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INDUSTRIAL APPLICATION

Computer-Aided Pre- and Post-Earthquake Assessment of Buildings Involving Database Compilation, GIS Visualization, and Mobile Data Transmission

A. G. Sextos*

Division of Structures, Department of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece

&

A. J. Kappos & K. C. Stylianidis

Lab. of Concrete and Masonry Structures, Department of Civil Engineering,
Aristotle University of Thessaloniki, 54124, Greece

Abstract: *The aim of this article is to present a computer-aided comprehensive strategy for the rapid visual inspection of buildings and the optimal prioritization of strengthening and remedial actions that are necessary prior to, and after, a major earthquake event, respectively. Based on the visual screening procedures used in the United States and past experience in seismic assessment of buildings in Greece and Turkey (the two countries with the highest seismic risk in Europe), a building inventory is first compiled; then a vulnerability ranking procedure that is specifically tailored to the prevailing construction practice in Southeast Europe is implemented into a multi-functional, georeferenced computer tool, that accommodates the management, evaluation, processing and archiving of the data stock gathered during the pre- and post-earthquake assessment process, and the visualization of its spatial distribution. The methodology proposed and the computer system developed is then applied to the city of Düzce, Turkey, a city strongly damaged during the devastating 1999 earthquake.*

*To whom correspondence should be addressed. E-mail: *asextos@civil.auth.gr.*

1 BACKGROUND AND OBJECTIVES OF THE STUDY

As the socio-economic cost of a possible earthquake may be significant, a major effort has been made worldwide, mainly during the last two decades, toward the development of organized large-scale action schemes for the enhancement of the safety and serviceability of the building stock, the upgrade of the seismic performance of the infrastructure, as well as for the mitigation of potential environmental impacts and any other direct or indirect consequence.

This effort, which is primarily made in countries exposed to high seismic risk (due to high seismic hazard and/or high exposure caused by dramatic increase in the size of the urban habitat), is related not only to the pre- and post-earthquake disaster preparation and management methods to be employed, but also to the subsequent technical, social, administrative, legal, and financial measures necessary for the implementation of the foreseen schemes. A major component of the above strategic planning concerns buildings, whose performance is expected to affect considerably the overall

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earthquake loss in urban areas. As such, the (pre- and post-earthquake) assessment of buildings has attracted major scientific interest worldwide and it is materialized through two main engineering procedures:

1. *Pre-earthquake Assessment* of buildings, which is aimed at evaluating the safety level of public and/or important buildings against the maximum considered seismic action, and the prioritization of strengthening activities, to assure safety against collapse of the general building stock and serviceability of the most critical buildings after a major earthquake event. It is noted that, in general, pre-earthquake rapid visual inspection (RVI) is normally carried out starting from important and/or public buildings, and aims at assessing their seismic capacity, as well as setting the priorities for the various strengthening/upgrading schemes that should be implemented. The ranking of buildings is performed on the basis of qualitative, and sometimes quantitative, criteria, which involve the period of construction (or seismic code used), the structural system, the level of seismic hazard, and a number of structural characteristics. The evaluation of buildings on the basis of such criteria typically culminates into a "score"; poor seismic performance of the building is associated with low scores, indicating a high priority for strengthening.

The framework for the pre-earthquake assessment has been set by recent United States standards and guidelines, such as ATC-13 (1985) and ATC-38 (2003), which primarily refer to California building types, the FEMA 154-ATC 21 (2002) and the FEMA 310 (1998) documents for rapid visual screening, and also by the UNDP/UNIDO (1985) document targeting the Balkan countries. Similar methods have been used in Japan (Japan Building Disaster Prevention Association, 1990) and Greece (Ministry of Public Works, 1997, 2000), although large scale application after major earthquake events of the country-dependent provisions has been made in the United States (ATC-38 project in California, 2003), in Greece (Penelis & Kappos, 1997; Kappos, 1997; Stylianidis et al., 2003a, b; Anagnostopoulos & Moretti, 2006a, b) and in Turkey (Spence et al., 2002; Ansal, 2003) among other countries.

2. *Post-earthquake Inspection* of buildings, which allows the local and central authorities to obtain a quick but fairly detailed statistical overview of the damage extent (in terms of spatial distribution, degree, and total number of buildings associated with a particular damage level), thus assisting decision-making regarding the required remedial and recovery measures. Such experience with post-earthquake inspection of buildings and gathering of damage data has been also gained in the United States, especially after the Loma Prieta and Northridge earthquakes, as well as in Southeast Europe from the recovery strategies adopted following a number of recent major earthquakes. In certain cases, the post-earthquake assessment is nowadays assisted by the processing of satellite images (Eguchi et al., 2000; Matsuoka & Yamazaki, 2004; Saito et al., 2005), however, so far only a macroscoping assessment of damage is feasible.

Notwithstanding the development of various pre- and post-earthquake assessment methodologies, a number of issues are still open regarding their application, hence posing the challenge to propose more comprehensive solutions toward the data-based, quantitative, and computer-aided management of seismic risk.

The most significant problem is the lack of a unified framework for conducting joint pre- and post-earthquake assessment studies and making decisions based on the complete seismic history of buildings, a quantified estimate of their current vulnerability and the data regarding the damage observed after a potential future earthquake, inclusive of the strengthening/rehabilitation measures and the associated cost. Unfortunately, the current practice is to perform post-earthquake assessment independently from the screening process prior to the earthquake, using different and incompatible methodologies that do not allow any data flow between the two procedures. Moreover, especially in terms of pre-earthquake assessment, the more detailed procedures that are used in the United Status are not directly applicable overseas, since the building types, construction processes, and materials used often differ substantially.

Another important issue is that, in most cases, the visual inspection results are either not organized electronically (i.e., large scale inspections are performed on-site by local personnel using hard-copies of standardized forms) or their visualization in GIS is not a standard part of the procedure followed, while the process to review the data and ensure their reliability is rather long. As a result, huge effort and time may be required until the authorities obtain a reliable and clear overview of the structural vulnerability (prior to an earthquake) or of the extent of damage (after an earthquake), a fact that is of paramount importance, especially during an earthquake crisis.

