

Fact Finding Workshop on the active Tectonics of the Krško Region



Technical Workshop, Klagenfurt/Celovec



FACT FINDING WORKSHOP ON THE ACTIVE TECTONICS OF THE KRŠKO REGION

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Kurt Decker

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SUMMARY

The Environment Agency Austria and the Land Kärnten invited 26 geoscientists from six countries to a technical workshop on the seismicity and active tectonics of the region around the Slovenian nuclear power plant (NPP) Krško. The workshop was supported by the Austrian Federal Ministry for Agriculture, Forestry, Environment and Water Management (BMLFUW). It was held in Klagenfurt on 07. April 2016.

The Austrian concerns about the seismic safety of the NPP root in the assessment of the plant during the Stress Tests performed on European Nuclear Power Plants in 2012. Based on this assessment the European Nuclear Safety Regulators Group (ENSREG) suggested in its Stress Tests Country Report for Slovenia that *“The regulator should consider requesting to update the seismic design basis”*. Concerns are aggravated by the discovery of a number of active faults next to the NPP in the time after the Stress Tests¹.

The workshop confirmed that Krško is located in a tectonically and seismically active area. It further confirmed the existence of several active faults close to the NPP. Geological data particularly highlight the Orlica-, Artiče- and Libna faults as well as an unnamed thrust fault below the Artiče flexure as potential sources for earthquakes. The correct assessment of the degree of activity of these faults is of vital importance for the derivation of reliable seismic hazard values. Although experts mostly agreed on the existence of these faults, no common opinion existed on their degree of activity. It appeared that this is mainly due to a lack of paleoseismological data. Many experts therefore highlighted the importance of acquiring additional data to proof or disproof the activity of the faults and to establish a reliable dataset of fault geometry, kinematics, and slip rates as input for seismic hazard assessment.

The workshop results lead to the suggestion that BMLFUW should follow up the issue and consider to stress in its communication with Slovenian institutions that:

- seismic safety of the NPP Krško is of key importance;
- a new and broadly accepted seismic hazard assessment should be completed by independent experts as soon as possible;
- seismic hazard assessment should be based on reliable paleoseismic data;
- the possibility for Austrian and international observers to follow up data collection and seismic hazard assessment would foster confidence in the reliability of the results;

the seismic design basis of the NPP Krško should be updated as soon as possible.

¹ The concerns of Austrian experts are detailed in the so-called Issue Paper Slovenia which was published by BMLFUW in 2015 (<https://www.bmlfuw.gv.at/umwelt/strahlen-atom/antiakwpolitik/euroatom-internat/stresstest.html>).

KURZFASSUNG

Das Umweltbundesamt und das Land Kärnten haben mit Unterstützung des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW) 26 Expertinnen und Experten für Geologie und Seismologie aus sechs Ländern zu einem technischen Arbeitstreffen über die Seismizität und aktive Tektonik in der Region um das slowenische Kernkraftwerk Krško geladen. Dieses Treffen hat am 07. April 2016 in Klagenfurt stattgefunden.

Die österreichischen Vorbehalte über die Erdbebensicherheit von Krško resultieren aus der Beurteilung des Kraftwerks durch die Stress Tests der europäischen Kernkraftwerke 2012. Aufgrund dieser Beurteilung empfahl die European Nuclear Safety Regulators Group (ENSREG) in ihrem Bericht für Slowenien, dass „die Aufsichtsbehörde in Betracht ziehen möge, eine Aktualisierung der Auslegungsgrundlage für Erdbebenbelastungen zu fordern“. Die Vorbehalte werden durch mehrere aktive Störungen verstärkt, die nach den Stress Tests in der Nähe des Kraftwerks gefunden wurden².

Das Arbeitstreffen bestätigt, dass Krško in einer tektonisch und seismisch aktiven Zone liegt. Es bestätigt außerdem die Existenz von mehreren aktiven Störungen in der Nähe des Kraftwerks. Geologische Daten identifizieren die Orlica-, Artiče- und Libna-Störung sowie eine Überschiebung unter der Artiče-Falte als mögliche Erdbebenquellen. Eine korrekte Einschätzung der Aktivität dieser Störungen ist für eine verlässliche Einschätzung der Erdbebengefährdung von höchster Bedeutung. Unter den Expertinnen und Experten bestand größtenteils Einigkeit über die Existenz der Störungen. Ihre Aktivität wurde dagegen nicht einheitlich eingeschätzt. Letzteres wird auf das Fehlen von paläoseismologischen Daten zurückgeführt. Zahlreiche Expertinnen und Experten betonten daher die Wichtigkeit neuer Untersuchungen um zweifelsfrei feststellen zu können, ob diese Störungen aktiv sind und um verlässliche Daten über die Geometrie der Störungen, ihre Kinematik und Bewegungsgeschwindigkeit als Eingangswerte für eine Erdbebengefährdungsstudie zu gewinnen.

