiling, wall, floor, the interior and the exterior. This software has been programmed based on the Damage Index (DI) algorithm that was developed by Pirasteh et al. (Int J Geoinformatics 5(4): 34–41, 2009). Later, based on the proposed algorithm or model the essential parameters have been adopted in Matrix laboratory (MATLAB) environment to yield a new software program for the meliorating earthquake mitigation and preparedness processes. This software program can identify vulnerability of the buildings ranking from 1 to 100. In addition, this paper recommends establishing a scientific procedure in determining the vulnerability of the buildings for earthquake

preparedness within a GIS environment. However, this software program can amend in detecting weak structures for rehabilitation.

Keywords Geographical information systems (GIS) · Building evaluation · Civil engineering · FEMA · MATLAB · Damage index model (DIM) · Damage index (DI)

Background and introduction

According to the literature, an earthquake occurs when we have a sudden release of energy in the Earth's crust that creates seismic waves. Earthquakes can be recorded with a seismograph. The magnitude momentum of an earthquake can be conventionally measured by Richter magnitude. If the magnitude is three or lower for earthquakes, it will be considered to be mostly imperceptible, and the magnitude seven causes a catastrophic damage over large areas. In addition, the intensity is measured by the modified Mercalli scale. Usually, earthquakes are divided into three categories: minor, medium and major. Earthquakes can occur almost anywhere, including Canada, New York City, England, Australia, India, Pakistan, and Iran. Larger earthquakes produce less frequently, the relationship being exponential.

Some of the mentioned countries are exposed to many minor and major earthquakes annually. It needs major consideration to formulate the strengthened of the buildings against future earthquakes. At the present time, there are numerous weak structures that are not able to withstand an earthquake. Public and private developers are intending to use the scientific methods to priorities and allocate budget in order to reinforce the structures, because of limited financial resources, time and availability of an appropriate model. In the recent years, this procedure has been applied in many countries. It

Communicated by: H. A. Babaie

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seems logical to renew our structures now that we are equipped with sufficient data about the effects that are caused by earthquakes.

The cost-rebuilt ratio is defined as an indicator for determining the vulnerability rate of a building. This indicator is defined for different primary sectors of a building that is computed for the whole of the building in the end. Simac et al. (1991) introduced a method concerning the short reinforced concrete buildings assessment for education purposes. In this method (i.e., screening method) the assessment of the structure takes place step by step.

Pirasteh et al. (2009) evaluated the number of buildings in Esfahan city, central of Iran. They determine low to high venerable buildings to seismic activity that are prone to collapse due to the potential earthquakes. In this study, they have studied the mitigation and prevention of an earthquake with a disaster management consideration. However, it found that at the present time there have been still numerous weak structures that are not able to withstand an earthquake.

Earthquakes can destroy human infrastructure and habitat, killing and impacting large populations, especially in urban areas. Although the 2002 Bam (Pirasteh et al. 2009) Iran earthquake was considered by some to be a wake-up call, it certainly reminded others that proactive mitigation efforts pay off as damage and loss of life were minimal for such a large earthquake in a populated area. Earthquakes can affect any area within a broad zone and it may poses a great risk to human lives and fatalities that is depending on settlement distribution and densities, in addition to building materials, engineering standards, and the like. Recently, many scientists (Barzangi 1989; Zhang and Wang 1995; Kijko and Sellevoll 1992; Berberian 1994; Berberian 1995; Zhenzhong and Lanmin 1995; Ambrasys et al. 1996; McClusky 2000; Maiti 2001; Saraf et al. 2002; Ali and Pirasteh 2004; Cavallaro et al. 2012; Pirasteh et al. 2008; Alam et al. 2009; Pirasteh et al. 2009; Grasso and Maugeri 2009; Erdik et al. 2011; Grasso and Maugeri 2012; Sadra et al. 2014) work on challenges at the various scales by using the GIS in an emergency preparedness and response. They examined the challenges that occur between human and their environment under the conditions suspected to be hazardous to life and habitat. It recommended priorities for the research, the educational, and the policy contributions insight emergency preparedness and response that to be documented.