Along these lines, a knowledge-based expert system (KBES) is developed which utilizes state-of-the-art knowledge in earthquake engineering and information technologies (IT) to develop a tool that will serve the following five main goals:

1. Develop a comprehensive framework for the *joint* management of the data gathered during the

pre- and post-earthquake assessment of buildings in any given city, and of a GIS-oriented database system that can assist the local authorities to make decisions to mitigate seismic risk, based on complete information regarding the building history at a city scale (regarding earthquake-induced damage, strengthening, and rehabilitation works) and a set of quantitative assessments for both the preparedness and recovery period.

2. Improve the existing methodologies for the pre- and post-earthquake assessment by proposing additional structural types and scoring matrices for the case of moderate to large size Southeast European cities based on expert knowledge and the prevailing construction and assessment practices in Greece and Turkey.
3. Establish the framework to combine the building vulnerability scoring values obtained (prior to the earthquake) with the, also quantitative, actual damage level observed (after the earthquake), to update the weighting factors proposed by the experts for the various structural parameters that affect the vulnerability evaluation.
4. Enhance the reliability of the collected data by introducing internal logical error trapping checks, programmed through the database, to spot out potential conceptual controversies in the data as they are input into the system and thus automatically increase their reliability.
5. Eliminate the time required to digitize the data gathered on-site with the aid of mobile clients (pocket PCs or new generation cellphones) that permit electronic filling-out of the forms, mobile synchronization with the main system database (planned to be directly accessible by the local authorities), sorting of the city buildings according to their relative vulnerability (prior to the earthquake) or damage score (after the earthquake), immediate filtering of potential errors (in the main database), and final visualization in GIS of the results *almost in real tim*e.

It is noted that this combination of a computer-aided building assessment procedure and a GIS approach, as well as the joint management of pre- and post-earthquake assessment, is deemed a valuable contribution; it is noted that even the latest version of FEMA154 (2002) considers it as “beyond its scope.” Moreover, the particular system has already been implemented in the city of Düzce in Turkey (a city strongly damaged during the devastating 1999 earthquake as described in Section 3), although several of its components are currently being implemented for the pre-earthquake assessment of buildings in Greece as well. The main aspects of the particular comprehensive methodology and the architecture of the system developed are presented in the following.

2 OVERVIEW OF THE INTERACTIVE GIS/DATABASE DECISION-MAKING FRAMEWORK

2.1 Database architecture and work flow

The GIS-database developed has to be installed at an operating server located in an administration building or, in case of an earthquake, on a portable computer to control the data flow during a field campaign. Depending on the expertise of the local engineers responsible for assessing the buildings and the available hardware, either the quick inspection forms are filled out in hardcopy form or a PDA/cell phone is used for direct data input. The database is built using Microsoft Access and is internally programmed using the VISUAL BASIC for APPLICATIONS (VBA) programming language and STRUCTURED QUERY LANGUAGE (SQL) for data filtering and building scoring. The former is also used for structuring a framework of logical checks aiming to eliminate the possibility of inconsistent data input. The data are recorded into three relational tables (for pre- and post-earthquake assessment, and building a common profile) consisting of a large number (102 in the version presented herein) of data fields.

As the most important information gathered for the assessed buildings is related to their structural integrity, it is apparent that the main interface of the electronic management computer system developed closely simulates the (pre- and post-earthquake) quick inspection forms adopted (and specifically adapted) for the area under study. Through this interface, or ideally by filling out data on-site using a PDA/cell phone, the building data are stored in the database and the building scores are automatically computed according to the predefined multi-parametric scoring schemes provided by experts (as is described in detail in the following Section 2.2). Finally, all buildings are ranked and classified in terms of their structural vulnerability.

The electronic database automatically provides all the statistics of both the gathered and computed data, although it communicates directly with a GIS environment for visualization of the assessment results in space using MapInfo (2001) software and specific workspaces. The use of advanced GIS mapping tools for building assessment and seismic hazard data has also been presented in Turkey in the framework of the Istanbul Earthquake Master Plan (Ansal, 2003) and for the city’s Early Warning System (Erdik et al, 2003), as well as in other countries (e.g., O'Rourke et al., 2001) among other applications. However, the database presented herein is considered to be an extension of the aforementioned pioneering developments, since it integrates the pre- and post-earthquake assessment data, their visualization in space through GIS, and the expert system for rating/scoring of buildings, all into a comprehensive computer framework. Another significant advantage of the particular system is that the GIS built-in database and the external database (separately developed to be fully programmable) share a common table, hence no import and export procedures are needed and the user can retrieve or import data using any of the two different interfaces. The overall system architecture is shown in Figure 1.

2.2 Overview of a comprehensive procedure for the pre- and post-earthquake assessment of buildings and ensuing algorithm

An important part of the overall system developed is the building evaluation process, related to the (pre- and post-) earthquake assessment methodologies to be used. As mentioned previously, the idea was to adapt widely used existing methodologies to create a model process applicable to cities of moderate to large size, mainly in Southeast Europe that are exposed to high seismic risk.

Regarding the pre-earthquake assessment of buildings, a simplified standard (hardcopy) form was initially adopted for data collection, mainly based on the inspection forms proposed in the Istanbul Master-plan study (Ansal et al., 1999). This hardcopy pre-earthquake inspection form (sheet) consists of five sections distinguished according to the nature of the information they refer to. More specifically: Section A contains the building identification data (i.e., ID, city section, address, ownership, authorities for inspection, number of residents etc); Section B the building's technical characteristics (i.e., number of storeys and basements, plan area, total built area, year of construction, building importance, previous rehabilitation or repair inclusive of time and reason, engineers carrying out the inspection, etc); Section C the relevant seismological and geotechnical data (i.e., seismic hazard zone and soil classification, as seen in Table 2); Section D the data related to the structural system (Table 1); and Section E the structural characteristics of the building that affect its seismic performance (Table 3). It is noted that both the structural types and the scoring matrices summarized in Tables 1–3 that present the relative importance of the various structural, geotechnical, and seismotectonic parameters with respect to seismic risk, are proposed by the authors and the board of experts (acknowledged at the end of the *article*) for the case of Southeast European cities. These values are based on experience from the statistical processing of the damage observed in a number of past earthquakes (in Greece and Turkey), numerical analyses performed by the authors, monitoring data, and experimental results. As an example, Tables 1–3 correspond to the particular code (defining the seismic zonation and soil categorization) valid for the country where the large scale application was foreseen (i.e., Turkey and more specifically the city of Düzce). Clearly, though, as shown in Section 3.2, the overall methodology is of broader use.