Aufgrund dieser Ergebnisse wird BMLFUW empfohlen, das Thema weiter zu verfolgen und in seiner Kommunikation mit slowenischen Institutionen zu betonen, dass:

- die Erdbebensicherheit von Krško von höchster Bedeutung ist
- eine neue und allgemein anerkannte Bewertung der Erdbebengefährdung von unabhängigen Expertinnen und Experten so bald wie möglich abgeschlossen werden sollte
- die Bewertung der Erdbebengefährdung auf verlässlichen paläoseismologischen Daten beruhen sollte
- eine Beobachtung der Datenerhebung und der Durchführung der Gefährdungsanalyse durch österreichische und internationale Expertinnen und Experten das Vertrauen in die Ergebnisse stärken würde
- die seismische Auslegungsgrundlage des Kernkraftwerks Krško so rasch wie möglich aktualisiert werden sollte.

² Die Vorbehalte österreichischer Experten werden im sogenannten "Issue Paper Slovenia" erläutert, das von BMLFUW 2015 veröffentlicht wurde (<https://www.bmlfuw.gv.at/umwelt/strahlen-atom/antiakwpolitik/euroatom-internat/stresstest.html>).

1 BACKGROUND AND WORKSHOP OBJECTIVES

Seismic hazards and the protection of nuclear installations against the effects of earthquakes are key issues of nuclear safety. This was clearly demonstrated by the Fukushima accident, the subsequent *Stress Tests performed on European Nuclear Power Plants* (ENSREG Stress Tests) performed by the EC in 2012, and the development of common European standards for hazard assessment and safety demands by the Western European Nuclear Regulator's Association (WENRA-RHWG) in 2014³.

In both, the Stress Tests and the development of new safety standards Austria was among the driving countries highlighting that the assessment of seismic hazards requires the application of the latest scientific and technical methodologies and that hazard assessments should be updated regularly. These Austrian positions are widely reflected in the Stress Tests report⁴ and the WENRA Safety Reference Levels which stipulate that nuclear power plants (NPPs) must resist earthquakes with an average return period of 10,000 years⁵, and that hazards and protective measures shall be re-evaluated as frequently as necessary, but at least every 10 years. The latter ensures that assessments account for the rapid advance of science and technology.

The assessment of seismic hazards for the NPP Krško has been a matter of almost permanent debate between Slovenia and Austria since Slovenia's independence. Discussions started in 1992 and 1993 when Austria was engaged in the international commission "*Independent Analysis of the Safety of the Nuclear Power Plant Krško – ICISA*" and continued after the implementation of the bilateral agreement on the exchange of information on nuclear issues („Nuklearinformationsabkommen“) in 1998. Since then seismic safety was regularly discussed at bilateral consultations and expert workshops.

In the past Slovenia has performed a number of geological and geophysical investigations to update the seismic hazard assessment for the NPP Krško including investigations in the PHARE-Program, which was supported by the European Commission. The Austrian request to perform state of the art paleoseismological investigations, however, has not been addressed.

Paleoseismological investigations are an important tool to assess rare strong earthquakes with long return periods⁶. Earthquakes with average return periods of 10,000 years which must be considered for nuclear safety cannot be assessed from historical records alone as historical earthquake data only cover few hundred years. It is therefore necessary to expand the historical observation period by paleoseismological methods which are able to provide data from pre-historic earthquakes which occurred up to several hundred thousand years ago.

³ WENRA-RHWG, 2014. WENRA Safety Reference Levels for Existing Reactors. Update in Relation to Lessons Learned from TEPCO Fukushima Dai-ichi Accident.
<http://www.wenra.org/publications/>

⁴ ENSREG, 2012. Compilation of recommendations and suggestions. Peer review of Stress Tests performed on European nuclear power plants. <http://www.ensreg.eu/node/512>

⁵ This corresponds to an occurrence probability of 10^{-4} per year or "the strongest earthquake that occurs once in 10,000 years".

⁶ The importance of paleoseismological methods for the site assessment of nuclear installations has recently be stressed by IAEA (2015).

Paleoseismological investigations were only initiated when EVU GEN-Energija started investigating a site for the construction of a possible new NPP adjacent to the existing power plant. The investigations were performed by an expert consortium which initially included the Slovenian Geological Survey (GeoZS), the French Geological Survey (BRGM) and the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN). The results of these investigations, which are highly relevant for the hazard assessment of the existing NPP, led to a controversial discussion between the members of the consortium which was made public via the web page of the Slovenian nuclear regulator SNSA.

At the 15th Bilateral Meeting between Austria and Slovenia in 2013 the Austrian side consequently asked the Slovenian counterpart for more information on this issue. At this time, however, the Slovenian regulator preferred not to interfere with the ongoing scientific discussion.

Having a keen interest in the safety of the NPP Krško, the Austrian Federal Ministry for Agriculture, Forestry, Environment and Water Management (BMLFUW) supported the initiative of the Province of Carinthia (Land Kärnten) and the Environment Agency Austria to organize a technical workshop on the seismicity and active tectonics in the surrounding of the Slovenian Nuclear Power Plant (NPP) at Krško. The purely technical meeting should provide an opportunity to follow up the continued scientific and technical discussion on the assessment of seismic hazards and the protection against such hazards of the NPP.

