Earthquake Risk Assessment for Romania

Friedemann Wenzel[1], Dan Lungu[2]

[1] *Geophysical Institute, CRC 461, University of Karlsruhe, Karlsruhe, Germany,*
Email: friedemann.wenzel@gpi.uni-karlsruhe.de
[2] *Technical University of Civil Engineering, Dept. Civil Engineering, Bucharest,Romania,*
Email: lungud@hidro.utcb.ro

Abstract

Strong earthquakes in the Romanian Vrancea area have caused a high toll of casualties and extensive damage over the last centuries. The average recurrence rates make another strong event within the next 2 decades highly probable and provide a challenge to mitigate its impact. Romanian and German scientists from various fields (geology, seismology, civil engineering, operation research) organized themselves in the Collaborative Research Center (CRC) 461 'Strong Earthquakes: A Challenge for Geosciences and Civil Engineering' (Germany) and the Romanian Group for Strong Vrancea Earthquakes (RGVE) in a multidisciplinary attempt towards earthquake mitigation [17]. Key objectives of joint research activities are:

- Understanding of the tectonic processes that are responsible for the strong intermediate depth seismicity beneath Vrancea.
- Developing realistic models and predictions of ground motion.
- Development of damage projections for the inner city of Bucharest based on seismological data, quantification of site effects and analysis of the built environment.
- Detailed experimental study of the entire sequence relevant in earthquake engineering: source physics, wave propagation, site effects, soil-structure interaction, building performance. The Multidisciplinary Seismic Test Site located at INCERC, in the Eastern part of Bucharest serves as a focus to verify theoretical predictions by experimental data. Non-linear soil behaviour is a key issue in this context.
- Development of novel approaches for mitigation of earthquake risk such as dynamic disaster management, new techniques for rescue and retrieval, retrofitting with fiber glass materials, rapid assessment of damage with photogrammetric methods and post-event shake maps.

1. Introduction

Strong earthquakes in the Romanian Vrancea area have caused a high toll of casualties and extensive damage over the last centuries [1]. The average recurrence rates make another strong event within the next 2 decades highly probable and provide a challenge to mitigate its impact. Romanian and German scientists from various fields (geology, seismology, civil engineering, operation research) organized themselves in the **Collaborative Research Center (CRC) 'Strong Earthquakes: A Challenge for Geosciences and Civil Engineering'** (Germany) and the **Romanian Group for 'Strong Vrancea Earthquakes'** in a multidisciplinary attempt towards earthquake mitigation [17]. This brochure highlights recent achievements and specifies research objectives of the forthcoming years. Key objectives of joint research activities are:

- Understanding of the tectonic processes that are responsible for the strong intermediate depth seismicity beneath Vrancea
- Developing realistic models and predictions of ground motion
- Prognosis of potential damage in case of a strong earthquake
- Risk reduction by appropriate civil engineering concepts.

Specific goals for the period 1999 to 2002 are:

⇒ Development of a **consistent geodynamic model** of the Neogene evolution of the Southeast Carpathians. This model should explain the specific features of the Vrancea seismicity (intermediate depth, small seismogenic volume, high activity) and provide boundary conditions for hazard assessment.

⇒ Development of **damage projections for the inner city of Bucharest** based on seismological data, quantification of site effects and analysis of the built environment.

⇒ Detailed experimental study of the entire sequence relevant in engineering seismology: source physics, wave propagation, site effects, soil-structure interaction, building performance. The **Multidisciplinary Seismic Test Site** INCERC, in the eastern part of Bucharest serves as a focus to verify theoretical predictions by experimental data. Non-linear soil behavior is a key issue in this context.

⇒ Development of novel approaches for **mitigation of earthquake risk** such as dynamic disaster management, new techniques for rescue and retrieval, retrofitting with fiber glass materials, rapid assessment of damage with photogrammetric methods and post-event shake maps.

