Seismology in Croatia, 1999–2002

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The seismological research in Croatia is carried almost exclusively within the Department of Geophysics, Faculty of Sciences, University of Zagreb. Scientific investigations are mostly organized within the framework of the project »Seismicity of Croatia«, which is financed by the Ministry of Science and Technology of the Republic of Croatia. The staff of Croatian Seismological Survey (a part of the Department) maintain and deploy the network of seismographs and strong-motion instruments, compile the earthquake catalogue and analyse and exchange the seismological data. In this period the number of seismological instruments increased and two new seismological stations were opened (Sisak – SISC and Novalja – NVLJ). Also, two BB stations (DUOK and HVAR) operated in the framework of the MIDSEA project. Most of the existing stations have been upgraded with digital, broad-band instruments.

12 researchers (4 PhD, 6 MSc and 2 BSc) took part in seismological investigations. In the period 1999–2002 they published a total of 39 scientific and conference papers. Croatian seismologists were active in national scientific project as well as in international multilateral and bilateral programs. The research topics included seismic zonation of megacities around the world (UNESCO-IGCP sponsored project coordinated by the Department of Earth Sciences, University of Trieste), interpretation and analysis of historical seismograms (cooperation between Universities of Zagreb and Hamburg), seismic hazard assessment in the Adriatic region GSHAP (UN/IDNDR sponsored project, coordinated by ETH, Zurich in 1997–1999), and investigation of the Earth's mantle in the Europe-Africa region (MIDSEA project, coordinated by ETH, Zurich).

Significant part of seismological studies is related to Croatian seismicity, which was characterized by only a moderate earthquake activity in this period. An overview of Croatian seismicity in period 1997–2001 was presented by Ivančić et al. (2002) and Tomljenović et al. (2001) for NW Croatia. Herak and Herak (2000) presented overall seismicity of the Ston region. Also, the Croatian earthquake catalogue has been regularly updated and currently consists of 18861 records.

Herak M. et al. (2000, 2001) presented numerical modeling of the Ston-Slano (Croatia) aftershock sequence. Thousands of aftershocks after M6 Ston-Slano earthquake of 1996 enabled a sound statistical analysis. The rate

of aftershock occurrence was modeled as the Epidemic Type Aftershock Sequence (ETAS).

Several papers have been dedicated to seismic hazard assessment in Croatia (Herak, M., 1999, Slejko et al., 1999, Markušić et al., 2000, Herak M. et al., 2001, Allegretti and Herak, 2002, Lokmer et al., 2002, Markušić et al., 2002, Panza et al., 2002).

For instance, Markušić et al. (2000) proposed dividing the territory of Croatia and neighboring regions into 17 seismic source zones, considering available seismological and geological data. On this basis, seismic hazard elements (seismicity rate, maximum magnitude, b-value, probabilities of exceedance and return periods for a predefined set of magnitudes) are computed using maximum likelihood method appropriate for treating data sets with variable completeness thresholds. The values of long term expected peak horizontal acceleration obtained by using a combination of the deterministic and the probabilistic procedure are the highest in the Dubrovnik zone, while the Zagreb zone has the highest earthquake hazard in the continental part of Croatia. Papers by Herak et al. (2002) and Markušić et al. (2002) deal with peak ground acceleration (PGA) attenuation in the Dinarides region. The authors proposed PGA attenuation relations to be used in the Dinarides region for distances up to 100 km.

Seismic hazard in several parts of Croatia (Zagreb, some Dalmatian regions) was also estimated by stochastic approach, *i.e.* by Monte-Carlo simulations of earthquake occurrence. The hazard was estimated in terms of peak ground accelerations and expected intensities (*Imax*) computed for various return periods on the basis of statistical analyses of 5000 synthetic 50-years earthquake catalogues. The highest values of PGA are found along the border with Bosnia and Herzegovina with the absolute maximum of 0.35 g in the greater Dubrovnik area (Allegretti and M. Herak, 2002). Lokmer et al. (2002) used a hybrid technique consisting of modal summation and subsequent finite differences modeling for the computation of synthetic accelerograms along a profile crossing the city of Zagreb. According to the results of the paper, the largest amplification of ground motion (exceeding a factor of 3) may be expected beneath the very centre of the city.