The review literature shows that the state-of-the-art utilizing an integration of the damage index model (DIM) accompanying the engineering parameters in a GIS platform has been an interest of the researchers to enrich the quality of the hazard mitigation for the loss reduction. The significance of this paper is to compound structural

engineering and industrial design parameters to develop a software program and to visualize the 3D model in a GIS environment (Grasso and Maugeri 2005). It also allows the operator to store, to retrieve, to compute, and to analyze the data in a GIS environment, and identify weak structures for the rehabilitation and the buildings reinforcement improvement. The damage index method presented in this paper is based upon the damage index algorithm (Pirasteh et al. 2009). This allows to integrate the components such as, seismic data, structure, parcel, material type, foundation, ceiling, wall, floor, the interior and the exterior. This platform can be used in computing and analyzing the vulnerability of a building. However, this study contributes an integration model in calculating vulnerability of the buildings against an earthquake. In addition, rapid evaluation buildings software has been introduced to present the author contribution in the research and development innovation context to mitigate a disaster event, and to improve the disaster management based on FEMA for the quality management (Table 1) (Pirasteh et al. 2009; Alam et al. 2009).

The objective of this paper is i) to define the main parameters of vulnerability of the buildings, ii) to calculate the effect of parameters on an earthquake management, iii) to develop a software based on essential parameters, and finally iv) to collect data and to introduce a model for the future studies.

Study area

The study area situated in the center of Iran (Fig. 1). Esfahan city located in one of the earthquake regions in Iran. It lies between latitudes $32^{\circ} 00' 00''$ N to $32^{\circ} 42' 00''$ N and longitudes $50^{\circ} 00' 00''$ E to $51^{\circ} 00' 00''$. Esfahan is a historical city of Iran and goes to about more than 600 years back. It is about 360 km southeast of Tehran and easily reachable with road.

The seismic activities (Farrokhnia et al. 2011; Motlaq et al. 2011) in Iran are limited to the Zagros highland's regions in comparison with the center and the east of Iran. Recently, many studies have been conducted on the characteristics of earthquake in Iran (Barzangi 1989; Berberian 1995; Ahmad and Pirasteh 2004; Katsanos et al. 2010; Monaco et al. 2011; Pirasteh et al. 2009). Some of the major faults around Esfahan city (i.e., within 150 km Radius) are a) the main Zargos Belt, b) Ardal, c) Zardkoh, d) Dopolan, e) Sabzkoh, f) Dena, h) Kashan, i) Zafre, j) Chah Zangol and k) Kolaghazi. Geologically, the study area belongs to the Sanandaj-Sirjan Zone (SSZ) which consists of igneous and metamorphic rocks, volcanic and sedimentary rocks from Precambrian to Recent in age.

Table 1 The main constituents of FEMA process

No.	Qualitative system constituents	System’s constituent’s function in FMEA process
1	Leadership	Encourage the FEMA and assure the availability of sufficient tools, resources, and manpower
2	Procedural planning	Using FEMA results for future development activities
3	Evaluation of the process and conduct	Evaluation FEMA results quality wise and the end product
4	Proper application of data	Controlling the facts, data, and analysis; end result evaluation
5	Process control	Making sure that projects are initiated based on FEMA and statistical improvement, and advances are being controlled
6	Human resources	Supporting the group in all aspects of the process
7	Education	Providing for a continues educational plan for advanced studies
8	Fundamentalism (Qualitative)	Recognition of FEMA as a part of qualitative procedure in plant/work and proper application of it
9	Fundamentalism (Executive procedures)	Assuring uniformity and reducing potential unnecessary changes
10	Design control	Assuring harmony in the process design
11	Customer-Oriented	Providing information for FMEA group regarding the customer requirements in the process
12	Opinion gathering system from customers	Collecting and recording additional information for the FMEA group during the process

Methodology

The algorithm and engineering parameters

The damage index approach has been proposed base on the engineering parameters such as, seismic data, structure, parcel

and material type, foundation, ceiling, wall, floor, the interior and the exterior. This algorithm was developed by (Pirasteh et al. 2009) (Eq. 1). This algorithm have been used in MATLAB environment accompanied by the essential parameters.