Seismicity beneath Vrancea is characterized by the occurrence of intermediate depth earthquakes in a narrow epicentral and hypocentral region. The epicentral area is confined to about 30 km x 70 km (Figure 1). Earthquakes occur between 70 and 200 km depth within an almost vertical column. Deeper and shallower events have also been recorded but only with small magnitudes. Depth and estimated moment magnitudes (M_w) of all instrumentally recorded events are summarized in Oncescu and Bonjer [8]. The depth interval of the strong events is bounded by zones of low seismicity between 40 and 60 km and beneath 180 km.
Four major events struck within this century:

Date	Depth (km)	Moment Magnitude
Nov. 10, 1940	150 - 180	7.7
March 4, 1977	90 - 110	7.5
Aug. 30, 1986	130 - 150	7.2
May, 30, 1990	70 - 90	6.9

The frequency of Vrancea events can be assessed from available catalogues. Earthquakes with Richter magnitudes in excess of 6.0 taken from Radu's [12] compilation covering this century and transformed to moment magnitudes with Oncescu's [9] relation satisfy a Gutenberg/Richter law [6]:

$$\log_{10} N = 4.1 - 0.78\, M_w$$

with N as the number of events per year with magnitudes larger or equal to M_w.
This provides recurrence times of 10 years for $M_w \geq 6.5$, 25 years for $M_w \geq 7.0$ and 50 years for $M_w \geq 7.4$. Historical data have been compiled by Radu [11]. Assuming that the data are complete for large magnitudes for the last 600 years, this time interval shows 3 earthquakes/century with $M_w \geq 7.2$ and 6 events/century with $M_w \geq 6.8$ in good agreement with the Gutenberg/Richter relation.
The Romanian literature identifies various types of buildings classified according to the time of construction [7]. Residential buildings of pre-World War II with 8 to 14 stories are built as reinforced concrete frames with infill brick walls. They suffered most in 1977 because they were designed to resist vertical loads only. 32 buildings of this type collapsed, although they survived the 1940 earthquake. The second group of buildings which suffered substantially are monolithic reinforced concrete buildings with 2 to 16 stories. Their quality ranges from poor for residential buildings to relatively good for hotels and public buildings. Rural houses with 1 or 2 stories, supported by light timber systems or adobe constructions with mud cast into framework collapsed in large numbers mostly in the epicentral area.
According to data summarized subsequently to the 1977 earthquake, 1,570 casualties occurred and more than 11,300 cases of injured persons (90% of the victims in Bucharest) were reported. 32,900 apartments were destroyed or severely affected, and the overall seismic loss was estimated at more than 2 Billion US $. The foreign trade balance, subsequently to the 1977 earthquake, was severely upset and it is likely that the earthquake impact considerably contributed to this fact. The 1986 event caused only little damage in Bucharest but severely affected the Moldavian capital Kishinev with a damage of about 1 Billion US $.

2. Research Objectives

The Carpathians can geologically be subdivided [e.g.14, 15] into two main units, the Outer Carpathians with the Molasse foredeep and the flysch belt (=accretionary wedge), and the Inner Carpathians with pre-Neogene rocks, and Tertiary to Quaternary sedimentary and volcanic rocks (Figure 2). During Neogene subduction the Outer Carpathians were located on the lower plate, while the Inner Carpathians represented the upper plate which