Based on the above, the adapted pre-earthquake assessment-rating scheme (basic scores for each typology, and score modifiers accounting for particular features affecting the seismic vulnerability) finally depends on a number of parameters as described in the following. The final score (S_{fin}) is derived according to the following simple expression:

$$S_{fin} = S_{ABSC} + S_{ZSE} + S_{sc} + S_{VUL} \quad (1)$$

where S_{ABSC} is the basic score and is a function of the structural type of each building (Table 1), S_{ZSE} depends on seismological parameters (i.e., the seismic zone factor, as displayed in Table 2), S_{sc} depends on geotechnical parameters (i.e., the soil factor as displayed in Table 2) and S_{VUL} depends on structural vulnerability parameters (i.e., seismic code used, modification of use, damage by previous earthquakes, inadequate maintenance, pounding possibility, presence of soft storey or short columns, irregularly arranged infills, significant overall height, irregularities in plan and height and possibility of torsion, as summarized in Table 3). The overall procedure, illustrated in detail in Figure 2, is followed for all buildings assessed, and a final score is given to each one to prioritize (through appropriate sorting) the buildings with the lowest score (i.e., the most vulnerable ones).

Despite the expertise background required, the above calculation process related to the specific scoring matrices of Tables 1 to 3, is intentionally kept simple enough to be applied quickly on-site by the local personnel.

The post-earthquake quick inspection procedure, on the other hand, that is presented herein, is based on the inspection form issued by the Turkish Ministry of Public Works and Settlement-–General Directorate of Disaster Affairs (1999). It consists of six quantitative criteria to decide on structural safety (in terms of settlement, inclination, pounding with adjacent buildings, percentage of moderate or severe damage in the columns of the most heavily damaged storey) and six qualitative criteria to assess the safety of non-structural elements. Each procedure runs separately for two main categories of damage type (structural and non-structural) and ranks the buildings on the scale of "Inspected" (or "safe" or "checked"), "Limited Entry," and "Unsafe" (Figure 2). The system developed computes the quantitative factors, examines the various criteria, and provides a final

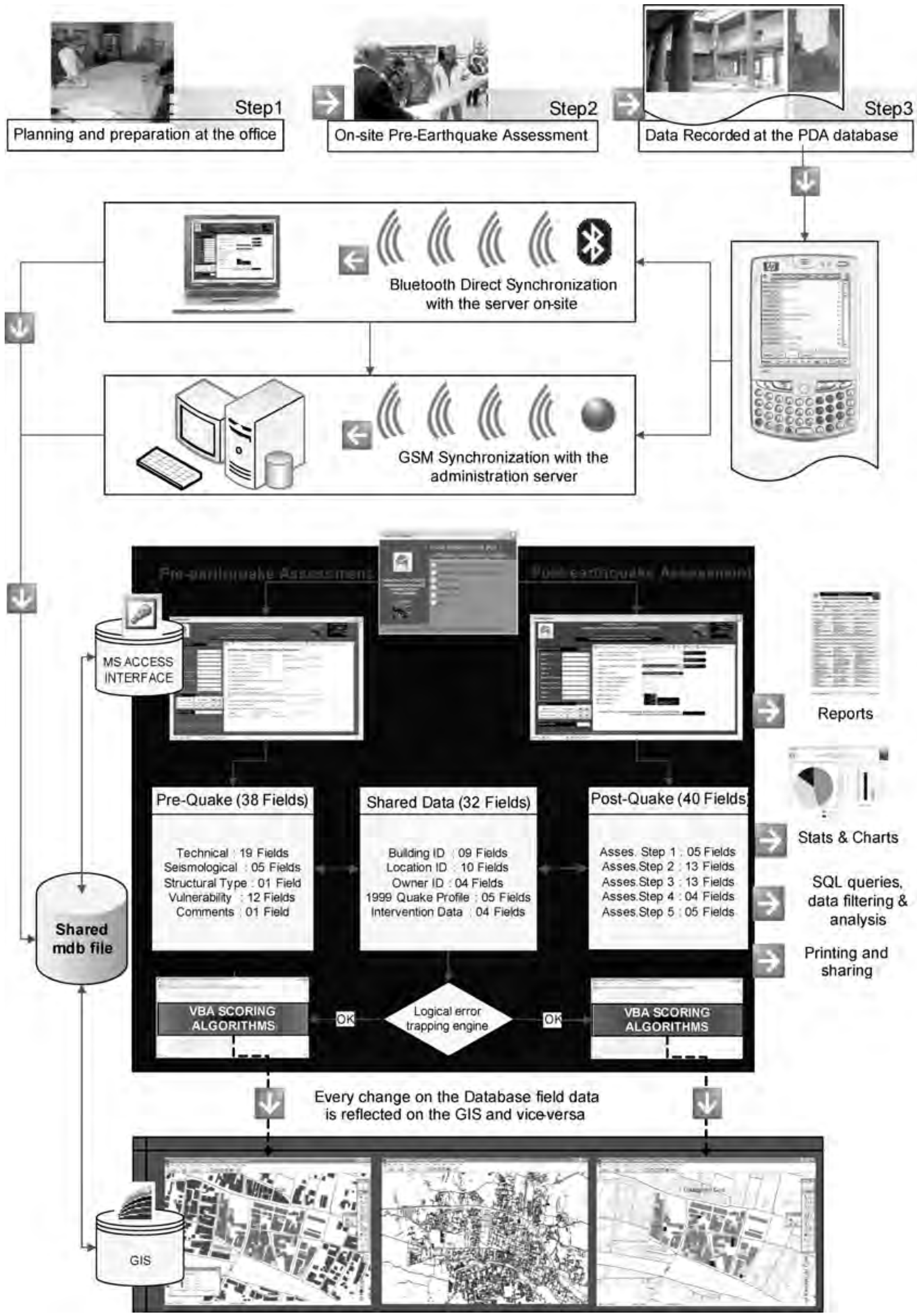


Fig. 1. GIS-Database structure for data management as a part of the pre- and post-earthquake assessment process.