Intermediate term earthquake prediction algorithm CN was used by Herak D. et al. (1999a, 1999b) to investigate seismicity prior to 9 strong events in the Southern External Dinarides. They have found that 8 of them were preceded by a time period of increased probability (TIP) of earthquake occurrence.

The papers by Van der Lee et al. (1999a, 1999b, 2000, 2001a, 2001b) describe the results of the MIDSEA project. The goal of this project is to obtain key information on the upper mantle structure in the greater Mediterranean region and Eurasia-Africa plate boundary region.

Historical seismograms recorded in Göttingen and Zagreb were studied by Allegretti et al. (2000). The magnitudes of the largest historical earthquakes in the first half of the 20th century, calculated on the basis of records of Wiechert horizontal seismographs in Göttingen and Zagreb were compared with one another, as well as with the magnitudes reported worldwide. It was shown that systematic trends exist in the data regarding the temporal stability of magnitude estimations in the Gottingen case, as well as the apparent non-linearity of the instrument response in the case of the Wiechert seismograph in Zagreb.

Herak M. et al. (2001) have presented theoretical basis for Ms depth correction. They used modal summation technique to generate 5000, three component theoretical seismograms of surface waves assuming validity of generally accepted global Earth models (PREM-C and AK135F). They observed the theoretical amplitude decay with the source depth in agreement with observational data.

Anisotropy of Pg-wave velocity was considered for two regions: Central External Dinarides and in the hypocentral volume of the Krn Mt. (Slovenia) earthquake sequence (Lokmer and M. Herak, 1999; Herak M. et al., 2002).

The scientific productivity of Croatian seismologists retained the same level as in the previous 4-year period.

List of publications

Allegretti, I., Herak D., Herak M., S.J. Duda (2000): Consistency of magnitudes of the largest historical earthquakes of the first half of 20th century determined on the basis of Gottingen and Zagreb Wiechert seismograms. Studia Geophysica et Geodaetica **44**, 13–25.

Allegretti, I., M. Herak (2000): Influence of uncertainties of input parameters on earthquake hazard for the city of Zagreb estimated by Monte-Carlo simulations, European Seismological Commission (ESC), XXVII General Assembly, Lisbon, Portugal, 10–15 September 2000, Book of Abstracts and Papers, 95.

Allegretti, I., M. Herak (2002): Seismic hazard in Dalmatia (Croatia) estimated by Monte-Carlo simulations, European Seismological Commission (ESC), XXVIII General Assembly, Genoa, 1–6 September 2002, Italy, 124.

Herak D., M. Herak (1999a): Application of the CN earthquake prediction algorithm to Croatian and neighbouring territories, 24th General Assembly of the European Geophysical Society, Nice, France, April, 1999, Geophysical Research Abstracts, **1**, 108.

Herak D., Herak M., Panza G.F., G. Costa (1999b): Application of the CN intermediate term earthquake prediction algorithm to the area of the Southern External Dinarides. PAGEOPH, **156**, 689–699.

Herak D., M. Herak (2000): Seizmičnost Stonskog područja. Dubrovnik, **XI**, 192–198

Herak, D., M. Herak (2001): Lapse-time and frequency dependence of coda-Q in the Adriatic region, EGS XXVI General Assembly, Nice, France, 25–30 March 2001, Geophysical Research Abstracts.

Herak, M. (1999): Principal contributor for Croatia in Giardini D., Grunthal G., Shedlock K., P. Zhang. (Eds.): Global seismic hazard map (GSHAP Project). Attachment to Annali di Geofisica, 42.

Herak, M., M. Orlić, M. Kunovec-Varga (1999): Tsunami excitation and propagation in the Central Adriatic archipelago – the case of Makarska earthquake (1962), 24th EGS General Assembly, The Hague, Netherlands, 19–23 April, 1999.

Herak M., Herak D., Markušić S., I. Ivančić (2001): Numerical modeling of the Ston-Slano (Croatia) aftershock sequence. Studia Geophysica et Geodaetica, **45**, 251–266.