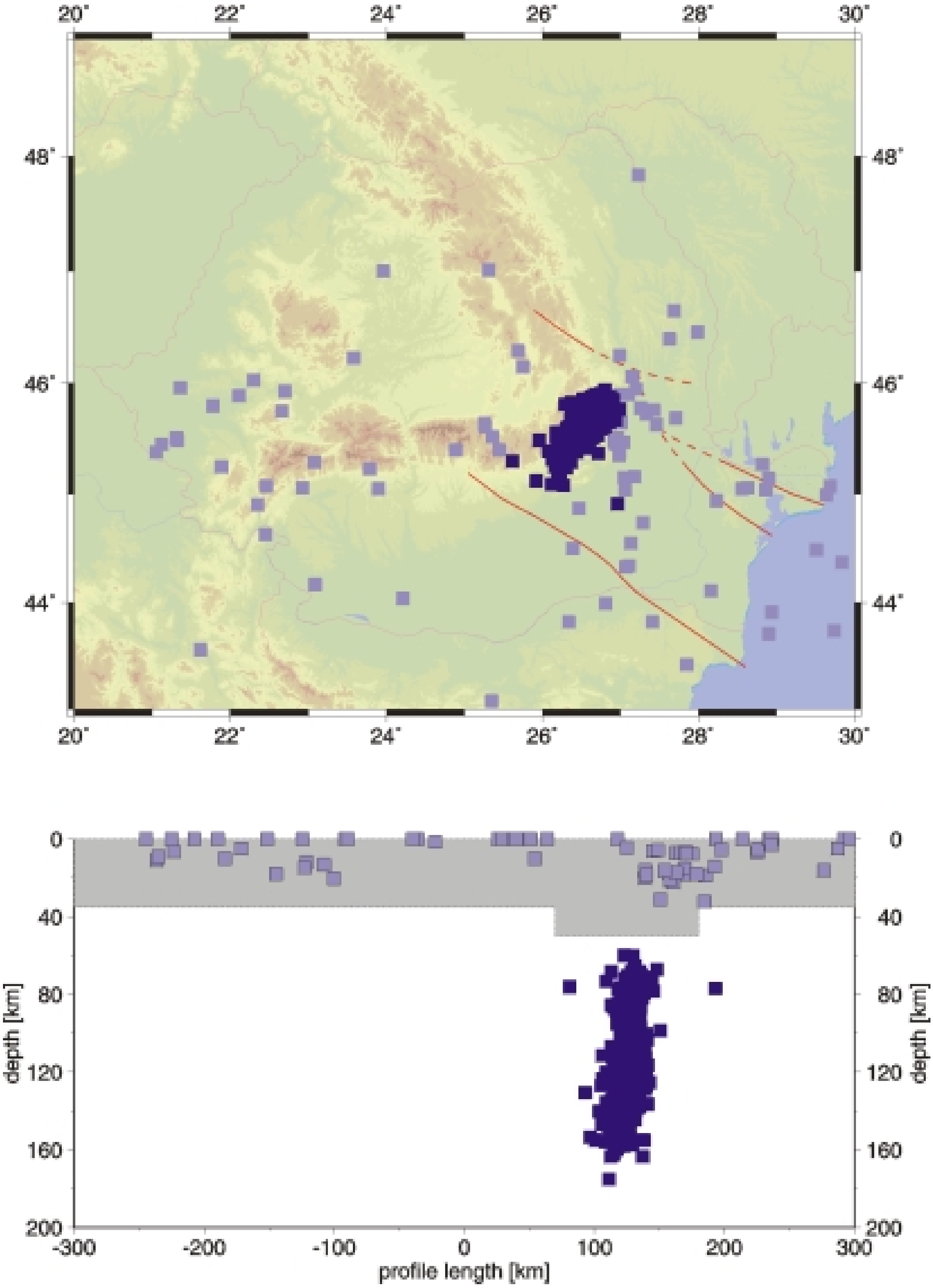

Figure 1: Schematic representation of the seismicity in Romania. Intermediate depth earthquakes are strongly clustered

consisted of two crustal blocks. Both blocks are now separated by the Mid-Hungarian fault zone (Figure 2). They moved differently during the Miocene tectonic evolution of the Carpathian arc.