Table 1
Proposed building typology as applied to the city of Düzce, Turkey

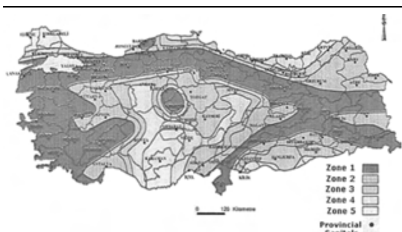
Material	*Structural type*	*Structure's description*	*Seismic code*
REINFORCED CONCRETE	**RC1**	Reinforced concrete building (Beam-Column framed system)	No seismic code (pre 1975 in Turkey)
	RC2	Reinforced concrete building (columns and some concrete shear walls)	No seismic code (pre 1975 in Turkey)
	RC3	Reinforced concrete dual building (columns and adequate concrete shear walls having an area ≥0.5% the total area of floors)	No seismic code (pre 1975 in Turkey)
	RC4	Reinforced concrete building (Beam-Column framed system)	Previous seismic code (post 1975–pre 1998 in Turkey)
	RC5	Reinforced concrete dual building (Beam-Column framed system)	Previous seismic code (post 1975–pre 1998 in Turkey)
	RC6	Reinforced concrete building (Beam-Column framed system)	Modern seismic code (post 1998 in Turkey)
	RC7a	Reinforced concrete dual building (frames and concrete shear walls)	Modern seismic code (post 1998 in Turkey)
	RC7b	Reinforced concrete box/tube or cell system (tunnel formwork system)	Modern seismic code (post 1998 in Turkey)
PRECAST	**PR1**	Prefabricated reinforced concrete frame building	
	PR2	Prefabricated reinforced concrete shear wall building	
MASONRY	**URM1**	Unreinforced masonry buildings, mainly in hewn stone, without diaphragms at floor levels or belts	
	URM2	Unreinforced masonry buildings with diaphragms at floor levels	
	CM	Unreinforced masonry buildings with R/C diaphragms at floor levels and R/C belts	
	RM	Reinforced masonry buildings with R/C diaphragm at floor levels and R/C belts	
	SM	Unreinforced masonry buildings strengthened with belts, diaphragms and one-sided or two sided R/C jackets appropriately connected to the masonry and resting on adequate foundations	
	Notes: 1. Belts are horizontal and vertical R/C elements strongly connected to the walls and rigid at their corners, confirming to the current trends and code provisions or specifications for confined masonry 2. Diaphragms are continuous R/C slabs, strongly connected to the walls, as well as to the horizontal and vertical belt system, without significant openings		
STEEL	**ST1**	Single storey industrial buildings	a) No seismic code (pre 1975 in Turkey) b) Previous seismic code (post 1975–pre 1998 in Turkey) c) Modern seismic code (post 1998 in Turkey) d) DIN or other foreign codes
	ST2	Multi storey buildings consisting of 3D steel frames with or without vertically-oriented inclined steel braces	a) No seismic code (pre 1975 in Turkey) b) Previous seismic code (post 1975-pre 1998 in Turkey) c) Modern seismic code (post 1998 in Turkey) d) DIN or other foreign codes

Note: Steel buildings with reinforced concrete shear walls are assumed to behave similarly to corresponding reinforced concrete wall types.

Table 2
Proposed rating scheme (basic scores) for the pre-earthquake assessment of buildings as applied in the city of Düzce, Turkey

			Seismic zone factor according to Turkish seismic zonation				*Soil factors according to Turkish code categorization*			
Material	*Structural type*	*Initial score*	*I*	*II*	*III*	*IV*	*Z1*	*Z2*	*Z3*	*Z4*
REINFORCED CONCRETE	RC1	+3.0	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	RC2	+3.5	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	RC3	+4.0	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	RC4	+4.0	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	RC5	+4.0	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	RC6	+5.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	RC7a	+5.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	RC7b	+5.5	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
PRECAST	PR1	+2.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	PR2	+3.5	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
MASONRY	URM1	+2.5	−1.5	−1.0	−0.5	0	0	−0.3	−0.6	−0.8
	URM2	+3.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	CM	+3.5	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	RM	+4.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	SM	+3.5	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
STEEL	ST1	+7.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8
	ST2	+4.0	−1.0	−0.5	−0.5	0	0	−0.3	−0.6	−0.8

Notes



Seismic Zonation according to Turkish Code
Earthquake zonation map of Turkey in the 1998 seismic code (Zone I, indicated with the darkest color, corresponds to the highest seismic exposure, while Zone IV corresponds to the lowest seismic exposure).

Local site classes according to Turkish Code
Z1: Group A soils and Group B soils with $h_1<15$m. **Z2:** Group B with $h_1>15$m and Group C soils with $h_1<15$m. **Z3:** Group C with 15m<h1<50m and Group D with $h_1<10$m. **Z4:** Group C with h1>50m and Group D soils with h1>10m.

Group A: Massive volcanic rocks, metamorphic rocks, stiff cemented sedimentary rocks, very dense sand and hard clay. **Group B:** Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity, dense sand and very stiff clay. **Group C:** Highly weathered soft metamorphic rocks and cemented discontinuity, medium dense sand and silty clay. **Group D:** Soft, deep alluvial layers with high water table, loose sand and silty clay

statement for each building in the database based on the most unfavorable criterion. For instance, according to this procedure, if the structure is characterized as of "limited entry" according to 11 criteria, but ranked as "unsafe" on the basis of a single criterion (either related to structural or non-structural safety), then it is considered as "unsafe" as a whole. Apparently, in case that damage is clearly very heavy, or substantial inclination of a story is observed, or the structure is offset from its foundation, the building is characterized as unsafe and the detailed assessment procedure is omitted.