2 GEOLOGICAL BACKGROUND

The NPP Krško is located in a tectonically highly mobile belt between the Adriatic and European (Pannonian) plates where the collision of the two plates results in high seismicity (Fig. 1), relatively frequent strong earthquakes, and therefore high seismic hazard (Fig. 2). Examples are the earthquakes of Idrija 1511 (Magnitude $M=6.8$), Krško 1628 ($M=5.0$), Medvednica 1880 ($M=6.5$), Ljubljana 1895 ($M=6.1$), Medvednica 1905 ($M=5.6$), Medvednica 1906 ($M=6.1$), Brežice 1917 ($M=5.7$) and Bovec 1998 ($M=5.7$). Earthquakes are generated by the numerous active faults which compensate the Adriatic-European plate convergence.

Austrian institutions and scientists are particularly concerned about the recently discovered active faults in the site vicinity and near-region⁷ of Krško and their potential impact on the safety of the existing plant⁸. The Austrian concerns are mainly driven by the following findings:

- (1) Paleoseismological investigations performed for the siting of a possible new NPP near Krško included the excavation of paleoseismological trenches across the so-called Libna fault, which is located at a distance of only 1 to 5 km from the existing plant. Trenching indicated that the Libna fault is active and a “capable fault” in the sense of IAEA⁹. The paleoseismological evidences were heavily discussed among scientists from different countries and institutions. However, no agreement could be reached on whether the fault needs to be classified as capable or not. It must be noted that the identification of a capable fault in the site vicinity (less than 5 km distance) has severe consequences for the safety of a nuclear power plant¹⁰.
- (2) A probabilistic fault displacement analysis completed by RIZZO Assoc. in 2015 describes as many as 10 newly discovered active (“capable”) and potentially active faults in the near-region of the NPP (less than 25 km distance). The results have been published at an IAEA conference in Vienna (CLINE et al. 2015) and on the web page of the Slovenian Nuclear Safety Administration. A question of specific interest is whether the hazard contribution of these faults is reflected by previous seismic hazard assessments. It is questionable if the currently valid seismic design basis parameters envelope the associated hazard.
- (3) Analyses of the seismic robustness of the nuclear power plant at Krško performed during the European Stress Tests in 2012 showed that the plant has limited safety margins. This is due to the fact that the plant has originally

⁷ Site vicinity and near region: geographical area within a radius of 5 km and 25 km from the NPP site, respectively (IAEA 2010).

⁸ The concerns of Austrian experts are described in detail in the so-called Issue Paper Slovenia, which was prepared for and published by BMLFUW (<https://www.bmlfuw.gv.at/umwelt/strahlen-atom/antiakwpolitik/euroatom-intemat/stresstest.html>).

⁹ Capable fault: “A fault that has a significant potential for displacement at or near the ground surface.” (IAEA 2010, SSG 9, p.51).

¹⁰ “Where reliable evidence shows that there may be a capable fault with the potential to affect the safety of a plant at a site, the feasibility of design, construction and safe operation of a plant at this site should be re-evaluated and, if necessary, an alternative site should be considered.” (IAEA 2010, SSG 9, p. 31).

been designed for a hazard level¹¹ of a peak ground acceleration PGA=0.3 g. Repeated hazard re-assessments increased the hazard level from this initial design basis value to PGA=0.56 g as determined from the latest hazard assessment in 2004. Based on this very significant increase of the hazard level the ENSREG Stress Tests Country Report for Slovenia in 2012 suggested that *“The regulator should consider requesting to update the seismic design basis.”* Slovenia so far provided no conclusive information to the Austrian experts to show that this has been done and that adequate protection of the NPP for this hazard level is in place. In addition, a number of active faults have been identified in the vicinity of the Krško NPP since the hazard assessment in 2004 (see (1) and (2) above). The hazard contribution of these faults are consequently not included in the hazard assessment of 2004 raising severe doubts about the adequacy of the hazard level of 0.56 g and calling for a re-assessment of both, the seismic design basis and the adequacy of the seismic protection of the plant.

The technical meeting was scheduled as an international workshop to exchange scientific views on seismological and geological data and models in order to support the understanding of the seismic hazard of the Krško site. The workshop should discuss the information gained so far, by various scientists, on the active tectonics and seismicity of the Krško region.

The Environment Agency Austria and the Land Kärnten therefore invited 26 geoscientists from six countries (Slovenia, Croatia, Italy, France, USA and Austria) and 13 scientific institutions to discuss these issues. The scientists invited have been and partly still are involved in related scientific and technical projects.

Representatives of the federal and provincial governmental administrations of Austria participated as observers of the technical meeting.

¹¹ Hazard levels are expressed by peak ground acceleration values stated as fractions of the gravity acceleration of the Earth (1 g) for occurrence probabilities of 10⁻⁴ per year.