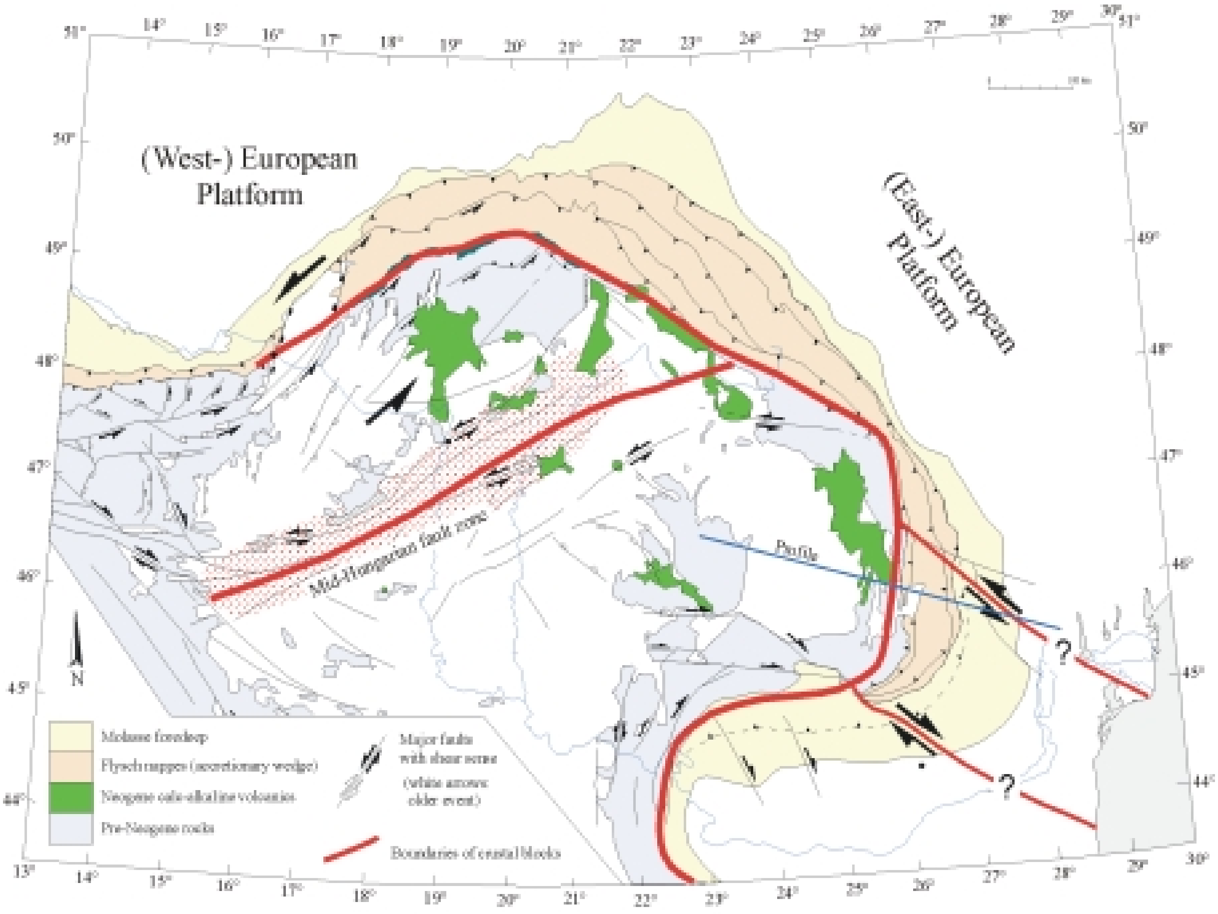

Figure 2: Tectonic overview map of the Carpathian region (after Horvarth [5])

In the last years considerable advances have been obtained in the understanding of the geodynamic evolution of the Carpathian region. New data (structural, sedimentological, paleomagnetic, geochronological, etc.) were compiled by several research groups. They are the basis for a geodynamic model [16, 3]. The reconstruction starts 25 Mio. years ago when the intra-Carpathian blocks were located several hundred kilometers more to the southwest. Subduction towards the southwest was coupled with a northeastward retreat of the subduction zone and thus forced the intra-Carpathian blocks to move into the same direction (northeastwards).

The northern block was the first one which collided with the European foreland, while subduction continued for a few Mio. years longer beneath the southern block. Collision was followed by slab break-off which again started in the north and propagated towards the south. Thus in the northern part of the Carpathians, the detached slab segments already sunk into the mantle, while beneath the southeastern bend of the Carpathian arc (Vrancea region) the last, just detaching slab segment seems to be responsible for the localized, intermediate-depth seismicity in this region.

The southeastern part of the Carpathians shows some special geological and geophysical features which have to be taken into account when reconstructing the youngest stage of the tectonic evolution:

- Earthquake hypocenters are shifted about 80 to100 km towards the SE with respect to the Miocene suture
- Very localized seismogenic volume (40 km x 80 km, max. depth: 220 km)
- High strain rates in the slab (2×10^{-7} / a)

- Changing slab orientation (direction of strike) with depth: NE-SW in the upper parts (70-150 km), N-S in the deeper parts (> 150 km)
- Mantle plume-related alkaline volcanism in close vicinity to calc-alkaline volcanics; a deep mantlesource is proven by noble gas isotopy of mantle xenoliths
- Evidence for the presence of CO_2-rich fluids in the upper mantle from fluid inclusions in xenoliths
- Minimum heat flow is located southeast of the foredeep basin (and not as usual above the down-going plate)