$$DI = \alpha_1 \cdot \log(\omega_1) \sum_{i=1}^{24} \beta_i + \alpha_2 \cdot \log(\omega_2) \sum_{i=1}^{10} \gamma_i + \alpha_3 \cdot \log(\omega_3) \sum_{i=1}^{10} \xi_i + \alpha_4 \cdot \log(\omega_4) \sum_{i=1}^4 \eta_i + \alpha_5 \cdot \log(\omega_5) \sum_{i=1}^4 \Omega_i \tag{1}$$

Where, DI is the damage index, α is the failure coefficient and ω is the intensity coefficient of observed defects. β is the effect coefficients for members, γ is the effect coefficients for connections, ξ is the effect coefficients for foundation, η is the effect coefficients for diaphragms and Ω is the effect coefficients for interaction, so foundation acts as when larger the value of the coefficient, the larger the damage risk will found.

The samples have been collected from 100 houses in the study area. Engineering parameters such as seismic data, structure, parcel, material type, foundation, ceiling, wall, floor, the interior and the exterior were analyzed in the laboratory and the output attribute data value has exported to the ArcGIS software to combine with the topography city map of Esfahan, and to visualize a 3D map. This algorithm (Eq. 1) has been used to incorporate the relationship between seismic and industrial engineering. Also, it has been considered to achieve a strategic rehabilitation management program within MATLAB environment.

Matrix laboratory (MATLAB) and rapid evaluation software design

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. MATLAB features a family of application-specific solutions and it is called toolboxes. Toolboxes allow programmers to learn and to apply the specialized technology. Toolboxes are comprehensive collections of the MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. One of the essential features of MATLAB is Graphic User Interface (GUI). It allows programmers to make a new program environment and develop stand-alone applications. This research has been used for all those features to design powerful software based on MATLAB. In MATLAB environment the buildings have been classified in high vulnerable, medium vulnerable, lowly vulnerable and invulnerable. The GUI has been used as the main tool for developing DIM software. All the above parameters in the

Eq. (1) have been considered as key variable to develop this software.

However, based on the following steps, this new software was developed. a) Understanding MATLAB capabilities in programming, b) analysis and formalize the problem based on the essential parameters in Eq. (1), c) design a new environment based on MATLAB GUI, d) to apply parameters on the proposed environment, f) using the MATLAB functions to make the relationships between the input parameters, g) using the MATLAB functions to calculate the input parameters and to acquire the outcomes, h) calibration on the results to

achieve the parameters performance, and i) showing the result and analysis of the parameters in an appropriate screen design.

As for the Rapid Evaluation Software design, a main bar from the software has been designed into the seven sections (Fig. 2). It consists of the member defects, joint defects, joint connection, concrete or brick, interaction of the structure, intensity coefficient and the result. Each section comprises a several information that must be completed by the operator to enter the discrete (i.e., attribute) data.

Moreover, by applying the software engineering analysis methods, we tried to make it a mature software. On the first