This approach is in fact very similar to that of the U.S. guidelines, in particular ATC-20 (2005), which also prescribes rapid and detailed evaluation procedures for ranking the buildings as "Inspected" (green placard), "Restricted use" (yellow placard) or "Unsafe"

Table 3
Proposed rating scheme (score modifiers) for the pre-earthquake assessment of buildings as applied to the city of Düzce, Turkey

	Structural vulnerability scoring parameters											
	No seismic code applied	*Modification of use*	*Damaged by a previous quake*	*Inadequate maintenance*	*Pounding possibility*	*Soft storey*	*Irregular infills*	*High rise building*	*Irregularity in height*	*Irregularity in plan*	*Possibility of torsion*	*Short columns*
RC1	−0.5	−0.5	−1.0	−0.5	−0.5	−1.5	−0.5	−1.0	−1.0	−1.0	−0.5	−0.5
RC2	−0.5	−0.5	−1.0	−0.5	−0.5	−1.5	−0.5	−1.0	−1.0	−1.0	−0.5	−0.5
RC3	0	−0.5	−1.0	−0.5	−0.5	−1.0	0	−1.0	−1.0	−1.0	−0.5	−0.5
RC4	0	−0.5	−0.5	−0.5	−0.5	−1.5	−0.5	−0.5	−0.5	−0.5	−0.5	−0.5
RC5	0	−0.5	−0.5	−0.5	−0.5	−1.5	−0.5	−0.5	−0.5	−0.5	−0.5	−0.5
RC6	0	−0.5	−0.5	−0.5	−0.5	−1.5	0	−0.5	−0.5	−0.5	−0.5	−0.5
RC7a	0	−0.5	−0.5	−0.5	0	−1.5	0	−0.5	−0.5	−0.5	−0.5	−0.5
RC7b	0	−0.5	−0.5	−0.5	0	−1.5	0	−0.5	−0.5	−0.5	−0.5	−0.5
PR1	0	−0.5	−1.0	−0.5	−0.5	−1.5	0	−0.5	−1.0	−1.0	−1.0	−0.5
PR2	0	−0.5	−1.0	−0.5	−0.5	0	0	−0.5	−1.0	−1.0	−1.0	−0.5
URM1	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	−0.5	−0.5	−1.0	−1.0	−0.5
URM2	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	−0.5	−0.5	−1.0	−1.0	−0.5
CM	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	−0.5	−0.5	−1.0	−1.0	−0.5
RM	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	−1.0	−0.5	−1.0	−1.0	−0.5
SM	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	−1.0	−0.5	−1.0	−1.0	−0.5
ST1	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	0	−0.5	−0.5	−1.0	−0.5
ST2	−0.5	−0.5	−0.5	−0.5	−0.5	0	0	0	−0.5	−0.5	−1.0	−0.5

Note: Vulnerability criteria according to the Turkish Seismic Code (Ministry of Public Works, 1997 & 2007) provisions.

(red placard). It is also more complex and quantitative compared to the one used in Greece after destructive earthquakes. The latter is issued by the Earthquake Planning and Protection Organization (Ministry of Public Works, 1997), provides a qualitative 1st level overview of the extent of damage, and is followed by a more detailed (2nd level) assessment, to finally decide on the structural integrity of buildings.

The methodology adopted and adapted therefore for the joint pre- and post-earthquake assessment of buildings in Southeast European cities, is primarily quantitative and is computationally implemented into the database in such a way that the building inventory data collected on-site are enriched with the results of the computer-aided assessment and scoring process. The rationale behind this process is presented in the following.

2.3 Background of the knowledge-based expert system

Having described the system architecture and the pre- and post earthquake assessment process, it is evident that, the system heavily relies on the structural vulnerability matrices (proposed by experts and presented in Tables 1–3) to be used for the pre-earthquake evaluation process as well as on the criteria (presented in Figure 2) set for the post-earthquake assessment. In this respect, the overall system developed (illustrated in Figure 1) can be considered as a (deterministic) knowledge-based expert system (KBES) for the visual risk management on a city-scale and a decision-making system for the local authorities. In particular, the main system *input* is the data gathered on site, the main computational process is the quantification of the structural vulnerability prior to an earthquake or of the structural integrity after an earthquake (based on expert knowledge), although the system's *output* is the prioritization of the most vulnerable buildings prior to, or following an earthquake event, localized in space and visualized in GIS. The structure of the GIS-Database system as a means to mobilize expert knowledge is illustrated in Figure 3, where it can be seen that it consists of a number of different components, typical of an Expert System in Structural Engineering (Adeli, 1988).

An additional error-trapping module is also developed as part of the Expert System Shell, that automatically validates the consistency of the data entered by the engineer and presents warning messages if the internal logic is violated. It is noted that the particular error-trapping module is also a set of simple rules imposed by experts that aim at filtering a number of possible logical errors that the engineers may have done accidentally or due to limited knowledge when filling-out the (hardcopy or