3. Multidisciplinary Seismic Test Site

The premises of the Romanian Building Research Institute INCERC serve as the location for the Multidisciplinary Seismic Test Site installed in 1998/1999. A rigid concrete block of 100 t mass is supported by rubber bearings on a rigid concrete footing of 72 t mass. Three-component accelerometers are installed on the footing, on top of the concrete block and at two depths (30 m and 180 m) and in the free field. Figure 3 shows the basic design of the test device, and Figure 4 shows the actual building. Geotechnical parameters of the subsurface are controlled to a depth of 200 m (Figure 5).

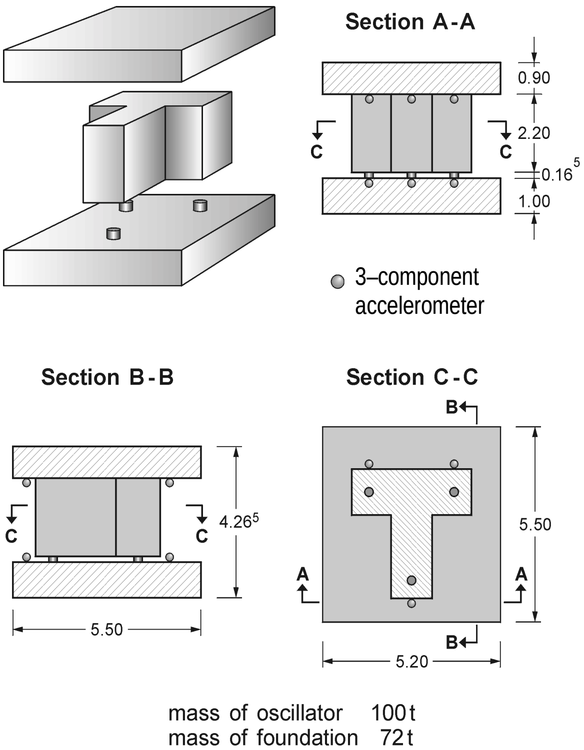

Figure 3: Design of the Test Building of the Multidisciplinary Seismic Test Site

Figure 4: Test building of the Multidisciplinary Seismic Test Site at the Romanian Building Research Institute INCERC

The conventional methods for earthquake-resistant structural design use high stiffness or high ductility concepts to mitigate damage from seismic effects. High stiffness can be achieved with shear walls. However, their fundamental frequencies of vibration are in the range where earthquake energy is strongest. This causes very high floor acceleration with a high potential for damage to equipment and machinery. In contrast, the capacity design method intends that parts of the energy transmitted into the structure by an earthquake is dissipated by plastic deformations. The capacity method is mostly used for flexible structures such as frames. Plastic deformations occur in structural elements, which are designed to sustain such large deformations. Obviously, the design of such yielding zones has to be planned carefully. As a disadvantage this concept may lead to a very high

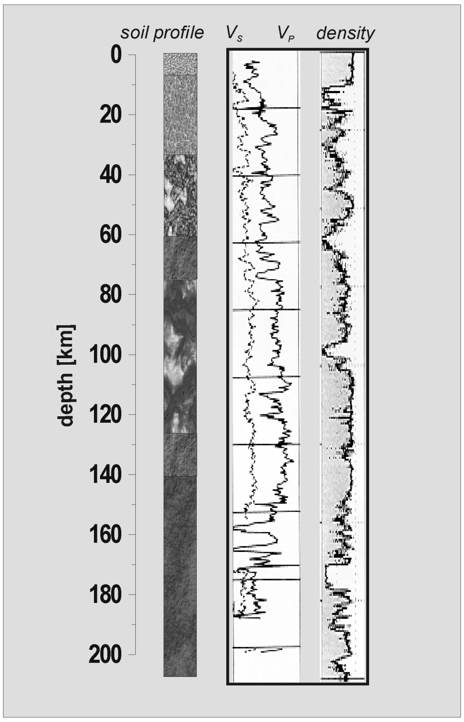

Figure 5: Illustration of soil profile with S- and P-wave velocities and density log

interstory drift, causing P-Δ effects and damage to non-structural elements and the costs for retrofitting or strengthening after a strong earthquake can be very high. An alternative approach consists in isolating the structure base from the ground by using rubber bearings.