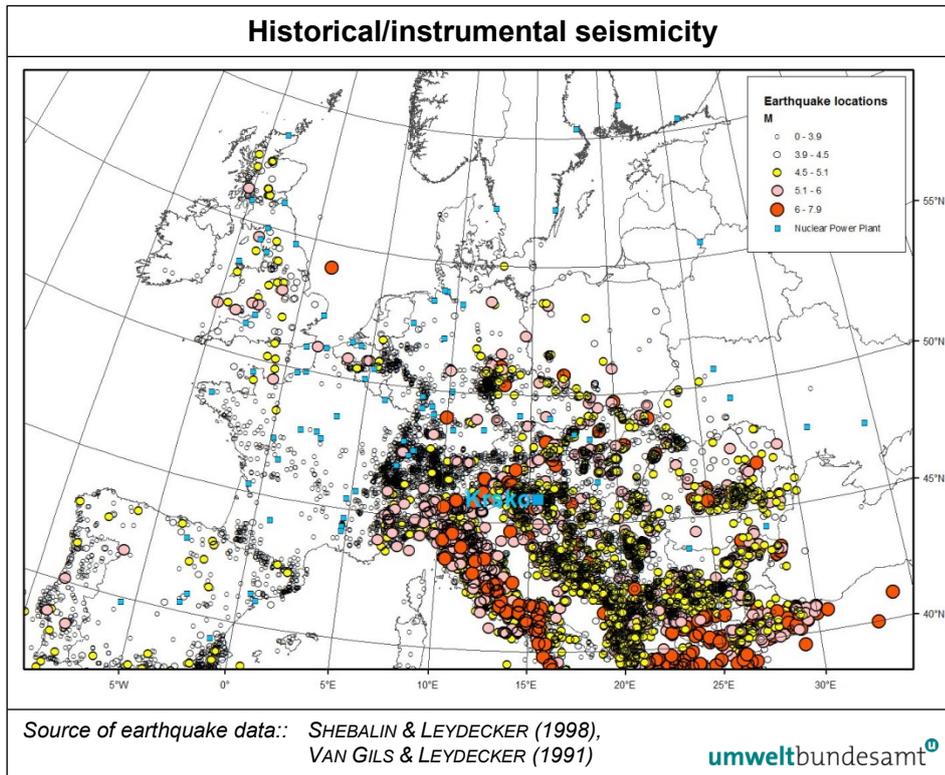


Fig. 1:
Historical/instrumental seismicity and the locations of Krško and other European NPPs.

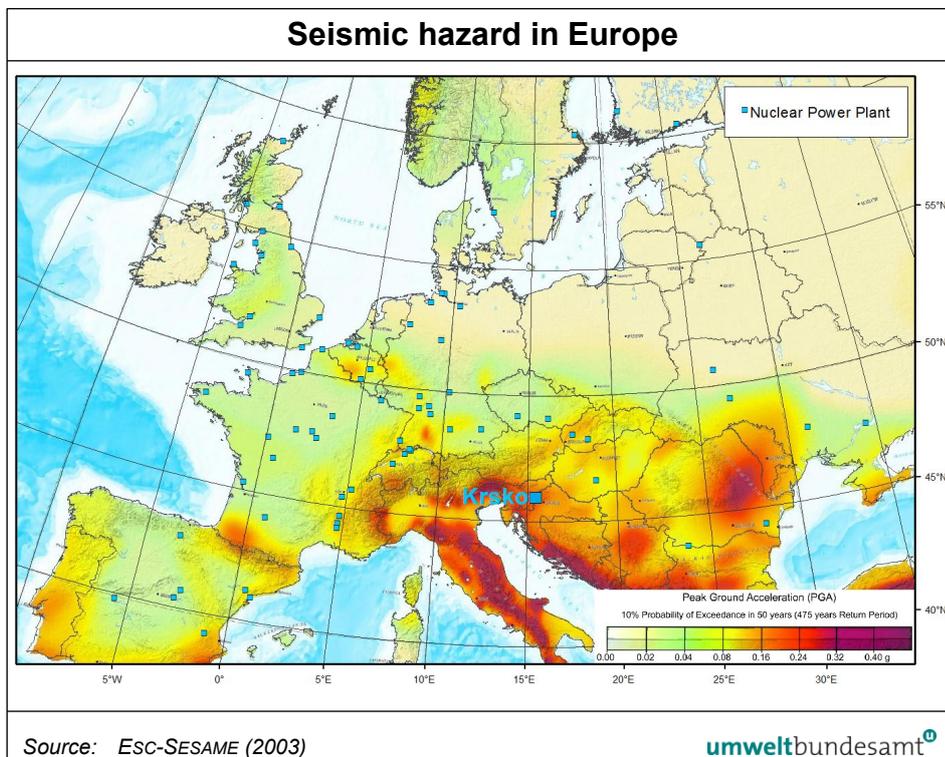


Fig. 2:
Seismic hazard in Europe and the locations of Krško and other European NPPs.