Herak M., D. Herak, S. Markušić, I. Ivančić (2000): Numerical modeling of aftershock activity in Southern External Dinarides, XXVII General Assembly of the European Seismological Commission (ESC), Lisbon, Portugal, 10–15 September 2000, Book of Abstracts and Papers, 59–60.

Herak, M., Markušić, S., I. Ivančić (2001): Attenuation of peak horizontal and vertical acceleration in the Dinarides area, Studia Geophysica et Geodaetica, **45**, 383–394.

Herak, M., G. F. Panza, G. Costa (2001): Theoretical and observed depth correction for MS, PAGEOPH, **158**, 1517–1530.

Herak, M., Orlić, M., Kunovec-Varga, M. (2001): Did the Makarska earthquake of 1962 generate a tsunami in the central Adriatic archipelago?, Journal of Geodynamics, **31**, 71–86.

Herak M., M. Živčić, D. Herak (2002): Pg-wave velocity anisotropy in the hypocentral volume of the Krn Mt. (Slovenia) earthquake sequence. 10. International Workshop on Seismic Anisotropy, Tutzing, April 14–19, 2002, 33.

Herak M., M. Živčić, D. Herak (2002): Pg-wave velocity anisotropy in the hypocentral volume of the Krn Mt. (Slovenia) earthquake sequence. European Seismological Commission (ESC), XXVIII General Assembly, Genoa, 1–6 September 2002, Italy, 109.

Herak M., Skoko D., D. Herak (2002): Seismology in Croatia. IASPEI International Handbook of Earthquake and Engineering Seismology (Eds.: P. Jenning, H. Kanamori, W. Lee), Part X, (National Centennial Report) (in press).

Ivančić, I., I. Allegretti (1999): Newsletter CSEM, **14**, 2.

Ivančić, I., Herak, D., Markušić, S., Sović, I., M. Herak (2002): Seismicity of Croatia in the period 1997–2001, Geofizika **18/19**, 17–29.

Jurak, V., Kvasnička, P. Dujmić, D. Kuk, V. (1999): Zbornik radova znanstvenog skupa »Andrija Mohorovičić – 140. obljetnica rođenja«, Bajić, A. (ed.). Zagreb: DHMZ, 1999. 125–139.

Lokmer, I., M. Herak (1999): Anisotropy of P-wave velocity in the upper crust of the central External Dinarides, Studia Geophysica et Geodaetica, **43**, 345–356.

Lokmer, I., M. Herak, G. F. Panza, F. Vaccari (2002): Amplification of strong-ground motion in the city of Zagreb, Croatia, estimated by computation of synthetic seismograms, Soil Dynamics and Earthquake Engineering, **22**, 105–113.

Markušić S., M. Herak (1999): Seismic zoning of Croatia, Natural Hazards, **18**, 269–285.

Markušić, S., Suhadolc, P., Herak, M., Vaccari, F. (2000): A contribution to seismic hazard assessment in Croatia from deterministic modeling. PAGEOPH, **157**, 1/2, 185–204.

Markušić S., Herak M., Herak D., I. Ivančić (2002): Peak horizontal-to-vertical acceleration ratio and local amplification of strong ground motion. Studia Geophysica et Geodaetica, **46**, 83–92.

Pamić, J., D. Balen., M. Herak (2002): Origin and geodynamic evolution of Late Paleogene magmatic associations along the Periadriatic-Sava-Vardar magmatic belt, Geodynamica acta, **15**, 209–231.

Panza, G. F., Alvarez, L., Aoudia, A., Ayadi, A., Benhallou, H., Benouar, D., Bus, Z., Chen,Y-T., Cioflan, C., Ding, Z., El-Sayed, A., Garcia, J., Garofalo, B., Gorshkov, A., Gribovszki, K., Harbi, A., Hatzidimitriou, P., Herak, M., Kouteva, M., Kuznetzov, I., Lokmer, I., Maouche, S., Marmureanu, G., Matova, M., Natale, M., Nunziata, C., Parvez, I., Paskaleva, I., Pico, R., Radulian, M., Romanelli, F., Soloviev, A., Suhadolc, P., Szeidovitz, G., Triantafyllidis, P.and F. Vaccari: (2002): Episodes, **25**, No. 3, 160–180.