Research Targets are defined as:

- The behavior of the test building will be studied numerically with Finite Element methods including soil-structure interaction and non-linear soil effects [2].
- Performance of rubber bearings will be quantified experimentally with the moderate to strong earthquakes that are likely to occur within the future.
- The test site also serves as a location for studying non-linear soil properties by specifically developed seismic sources for P- and S-waves. Non-linearity is approached by a physical model - the hypoplastic material law [10].
- The location serves as calibration site for geotechnical and seismological microzoning of Bucharest.

The Multidisciplinary Seismic Test Site is thus the focus of interactions between seismology, structural dynamics, soil mechanics, and engineering geology.

4. Quantitative Damage Estimates for Bucharest

Damage projections for realistic strong earthquakes are evolving as important tool for disaster mitigation. It enables

- to demonstrate the potential damage and loss the society has to cope with
- to assess the necessary amount of resources requested for mitigation
- to develop priorities in disaster mitigation policy on a scientifically sound basis
- to measure the efficiency of mitigation action
- to measure variations of risk with time

The anticipated damage and loss estimation tool consists of four modules that describe hazard, vulnerability, risk to the built environment and loss of lives (Figure 6). The data base for the modules is partly available but need to be refined before reasonable estimates emerge.

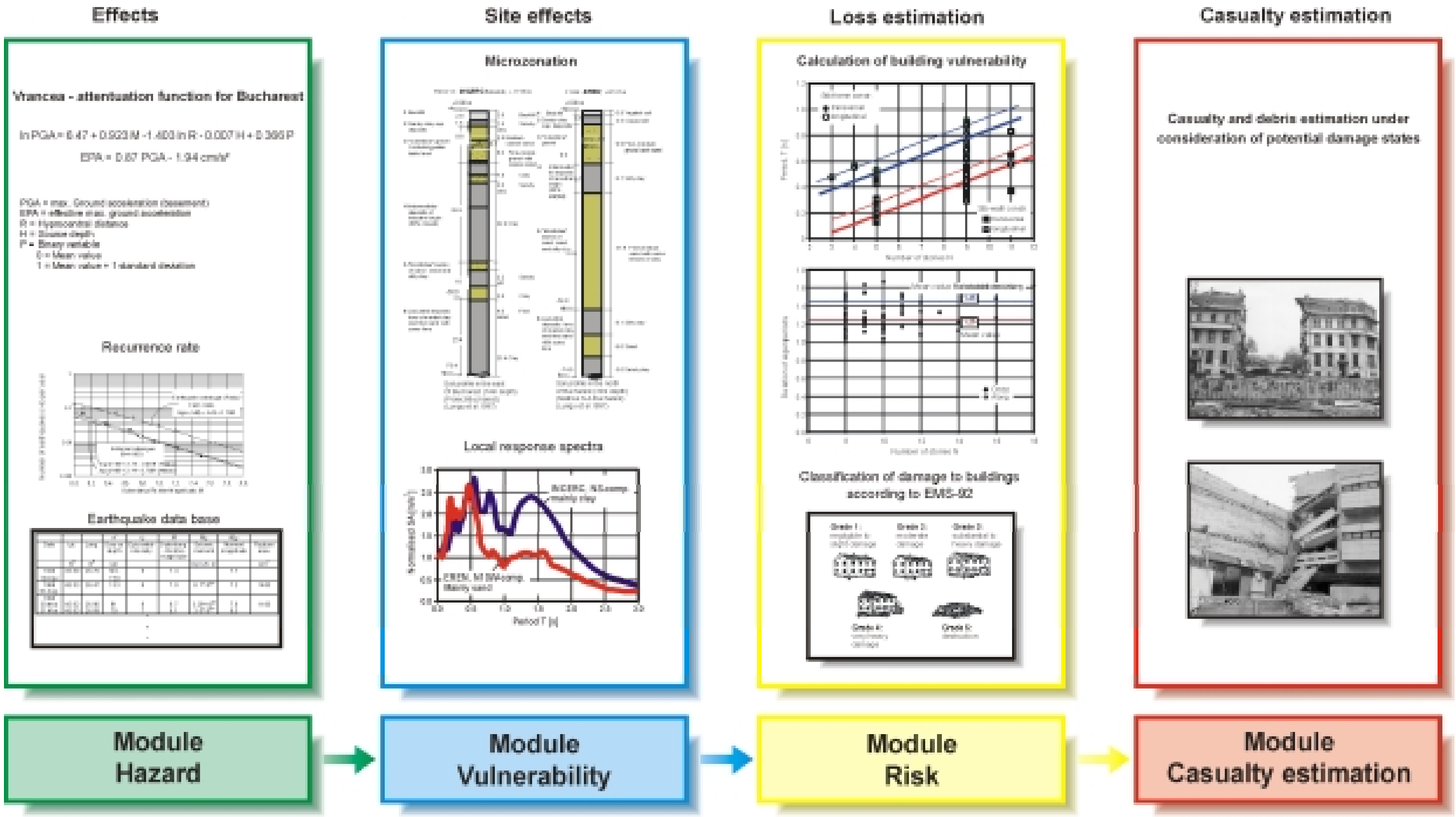

Figure 6: Scheme for modules of the damage and loss estimation tool (after Lungu and Coman [6] and Lungu et al. [7]

Horizontal peak acceleration for a Vrancea earthquake specified by magnitude and depth can be estimated from attenuation relations [7] together with an appropriate microzoning of Bucharest. An alternative approach is the deterministic computation of the realistic strong ground motion for seismic hazard and microzonation analysis [13]. Vulnerability curves will provide damage classes for different building types. The European Macroseismic Scale 1998 [4] will be used as