3 SUMMARY OF WORKSHOP CONTRIBUTIONS

To advance the mutual understanding of the different technical approaches and interpretations and to benefit from this enormous amount of combined expertise of the contributing scientists, all participants were asked to prepare presentations addressing their view on the active tectonics, site seismicity, and its effects on the safety of the NPP Krško. The following paragraphs include short outlines of the contents of these presentations. All outlines were reviewed by the authors¹².

Remarks printed in italic below the Outline of Contents contain explanations and assessments added by the author of this report. These comments solely reflect the opinion of the author of this report.

3.1 Marko Vrabec (University of Ljubljana)

Active tectonics at the Alps – Dinarides junction: Current data and ideas, and possible implications for the Krško site

Outline of contents: During his talk Marko Vrabec summarized the current plate tectonic boundary conditions in the region under consideration and provided insight into a regional seismotectonic model of the Slovenian territory. Active tectonics and seismicity in the region are driven by the convergence between the Adriatic Plate and stable Europe which amounts to about 3.5 mm/yr. GPS and geological data prove that fault slip rates of many of the major faults in the area exceed 1 mm/year (Periadriatic-, Lavanttal-, Idrija-, Sava-, and Vodice Fault). Robust GPS data also indicate that 1 mm/year of NNW-SSE shorting is accommodated across the Sava Folds in the geographic region around Krško. The presentation further described in great detail the advanced seismotectonic models which are available for the Sava fault system, the Sava folds, the Ljubljana basin, and the Idrija fault system.

3.2 Petra Jamšek Rupnik (Geological Survey of Slovenia GeoSZ)

Database of active faults in Slovenia

Outline of contents: The presentation informed about the ongoing activities to collect a comprehensive database of active faults in Slovenia as a basis for the re-evaluation of seismic hazard on the national scale. Previous hazard assessments are regarded insufficient as they are exclusively based on earthquake data. Hazard re-assessments are regarded crucial at the background of the seismicity in Slovenia with several strong historical earthquakes affecting the area (Idrija 1511, M=6.8; Villach 1348, M=6.4; Ljubljana 1895, M=6.1; Villach

¹² except Marko Vrabec

1690, M=5.9; Brežice 1917, M=5.7; Bovec 1998, M=5.7). Most of these earthquakes were generated by large or fault systems that generally do not extend into the site near-region of Krško (i.e. Idrija fault, Ravne fault, and the Periadriatic fault system).

The new parameterized fault database should include all currently known active and potentially active (Quaternary) faults which are longer than 5 km. Fault parameters considered in the database include slip rate, fault orientation, fault kinematics, fault dimensions and maximum earthquake magnitudes (estimated from fault dimensions) which are said to reach up to $M_{max}=7.6$ for multi-segment ruptures breaking the entire length of the Sava or Idrija fault (such events are regarded very unlikely) and $M_{max}=7$ for single-segment ruptures.

Remarks: *The version of the map of active and potentially active faults shown in the presentation included four faults (five fault segments) in the near-region of Krško (less than 25 km distance) with estimated slip rates of up to about 0.1 mm/year and maximum magnitudes reaching up to about $M_{max}=7$.*

3.3 Stephane Baize (IRSN)

Active Tectonics in the Krško Region and IRSN perspectives

Outline of contents: In the first part of his presentation Stephane Baize presented a concise and credible kinematic and seismotectonic model of the Krško Region highlighting the importance of the Orlica- and Artiče faults, which are located at very close distances to the NPP. According to the model which was proposed the consortium gathering IRSN, BRGM and GeoZS, the two sinistral faults are linked via a restraining bend forming the Artiče flexure. Evidence for the current uplift with a rate of about 1.7 mm/year is provided by geomorphological data and uplifted fluvial sediments. The surface flexure is related to a blind fault at depth which strikes towards the site of the Krško NPP and may continue into the Libna fold. In this tectonic scenario the Libna fault may be regarded as a small dextral tear fault at the termination of Artiče flexure which delimits two parts of the Libna fold. The Orlica-, Artiče- and the blind fault are regarded as the main seismotectonic structures in the near-region of Krško and were used to update previous seismogenic source models for the assessment of vibratory ground motion hazards (geometry, M_{max} , slip rates). The updated model formed the basis of a hazard assessment completed in 2010 (GG&S Report 2010). The results of this report are not public.

The second part of the presentation summarized the consortium's (IRSN, BRGM, GeoZS) conclusions 2011 on the paleoseismological trenching of the Libna fault, which is located at close distance to the NPP. Trenching revealed clear evidence for faulting of sediments which are younger than 200,000 years¹³. Physical age dating is confirmed by the finding of a human artefact (Mousterian tool). Trench data provide evidence for Pleistocene and even Holocene strike-slip faulting as fault planes include Holocene soil. Reopening of the fault plane must therefore have happened in the Holocene. These observations may be in-

¹³ Faults offsetting such young sediments are termed "capable" according to IAEA (2010).

dicative for coseismic and recurrent displacements. The Libna fault should consequently be considered capable in line with the definition by IAEA (2010). The interpretation was validated by expert consulting by Daniela Pantosti (INGV) who confirmed that fault slip was triggered either by tectonic reactivation of the fault or by ground shaking induced by an earthquake which occurred at another nearby fault. According to Stephane Baize and the other members of the geological team of the 2011 Consortium the observations in the Libna trenches cannot be explained by landsliding.