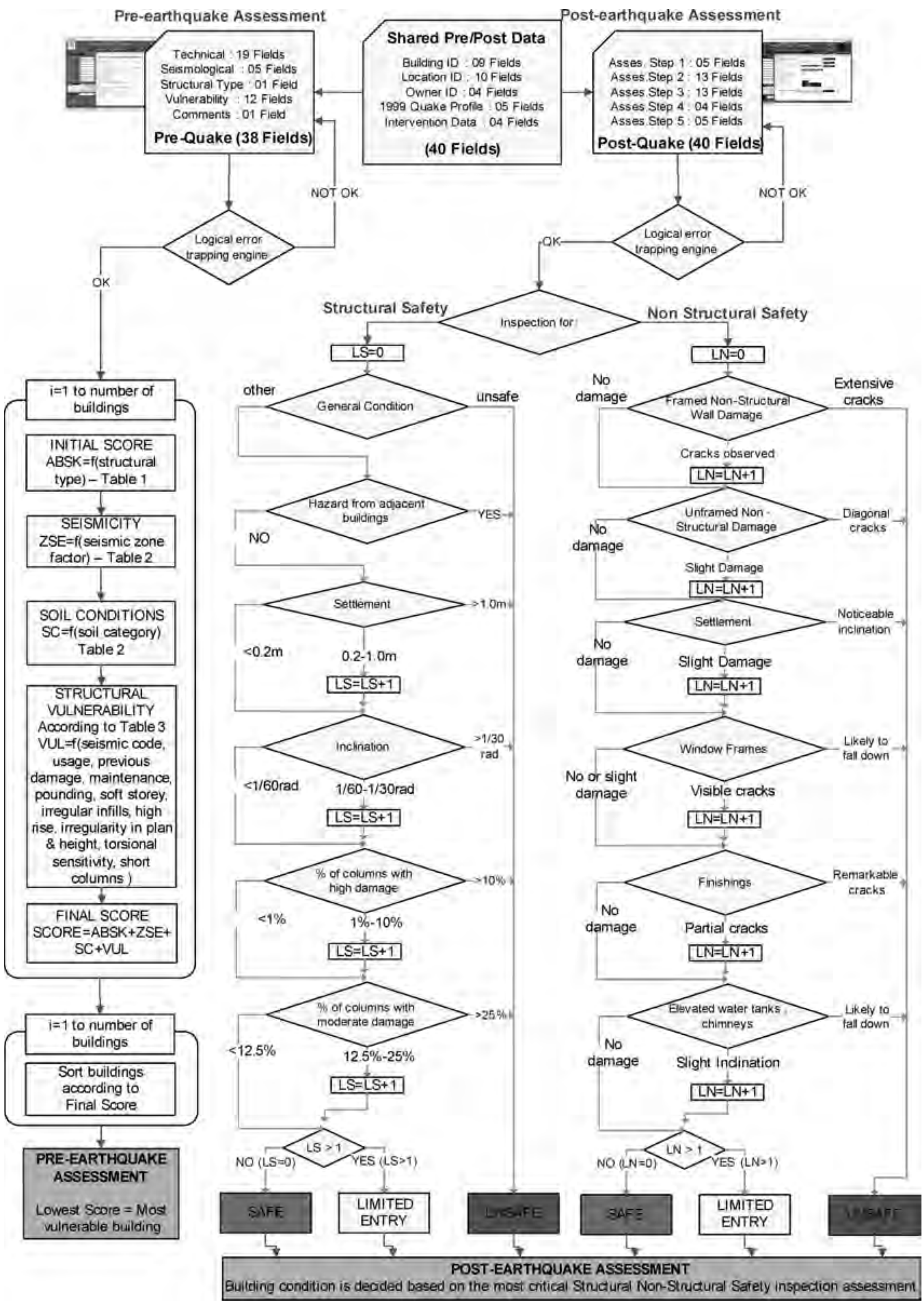


Fig. 2. Adopted and modeled procedure for the pre- and post-earthquake assessment of buildings.

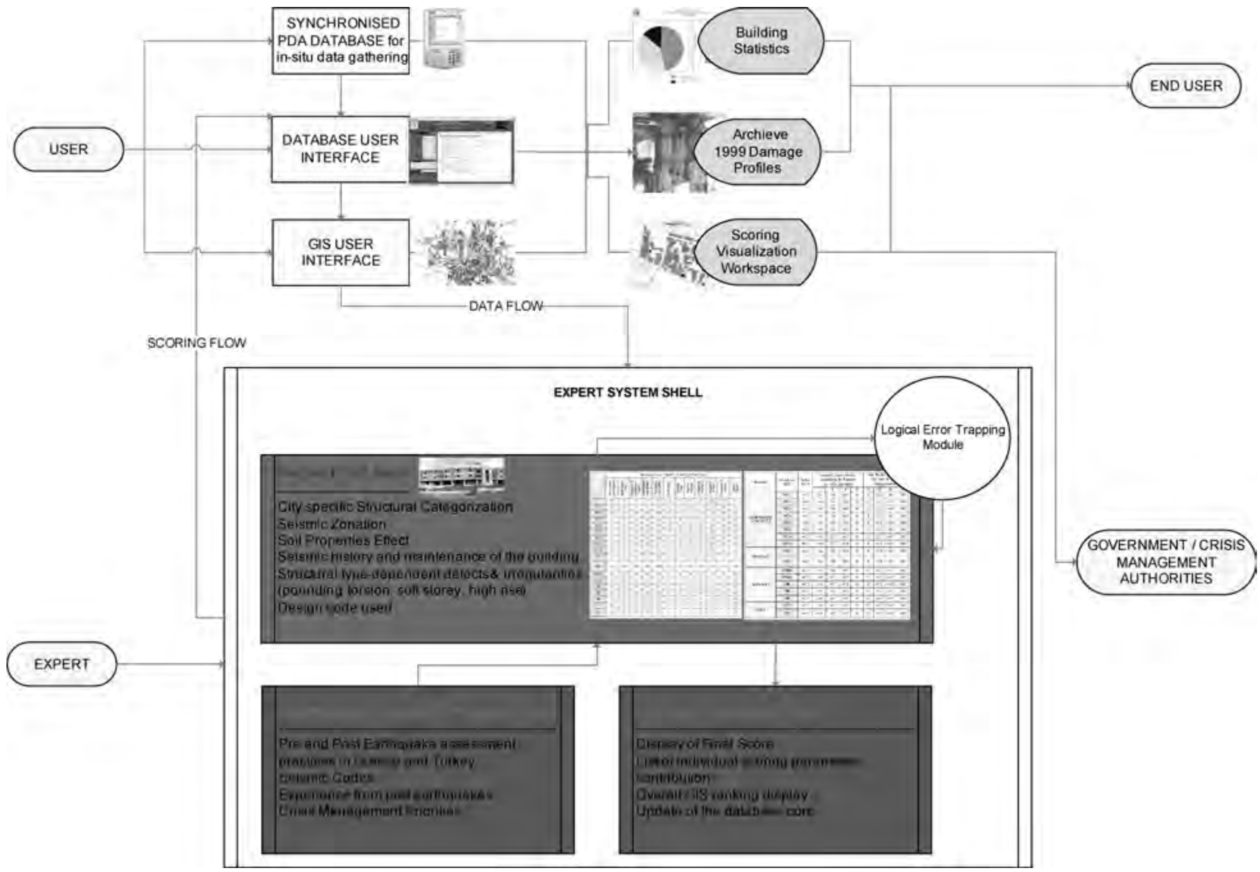


Fig. 3. Knowledge-based expert system structure.

electronic) forms on-site thus leading to significant errors during the scoring process. Examples of such logical inconsistencies of the latter are: masonry buildings (indicated to be) suffering from short reinforced concrete column failure, masonry buildings recorded as high-rise or torsionally sensitive, reinforced concrete buildings constructed before the enforcement of the seismic code but characterized as earthquake-resistant, cases where the building total area is given lower than the product of the number of storeys and the projected area covered, among many others. The particular set of checks, combined with warnings when numerical values are either violated (i.e., the year of construction is mistyped, and so on) or not completed properly, provide a set of tools that improve the quality of the data that are imported into the system before any scoring, calculation, or statistics processing takes place.