Prelogović E., D. Skoko, M. Herak (1999): Contributions to cognition of relation between recent tectonic movements and seismic activity of Dinarides in Croatia. EUG 10, Journal of Conference, Abstracts, **4/1** (ISSN 1362–0886), EUG, 450.

Prelogović, E., Kuk, V., Buljan, R., Tomljenović, B., Skoko, D. (1999): Proceeding of the 2nd Int. Simp. Geodynamics of the Alps-Adria Area by Means of Terrestrial and Satellite Methods, Čolić, K., Moritz, H. (eds.), 255–262.

Prelogović, E., Kuk, V. (1999): , Zbornik radova znanstvenog skupa »Andrija Mohorovičić« (Bajić, A., ed.), Zagreb, 115–124.

Skoko D., Herak M. (2002): Andrija Mohorovičić (1857–1936). IASPEI International Handbook of Earthquake and Engineering Seismology (Eds.: P. Jenning, H. Kanamori, W. Lee), Part XI, chpt. 89 (in press).

Slejko D., Camassi I., Cecić I., Herak D., Herak M., Kociu S., Kouskouna V., Lapajne J., Makropoulos C., Meletti C., Muco B., Papaioannou C., Peruzza L., Rebez A., Scandone P. Sulstarova E., Voulgaris N., Živčić M., P. Zupančič (1999): Seismic hazard assesment for Adria. Annali di Geofisica, **42**, 1085–1107.

Tomljenović B., Csontos L., Herak M., D. Herak (2001): Neogene-quaternary structures and recent seismicity in NW Croatia (Hrvatsko Zagorje and Karlovac Basins). The Stephan Mueller Topical Conference of the European Geophysical Society. Quantitative neotectonics and seismic hazard assesment: New integrated approaches for environmental management. Balatonfured, September 22–26, 2001, Hungary, 63.

Van der Lee, S.,, F. Marone, M. van der Meijde, D. Giardini, C. Chiarabba, M. Herak, R. Ortiz, A. Ugalde Aguirre, A.S. Suleiman, G. Chouliaras, J.M. Davila (1999a): New broadband stations for imaging crust and upper mantle structure of the Mediterranean region. XXV General Assembly EGS, Nice, France, 25–29 April 1999.

Van der Lee, F. Marone, M. van der Meijde, D. Giardini, C. Chiarabba, M. Herak, R. Ortiz, A. Ugalde Aguirre, A.S. Suleiman, G. Chouliaras, J.M. Davila (1999b): New broadband stations for imaging crust and upper mantle structure of the Mediterranean region. American Geophysical Union Spring Meeting, May 30–June 3, Washington D.C.

Van der Lee, S., F. Marone, M. van der Meijde, D. Giardini, A. Deschamps, C. Chiarabba, M. Herak, R. Ortiz, A.U. Aguirre, G. Chouliaras, A.S. Suleiman, J.M. Davila (2000): MIDSEA: New plate-boundary broadband stations from Greece to the Azores, XXVII General Assembly of the European Seismological Commission (ESC), Lisbon, Portugal, 10–15 September 2000, Book of Abstracts and Papers, 30.

Van der Lee, S., F. Marone, M. van der Meijde, D. Giardini, A. Deschamps, C. Chiarabba, M. Herak, R. Ortiz, Ugalde, A., Chouliaras, G., Suleiman, A.S., Eshwehdi, A., Davila, M., Yelles, K. (2001a): MIDSEA: New broadband stations for imaging crust and upper mantle structure of the Mediterranean region, EGS XXVI General Assembly, Nice, France, 25–30 March 2001, Geophysical Research Abstracts.

Van der Lee, S., F. Marone, M. van der Meijde, D. Giardini, A. Deschamps, L. Margheriti, P. Burkett, S. C. Solomon, P. M. Alves, M. Chouliaras, A. Eshwedi, A.S. Suleiman, H. Gashut, M. Herak, R. Ortiz, J.M. Davila, A. Aguirre, J. Vila, K. Yelles (2001b): Eurasia-Africa Plate Boundary Region Yields New Seismographic Data. EOS Trans. AGU, **82**, 637–646.

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