Remarks: *IRSN was actively involved in the assessment of potentially capable faults in the Krško area between 2007 and 2012. At this time the Institute was part of an expert consortium together with BRGM, ARSO and GeoZS. Work in the consortium ended due to a disagreement with GEN Energija on the necessity to acquire new data. The acquisition of additional geological data was regarded necessary by IRSN.*

The presentation stressed the importance of the Orlica- and Artiče faults and the blind fault below the Artiče flexure for the assessment of seismic hazards. It further concluded that trenching of the Libna fault provided strong indications for repeated fault slip in the last 200,000 years and in the Holocene (<14,000 years). This interpretation is not shared anymore by the Slovenian Geological Survey and Rizzo Assoc. who after 2012 question the reliability of age dating (although physical age dating is confirmed by different methods and the finding of human artefacts) and relate the surface displacement observed in the trench to landsliding although the observed fault geometries are apparently not in line with such an interpretation.

3.4 Miloš Bavec (Geological Survey of Slovenia GeoZS)

Seismotectonic characteristics of the Krško Basin in light of past and ongoing geologic investigations

Outline of contents: Miloš Bavec, geologist at the Geological Survey of Slovenia and manager of the recent geologic project in Krško for GeoZS, summarizes the contents of previous and on-going geological and geophysical investigations in the Krško basin and its surrounding. Past and current efforts include the acquisition of 2D reflection seismic, shallow geophysics, geological mapping and the analysis of earthquake data. Analyses further comprise the interpretation of high-resolution digital elevation models (LiDAR-data) with quantitative geomorphological techniques to identify active faults by lineament analyses, analyses of mountain-front sinuosity, channel sinuosity, stream profiles and drainage basin morphology. Earthquake records are shown to be of limited use for identifying active faults. Seismicity is scattered and only three faults can reasonably be associated with earthquake clusters. Analyses highlight the importance of NE-SW striking sinistral strike-slip faults.

Miloš Bavec further explains that four different seismic source zone models were used for a seismic hazard assessment performed in 2010 (GG&S Report 2010). Accordingly, Model A used in this study consists of four seismic zones (Dinarides, Sava, two sub-zones of the Mid Hungarian Zone [MHZ]), Model B comprises of three zones (Dinarides, Sava, MHZ), Model C includes two zones

(Dinarides, Sava including MHZ), and Model CRO is seismicity-focused and not structurally defined. A fault specific model of seismic sources (with a background seismicity zone) was also elaborated and used in calculation as one of the alternatives. He further informs that a novel probabilistic seismic hazard assessment (PSHA) shall be initiated for the NPP Krško.

Remarks: *The NE-SW striking sinistral strike-slip faults mentioned in the presentation correspond to the Orlica- and Artiče fault highlighted in the presentation by Stephane Baize. The cited seismic hazard study (GG&S Report 2010) is not public.*

3.5 K. Michel Cline, M. Logan Cline (RZZO Assoc.)

Probabilistic fault displacement hazard analysis – Krško NPP 2 sites – Slovenia

Outline of contents: The authors report on the outcome of a probabilistic fault displacement analysis (PFDHA) which was performed as part of the evaluation of two sites to support decision making by the utility and regulator regarding the safety of the site for the construction of a possible new NPP (“Krško 2”) adjacent to the existing plant. The approach used follows that of Petersen et al. (2011), with considers both on fault and off fault displacement for all faults considered in the analysis. 11 faults with assessed probabilities of being active between $P=0.3$ and $P=1$ were considered for the analysis [*Remark: Probability $P=1$ is assigned to proven active faults*]. The mean annual probability of exceeding 0.1 – 50 cm of surface displacement within a 200 x 200 m area at each site was calculated. The study procedure came to the conclusion that displacements between 5 and 10 cm (such displacements are generally considered by nuclear engineers to be significant for an NPP) are extremely unlikely with mean annual frequencies of exceedance less than 10^{-8} to 10^{-9} .

Remarks: *The study by Rizzo Assoc. exclusively addresses the hazard of surface displacement, the hazard of vibratory ground shaking is not considered. Rizzo’s study was reviewed by the independent experts L. Serva, C. Costantino and A. Gürpınar who state that: “A PSHA [for ground shaking hazards] study was recently completed for the KRŠKO site and a new study is currently being conducted. There are many common input parameters between the PSHA and PFDHA [for fault displacement hazards] related to fault characteristics, recurrence values, etc. The consistency of these studies need to be checked and differences (if any) need to be appropriately justified.” Seismic hazard assessment for the existing NPP must therefore properly account for the finding of these active faults.*

In his presentation M. Cline, however, stressed that the performed study assumed capable faults in the near region of the site rather than confirming them. It was explained that this more conservative approach was used because the analysis focused on site suitability and not on design purposes. This raises the question why very conservative assumptions should be made for the capable fault analysis (PFDHA) while much less conservative assumptions should be admissible for the analysis of vibratory ground motion hazards (PSHA).