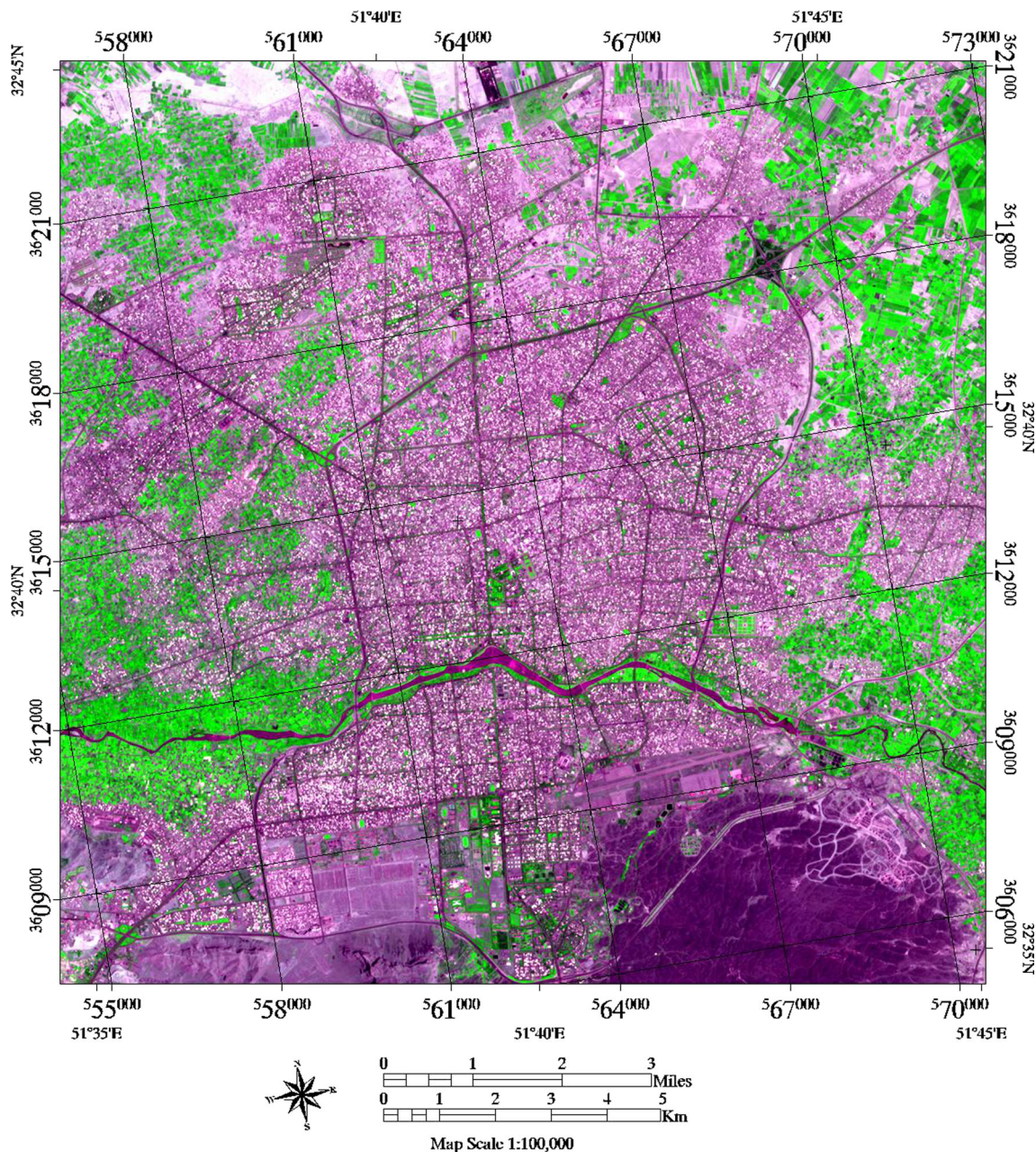


Fig. 1 Study area, Esfahan, central of Iran

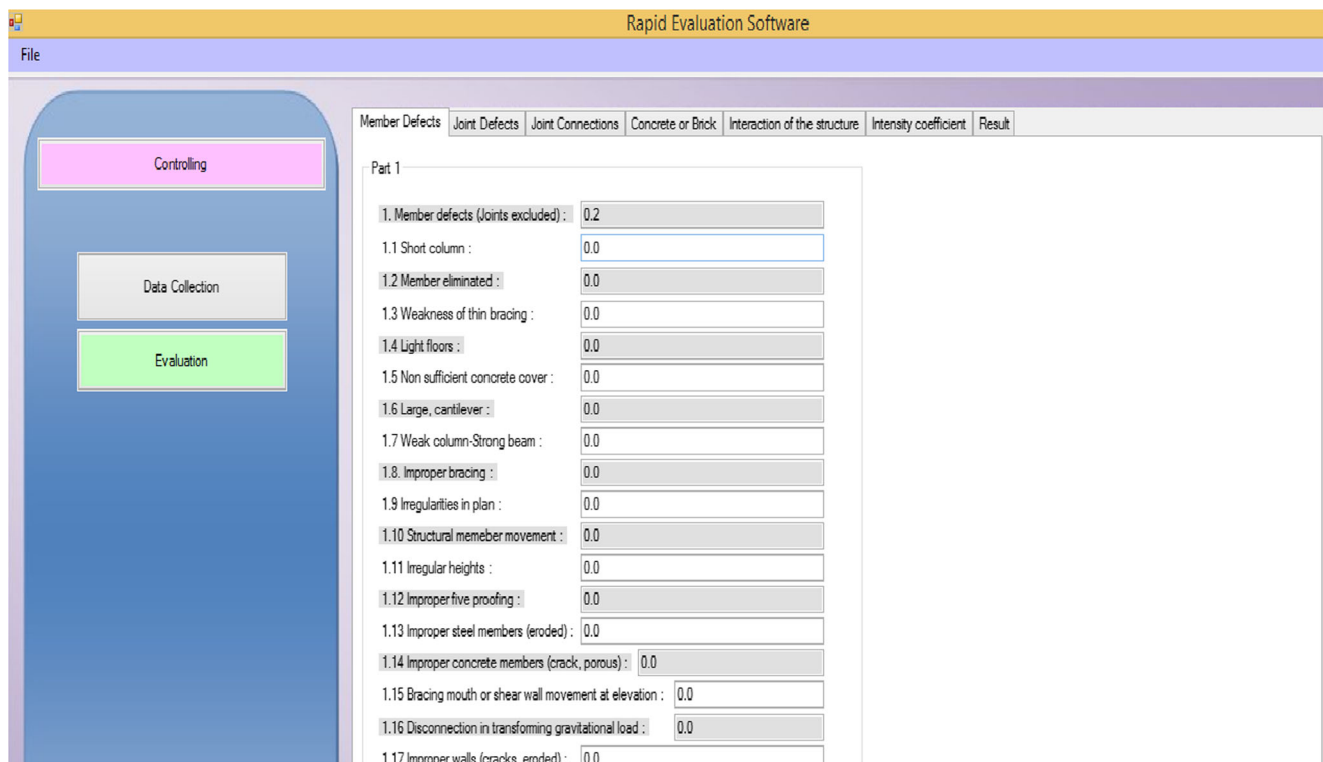


Fig. 2 Main interface of the rapid evaluation software

step, a software object-oriented method has been used, and the problems are analyzed. Alternatively, based on the Unified Modeling Language (UML) the relationships between input parameters and output parameters were acquired. MATLAB implemented this software, and further it accompanied by the algorithm for testing methods to remove any bug or unseen error in the developed software. It was carried out based on the pretest and the posttest specification method in testing level. The software was evaluated by applying some samples to the system's

input. The results have been analyzed in the step-by-step software tracking accompanied by the data testing performances. The data performance has been acquired from the collected dataset for each building material in the civil engineering laboratory and further introduced to the algorithm to produce Rapid Evaluation Software. In addition, to determine resistance of the building against future earthquakes, the digital schumize hammer, the share tester for masonry walls, and the cover meter have been used for hundred masonry houses.