Another interesting feature of the system developed is that the correlation of the data gathered regarding damage from previous earthquakes, intervention and rehabilitation costs, current structural vulnerability, and future seismic performance of the city buildings can offer rare information that can significantly improve the expert system in the future based on actual data. In other words, the scoring values presented in Tables 1–3 are expected to be updated in case the building stock predicted as most vulnerable (prior to an earthquake) and the most heavily damaged buildings (as assessed after the earthquake) are found to be partially or fully uncorrelated.

It is also noted herein that the fuzziness of the system (often dealt with fuzzy logic processes) is not accounted for, since the process as described above is currently purely deterministic. However, future extension is to some extent potentially feasible, since currently, an uncertainty factor is indeed required by the user when completing the field entitled "declare the fields where the data imported are not completely definite." As a result, although not quantified at this stage, information is indeed provided regarding the confidence level that is related to each data field imported for each specific building.

2.4 Direct synchronization with personal digital assistants and cell phones

Another feature of the Database/GIS system developed is that it can be fully synchronized with a pocket digital assistant (PDA) or a cell phone, either using a bluetooth protocol or remotely through a GSM/GPRS connection. This effort is inspired by the track-beating ATC-20i (2003) approach which incorporates a PDA as a means to eliminate the time spent in filling-in and processing the post-earthquake inspection forms (only). However, the ATC-20 process does not prescribe any simultaneous GIS visualization nor does it integrate the data related to the pre- and post-earthquake assessment. In the system presented herein, not only can the data be made available on the field, but it also can be gathered, modified, or improved on site. Currently (early 2007), as the phone and the PDA devices have been integrated into a unique cell phone, the data transmission is significantly improved (a mobile phone operating Windows Mobile 6.0 has been used successfully and much more easily). As a result, the wireless connection of the GIS-based database with a remote hand-held device in the field is not only considered feasible, but a very promising solution toward speeding up the data gathering process which adds significant value and potential to the particular system developed. A successful pilot application of the use of mobile clients on-site is described in the following section.

3 SPECIFIC ADAPTATIONS AND REAL-CASE APPLICATIONS

3.1 City-scale application in Düzce, Turkey

As an application, the GIS-–database system developed was applied to a specific city in Turkey (Düzce), that experienced a devastating earthquake on November 12, 1999 wherein heavy damage to more than 800 buildings occurred (Ansal et al., 1999; Durukal, 2002; Youd et al, 2000). For the particular city, the aforementioned building typologies and the associated scores and score modifiers based on the seismic zonation and soil categorization prescribed in the Turkish Seismic code were used. The key adaptations to apply the system in the city of Düzce are related to:

(1) the exact transfer of the *GIS topology* that was already available by the Municipality of Düzce into the system, so that each one of the 17,360 buildings in the city was georeferenced in GIS, connected to the external database, and characterized by the 102 data fields described in Section 2.1. It is also noted that due provisions were taken, so that both the buildings that had collapsed or been demolished and the new buildings at the new quarters of the city (built after the 1999 earthquake) can be easily imported in the future.
(2) the use of software and hardware already available at the municipality level, a fact that was further strengthened by the systematic training of the Düzce municipality team on the use of the new system developed.
(3) the implementation (on demand) of additional data fields related to the data gathered regarding damage from the 1999 earthquake and the personnel involved in the subsequent interventions. It is noted that the particular information, combined with the cost of the rehabilitation works may also contribute toward a more realistic estimate of earthquake insurance rates (Yucemen, 2005) for reinforced concrete buildings in Turkey as a whole.

Most importantly, following the development of the system, the municipality personnel were trained both in the concept of structural assessment as well as in the use of the GIS-database system developed. The latter was installed at the Municipal Technical Head Office for a trial use of approximately 1 year before official use. Moreover, specific workshops were organized by the Laboratory of Reinforced Concrete and Masonry Structures of the Aristotle University, to analyze the particular assessment methodology and apply on-site both the methodology and the tools developed for a number of public buildings, including a hospital under construction (in 2004) and the Polytechnic College of the city of Düzce. The pilot data acquisition using a mobile client was also performed on site together with the local engineers. It is notable that at the time that the first field demonstration took place (i.e., Spring 2004) higher bandwidth 3G networks were not operating in the area of application, hence a connection was established using a remote pocket PC (with Microsoft Windows Mobile 2003 operating system) and the modem of a separate cell phone activated on a bluetooth protocol and connected to the available service provided. Recently (i.e., 2006) the connection of the centrally located system with a cell phone was also performed successfully.

The result of this training allowed the local authorities to subsequently apply the aforementioned procedure throughout the city, *without the assistance of the developers*, resulting in the creation of detailed structural records for more than 2,400 buildings so far (early 2007). Moreover, thorough on-site inspections have been performed and are also currently in progress; approximately 200 buildings have been inspected by the trained

Table 4
Indicative individual building results of the pre-earthquake assessment for the city of Düzce, Turkey

	Building 1	*Building 2*	*Building 3*
Number of storeys	3	3	4
Structural type	RC2	RC1	RC7
Seismic Zone	I	I	I
Local site classes	Z3	Z3	Z4
No seismic code applied	x		
Modification of use			
Damaged by a previous earthquake	x	x	
Inadequate maintenance	x	x	
Pounding possibility	x	x	x
Soft Storey	x	x	x
Irregular infills			x
Irregularity in height	x	x	
Irregularity in plan			x
Possibility of torsion	x		x
Short columns			
TOTAL BUILDING SCORE	−4.1	−3.6	+1.2

local personnel and the electronic forms completed on-site have been automatically processed by the system developed, thus filtering potential inconsistencies, computing the corresponding building scores, and assessing the relative vulnerability of the examined buildings. An indicative example summarizing the exact building breakdown of the scoring parameters for three characteristic individual buildings (two of them exhibiting some of the lowest scores), is summarized in Table 4.