a guide. On the basis of an inventory of the inner city of Bucharest (buildings, lifelines, bridges, etc.) damage, injuries, and losses can be estimated. The system will function as a scenario based tool but also in a probabilistic mode where the probable damage within a given period of time is estimated. Once available it can be utilized as an add-on to the shake map that will be rapidly established after a large earthquake so that disaster relief forces may have rapid damage and loss projections, already some minutes after the event.

5. Innovative Techniques in Disaster Mitigation

A variety of novel approaches in disaster mitigation are pursued:

- Development of retrofitting techniques based on CFRP (Carbon Fiber Reinforced Plastics) sheets that allow to reduce the costs of retrofitting, CFRP sheets can be attached to walls without interrupting the functionality of a building. They increase the allowable load by a factor of 2 and can be utilized after an event to quickly secure unstable buildings.
- Airborne laserscanning of urban areas shortly after a strong earthquake for a change detection in man-made objects. Computer based comparisons of pre- and post-event datasets will help to recognize changes quickly. These are then classified accordingly and damage detected.
- Development of decision support systems for emergency response and emergency planning. Expert knowledge and Operations Research methods are combined to support emergency managers on a strategic level such as optimizing the allocations of scarce relief resources to the affected areas.
- Methods for detailed evaluation of damage, loss and number of victims to be rescues; novel approaches for rescue of people from collapsed buildings.
- Seismic instrumentation of Bucharest together with geologic microzoning enables fast post-event generation of shake maps showing the areal distribution of ground motion parameters (acceleration, intensity, etc.) within the city (Figure 7).
- An early warning system has been designed on the basis of traveltime differences between S- and P-waves from the epicenter of the Vrancea earthquakes to the capital. The warning time of 25 s is believed to be useful for a number of emergency measures (Figure 8).