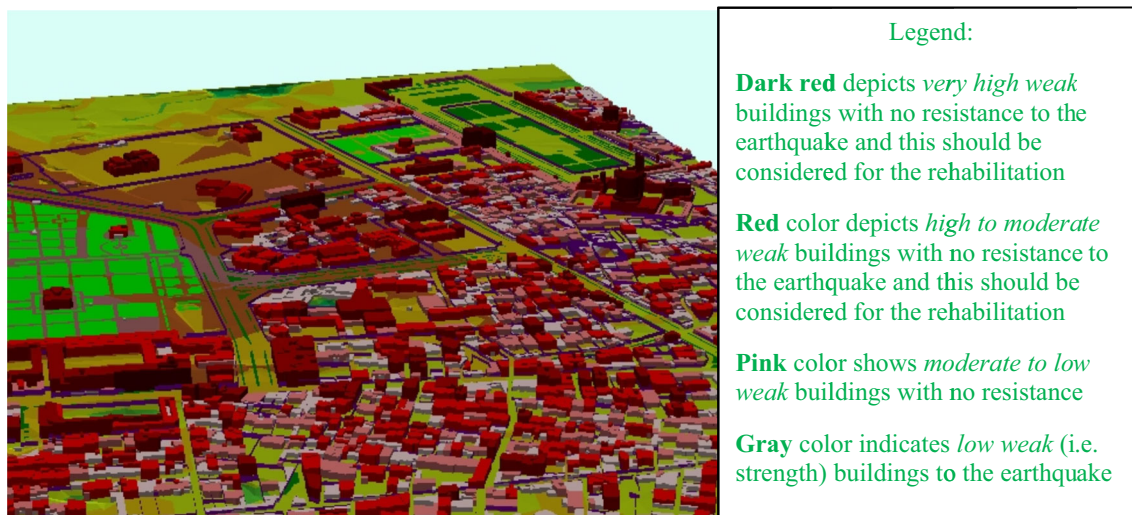


Fig. 3 Non-engineering building in Emam Square, Esfahan Iran

Table 2 Vulnerability scores on residential building

Score	Level of vulnerability
1–10	Demolishment
10–40	High vulnerability
40–70	Medium vulnerability
70–90	Low vulnerability
90–100	Invulnerability

GIS and vulnerability classification

As part of the above, the digital topography map consist x,y and z coordinates of Esfahan, Iran in scale 1:2000 was introduced into the GIS environment to determine the geographical location of the houses and to identify the masonry buildings accompanied by the ground observations. Land use map and the height of the houses were provided by the Esfahan city center in attribute and spatial data form. The 3D Analyst Tools of ArcGIS software allowed us to create a digital surface model (DSM) (Fig. 3). Alternatively, GIS has been used to create a 3D model for the objects visualization. The output of the developed software is discrete data (i.e., an attribute value) for each objective location and house. The data have been converted to the dbf or shp file format in the ArcGIS to represent a 3D visualization model. Every house has the x,y and z coordinates in GIS platform and

include discrete and continues data. Engineering specification of every house has been introduced to the Rapid Evaluation Software to evaluate the resistance of the buildings, and alternatively exported to the ArcGIS software for spatial distribution and 3D model visualization. Data collected of the buildings are added to ArcGIS environment to determine non-engineering and engineering buildings. In this method, we classify buildings from non-engineering to engineering buildings. It followed the MATLAB classification as we identified in the previous section; the buildings have been classified in high vulnerable, medium vulnerable, lowly vulnerable and invulnerable in ArcGIS software. The concept for the classification of the building is given on the basis of the properties of the material used in building against earthquakes for five Richters. The five Richters earthquakes also assumed on the basis of the statistic historical data that are recorded by Iranian Geophysics Organization (IGO). However, this software has a promising potential to link with ArcGIS as an extension or to export the results to ArcGIS software.

Results and discussion

Iran is situated in a seismic active region, and every year it has been seen that many parts of the country experience earthquakes and are triggered by the active faults, result in loss of