Snapshots from the computed ranking results as they are visualized in the corresponding GIS, are presented in Figure 4 (top) while the correlation between the various structural types and the corresponding average building score computed, is also depicted in the same Figure (bottom). It is observed that masonry buildings (i.e., structural types URM1, URM2, and SM) obtained the lowest average scores. It is also interesting to notice that structures constructed after 1975 (i.e., RC6, RC7) or designed with adequate shear walls (i.e., RC7) do indeed achieve higher ranking though not necessarily the highest one; this is attributed to the fact that, as the pre-earthquake assessment process normally initiates from the inspection of older buildings (since they are expected to be more vulnerable), the modern buildings examined in such high priority are often—on purpose— disproportionally problematic, compared with the overall building stock of the newer structures. It is clear however, that the actual implementation of the methodology and software developed for the strengthening strategy in the city of Düzce and the identification of the most vulnerable buildings, is a valuable tool for the local authorities, which combined with the post-earthquake assessment functionality of the system (set up for potential future use in case of the next major earthquake), significantly reduces the data acquisition and management effort while enhancing the decision-making process.

3.2 Applicability to other areas

Although the system presented above was developed for Southeast European cities, and was specifically applied to the city of Düzce, its open architecture encourages its use in other parts of the world as well. In fact, the key modification required for the system to be used in other jurisdictions, is to adapt the ranking parameters summarized in Tables 1–3 and the decisions made for pre- and post-earthquake assessment as depicted in Figure 2. Additionally, the GIS topology should be made available from the end-user authorities (which are also responsible for the accuracy of the GIS data provided), while a number of modifications may also be required depending on the seismic code framework enforced and the local construction practice. In general, though, the above adaptations relate to a specific part of the system's algorithm only, while the vast majority of the modules comprising the system (i.e., overall scoring methodology, joint pre- and post-earthquake assessment framework, real time connection of GIS-database and mobile clients) are essentially city-independent.

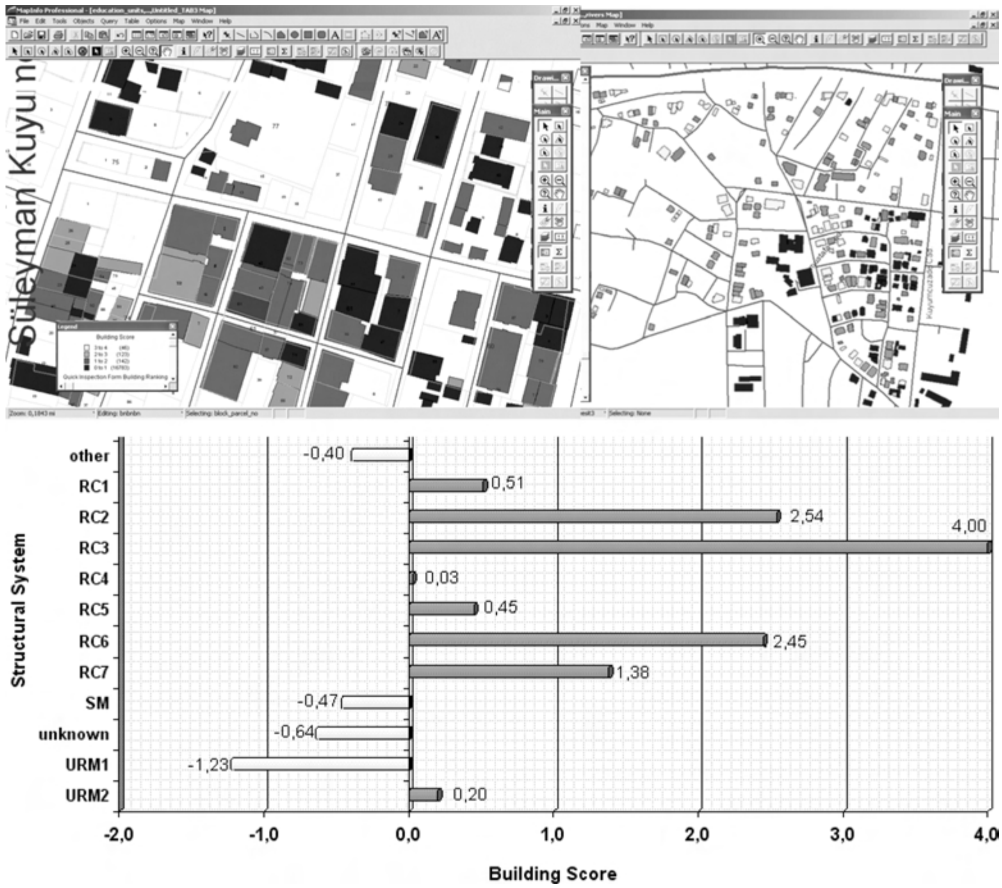


Fig. 4. Top: Automatic visualization on a GIS of the spatial distribution of the pre-earthquake building scores. Actual data processed in the framework of the building assessment in the city of Düzce (Serefiye District, top left and UzunMustafa District, top right). Bottom: Correlation between computed building score and structural system for the buildings that have been inspected in situ.

4 CONCLUDING REMARKS

(1) A multi-functional computer system is developed and presented herein as an effort to enhance the management, evaluation, processing, and archiving of data gathered during the pre- and post-earthquake assessment process, into a unique package. Its database capabilities and the integrated communication with a GIS platform, together with the remote data acquisition and transfer using PDA devices or new generation cell phones, can be considered as a step forward with respect to the use of IT in risk and crisis management.

(2) Moreover, both the overall assessment strategy and the computer tools developed, have been implemented and tested in real conditions in one of the most seismically active areas in Europe (the city of Düzce, in Turkey) through both seminars and demonstration applications, but also with the official adoption and use of the system by the local authorities for the assessment of a large number of buildings.

(3) It is hoped that the computer framework developed, has not only offered a useful rapid information system and a decision-making system to the local authorities of a specific city, but could also be adapted for implementation in other earthquake-prone areas.

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