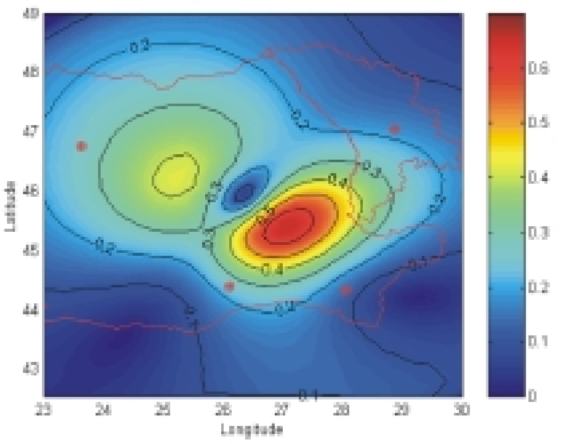

Figure 7: Expected level of ground shaking (PGA in g) from a Vrancea earthquake with a hundred years recurrence time. The radiation pattern of the event is incorporated

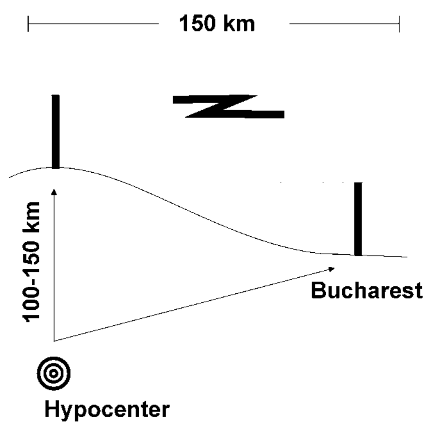

Figure 8: Sketch of the early warning system for Bucharest that will provide about 25 s warning time based on traveltime differences between S- and P-waves

6. Projects

- **Deep Seismic Sounding of the Vrancea Zone:** Definition of the elastic structure of crust and upper mantle along a profile from the Vrancea area across Bucharest to the Danube; derivation of reliable models of shearwave velocities and attenuation.
- **Seismic Tomography of the Carpathian Arc:** 3-D images of the elastic structure of the Vrancea subduction zone as constraints for the tectonic setting of the intermediate depth seismicity, for strong earthquake parameters such as maximum moment release, and wave propagation from the source site to Bucharest
- **Subduction Related Magmatism, Fluid Budget and Mantle Structure of the Carpathian Arc:** Definition of thermodynamic conditions in the upper mantle beneath Vrancea (the earthquake source volume); development of earthquake source models based on macroscopic and microscopic properties of mantle rocks
- **Stress Field and Geodynamics:** Establishment and verification of a consistent geodynamic model of the SE Carpathians; FE-modeling of the stress in the crust and earthquake source area
- **Three-Dimensional Plate Kinematics in Romania:** Periodically repeated GPS measurement campaigns aim at an improved neotectonic model of the area. This will provide boundary conditions on the earthquake process and the coupling of the subducting slab segment with the overthrusted lithosphere
- **Seismogenic Potential of the Vrancea Subduction Zone- Quantification of Source and Site Effects from Strong Earthquakes:** Hazard assessment, quantification of strong earthquake parameters; prediction of realistic acceleration time histories with Empirical Green's Functions; operation of the strong motion network
- **Non-linear Wave Phenomena in Soft Sediments:** Experimental and theoretical studies of non-linear wave phenomena associated with strong earthquakes
- **Geotechnical and Seismic Microzoning of Bucharest:** Compilation of available soil data in GIS format; geological interpretation and extrapolation of log data; verification by seismological site effect studies
- **Damage Estimation and Retrofitting of Buildings in Central Bucharest:** Quantitative evaluation of building vulnerabilities in Bucharest, development of novel retrofitting techniques
- **Disaster Management - Models and Simulation:** Analysis of emergency response plans, formalising of knowledge relevant for disaster management, development of a computer based decision support system for strategic decisions in emergency response, earthquake scenarios for the inner city of Bucharest
- **Image Analysis in Geosciences and Civil Engineering:** Aerial photography has proved to be a strong tool to acquire information about the pre- and post situation in a hazard environment. Additional support is expected from fusion with laser scanning technology, which is currently under development
- **Knowledge Representation for Disasters with a Technical Information System:** Data acquisition has to be followed by data analysis, leading to processing of knowledge. Available facts and rules have to be represented in graphs, e.g. by semantic or Bayesian networks. Knowledge processing must result in decision making based on deterministic and stochastic variables
- **Novel Rescue and Restauration Technologies:** Knowledgebase for the improvement of rescue actions in debris structures. Demand for rescue personnel and devices depending on building types and damage states. Experiments in debris structures and evaluation of rescue reports
- **Geographical Information System:** Operation of central GIS system

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