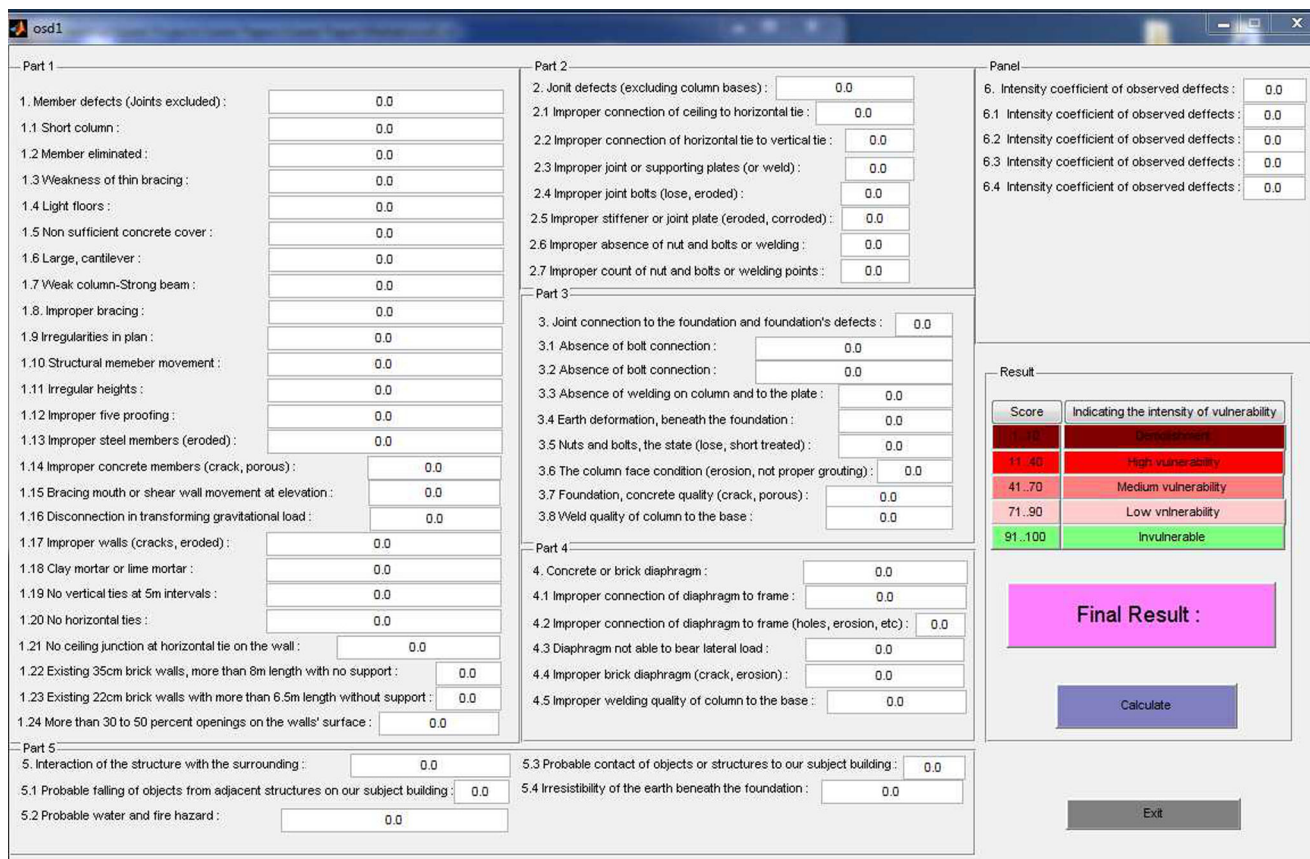


Fig. 4 Software and calculation of the parameters

lives and collapse buildings. The approach algorithm and the Rapid Evaluation Software have been developed for mitigation and loss reduction.

This paper represents the theoretical basis for the calculation of the damage index. It also describes the implementation and presents the use of GIS accompanying the MATLAB software to identify and to visualize the weak structures for rehabilitation. This software has its theoretical basis in the damage index model (DIM) with seismic data, structure, parcel, material type, foundation, ceiling, wall, floor, the interior and the exterior obtained from various sources and laboratory. According to the calculation by this software and a testing form in comparison to the manual analysis of the previous research work, it has been found that a good determination of the buildings vulnerability is achieved. Table 2 depicts the vulnerability scores on the residential buildings that is used for the building stability utilizing the Rapid Evaluation Software in this research.

By utilizing the geospatial techniques and integrated to the laboratory analysis accompanied by the techniques of software programming, engineering and non-engineering buildings have been discriminated for rehabilitation with the help of the Rapid Evaluation Software. Finally, a demo of the software in Fig. 4 illustrates the calculation of the parameters and how the software uses to assess the managers.

The Rapid Evaluation Software accompanied by the ArcGIS is a promising approach to computing, analyze, store, retrieve, model and map the building resistance for rehabilitation and disaster management. This research recommends that the DIM and this software interactively can be designed in the GIS to compute parameters and analyze data for a quality management purpose. It also indicates the usefulness of MATLAB in a friendly environment to develop software.

Conclusion

The study concludes the novelty of this research. By utilizing this new formula that is based on experimental works in the laboratory, this study presents a promising approach to the earthquakes mitigation. This study introduces a software in determining vulnerability of the buildings. It suggests that the proposed software accompany the ArcGIS is an excellent tool to analyze and to enhance the visualization in displaying the weak houses. The ground truth observation and hundred lab sampling tests have shown the output performance of this software program. This program can enrich the decision making for the future planning and to make a commercial version of the software use in the construction projects and industries.

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