3.6 Wolfgang Lenhardt (ZAMG Vienna)

Cross-border monitoring of seismic activity

Outline of contents: The author reports on the coverage of the Austrian seismic network, its linkage with the seismic observation networks in Austria's neighbouring countries, and data exchange with these countries. The presentation provides insight into the detection threshold of the network in Austria.

3.7 Marijan Herak, Davorka Herak, Bruno Tomljenović (University of Zagreb)

Seismicity and Neotectonics in the Greater Zagreb Area

Outline of contents: In the first part of the presentation Marijan Herak informs about the seismicity in the Croatian territory east of the NPP Krško. Historical earthquakes in the area reach up to about $M=6$. A significant effort was undertaken to relocate earthquakes which occurred between 2004 and 2014. The results revealed new and more reliable hypocenter depth distributions showing that all earthquakes occurred in the upper crust. First arrival analyses (fault plane solutions) show N- or S-dipping thrust faults (in particular in the area between the Slovenian border and the Medvednica Mountain) and NW-striking dextral strike-slip faults as seismic sources. Normal faulting is not observed. Shortening directions are uniformly oriented N-S. Gutenberg-Richter analyses for the greater Medvednica Mountain area indicate that one $M=6$ earthquake occurs about every 500 years. The hazard contribution from this area for Krško is $PGA=0.10$ g and $PGA=0.28$ g for the return periods of 475 years and 10,000 years, respectively. *[Remark: It is understood that this would be the hazard at the Krško site if no other seismic sources were considered.]*

In the second part Bruno Tomljenović discusses the active tectonics of the Medvednica Mountains and the greater Zagreb area. He shows that the main structural elements of the Krško basin, the ENE-WSW trending Krško syncline and the Orlica-Artiče uplift, extend to ENE into Croatia. Seismic and geological data show that the Medvednica Mountains are thrust towards the N over a syncline filled with Pliocene and Quaternary sediments. The location of the thrust coincides with the relocated hypocenters of earthquakes which occurred between 12 and 5 km depths. The fault surface of the Medvednica thrust is estimated with 300 km².

Remarks: *The Medvednica thrust is located at a distance between 26 and 32 km from the Krško site. The fault surface of 300 km² suggests that the fault is capable of producing earthquakes up to magnitude $M_{max}=6.6$. It appears that previous seismic hazard analyses for the Krško site did not consider the fault as a seismic source.*

3.8 Mladen Živčič (Slovenian Environment Agency)

Seismicity of the Krško region

Outline of contents: The presentation provides information on the history of the earthquake observation network in Slovenia. Accordingly, systematic earthquake records were made in the time between 1895 (starting after the Ljubljana earthquake) and 1918. Between 1918 and 1958 data were collected only sporadically. Seismic stations were established as follows: Ljubljana 1897 – 1918 (no records preserved); Zagreb from 1906 onwards; re-establishment of a seismograph in Ljubljana in 1958; installation of seismographs at Cernica 1973, Vojsko 1984, and Bojanci 1986. After the 1989 Krško earthquakes (28. December, $M=3.6$; 30. December, $M=2.6$, epicenter next to the NPP) seven additional stations were installed between 1990 and 2003. Stations were supplemented by the accelerometric network NEK II in 2008. The completeness of earthquake records was said to be very poor for the time interval between 1918 and about 1960. Completeness increased slowly from 1963. The strongest pre-instrumental earthquakes in Slovenia occurred in NW Slovenia 1511 (Intensity $I=X$), Krško 1628 ($I=VII$), Carniola 1632 and 1640 ($I=VII$ and $I=VI-VII$), Medvednica 1880 ($I=VIII$), and Brežice 1917 and 1928 ($I=VIII$ and $I=VII$). The currently used earthquake catalogue is the NEK 2015 catalogue covering an area of 200 km perimeter around Krško and Friuli. The catalogue is harmonized using moment magnitude and lists events with $M_w > 3.5$. However, most of the original data is based on macroseismic intensity.

The strongest recorded earthquake in the Krško area occurred on 29. January 1917 ($M_w=5.0$, $MLH=5.7$, $I_0=VIII$). It was analysed by a commission of the K&K Academy of Sciences.

Fault plane solutions from recent earthquakes around Krško include thrust faults (N- and S-dipping thrusts) and strike-slip faults (NW-striking dextral and NE-striking sinistral faults). P-axes and shortening directions inferred from the fault plane solutions are oriented mostly N-S.

Remarks: *The presentation provided detailed information on the completeness of earthquake observations in Slovenia showing that instrumental earthquake records are complete for 50 years at the best. Such short data records limit the reliability of seismic hazard assessments for long recurrence intervals¹⁴ very significantly as it is not allowable to extrapolate statistics over several orders of magnitude (i.e., from 50 to more than 10,000 years). It is further concluded that the accuracy of hypocentre determination is insufficient for seismotectonic interpretation and that large uncertainties exist with respect to the determination of the magnitudes of strong historical earthquakes. The insufficiency of the earthquake data stresses the need of accurate geological and paleoseismological data as input for the seismic hazard assessment.*

¹⁴ "For nuclear installations the exceedance frequencies of design basis events shall be not higher than 10^{-4} per annum" (WENRA 2014).

3.9 Esther Hintersberger (University Vienna)

Estimating paleo-earthquake parameters from multiple trench observations

Outline of contents: An important aspect of fault characterisation for seismic hazard assessment are the parameters of pre-historical earthquakes derived from paleoseismological trenching. Especially in regions with low or moderate seismicity, paleomagnitudes are normally much larger than those of historical earthquakes and therefore provide essential information about the seismic potential and expected maximum magnitudes of a certain region. The presentation introduced a novel method for deriving seismological parameters of paleo-earthquakes based on a probabilistic approach combining observations in several trenches across the same fault to better constrain the possible range of parameters such as earthquake magnitude. The contribution further showed that by combining several observations, the associated uncertainty for the magnitude of a paleoearthquake decreases rapidly, seemingly with a minimum of 4 to 6 observation points to obtain highly reliable results. Tests of the method with data from earthquakes with known magnitude and surface displacement reproduced magnitudes which are promisingly close to the instrumentally determined magnitude. Therefore, the approach is a suitable method to combine observations from different locations to derive paleo-earthquake parameter values accounting for the natural variances of observed along-strike surface displacement.

Remarks: *The presentation showed that the uncertainties of paleoseismological interpretations made in single trenches can be reduced very significantly by using data from multiple trenches. The approach is particularly suitable to reduce the uncertainties of the assessment of the Libna fault near Krško.*

3.10 Vanja Kastelic (INGV Roma)

Contribution of active fault and geodynamic data to seismic hazard assessment

Outline of contents: In her presentation Vanja Kastelic introduced methods for physical models-based seismic hazard studies in which predictions of the future seismicity are mainly or exclusively based on active fault and geodynamic data instead of historical/instrumental earthquake observations. The approach uses fault properties (dimension, orientation, kinematics and slip rate) to derive seismic moment rates. Earthquake rates for single faults or fault elements are subsequently computed using the SHIFT hypothesis (Bird and Liu 2007). The method was applied to three of the active faults identified in the vicinity of the NPP Krško, the Hrastnik-, Orlica- and Libna fault, using the fault parameters published by CLINE et al (2015). The results show the importance of good knowledge of fault geometry and even more so of the fault slip rates, as with just considering the used data, the expected number earthquakes for different magnitude varies significantly. Mrs. Kastelic also pointed out the need of developing self-consistent active fault models (considering 3D fault geometries) and that care is needed when estimating fault slip rates from surface data as the results may also be influenced by non-tectonic processes.

In general, the results of the study indicate that strong earthquakes ($M=6$ and higher) are expected to occur on the studied faults at time intervals of several hundred to few thousand years only. The purely physics-based predictions were validated by the historical and instrumental earthquake record. Vanja Kastelic concluded that active fault and geodynamic data are a valid input for probabilistic seismic hazard analysis (PSHA). For this purpose, it is of key importance to have good knowledge of fault geometry, kinematics, and slip rates.

Remarks: *The contribution introduced a novel physics-based approach of seismic hazard assessment and applied the methodology to estimate the expected number of future earthquakes and their related recurrence periods for the Hrastnik-, Orlica- and Libna fault near Krško. The estimate revealed that, based on the currently known fault data, severe earthquakes with $M>6$ are expected to occur in intervals of centuries to few thousand years. If proven by additional investigations such earthquake recurrence intervals would be highly relevant for the seismic hazard of Krško. Future active fault investigation should consider this fact and strive for a good knowledge of active faults as this data is of key importance for a reliable physics-based seismic hazard model.*

3.11 Livio Sirovich, Franco Pettenati (Università di Trieste), Giovanni Costa, Peter Suhadolc (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, O.G.S)

Questions and doubts on the seismic hazard of the Krško NPP site

Outline of contents: In their presentation the authors highlighted the need for a comprehensive seismic hazard assessment for the site. To support their viewpoint they cited a publicly available document of IRSN saying that IRSN considers “the Libna capable fault ... in the vicinity of the existing Krško I plant site ... as well as its potential structural relationship to nearby faults ...” of utmost importance for the safety of the existing plant.

The presentation showed that the site is located in a seismically active region with the 1917 Brežice earthquake as the strongest known historical event. For this earthquake different earthquake catalogues (Ribarič 1982, Grünthal & Wahlström 2012) list magnitudes ranging from $M_w=5.7$ to 6.2. However, this earthquake was either not included in a seismicity dataset which has been presented to the Slovenian Nuclear Safety Administration by GEN energija, or it was included with a too low magnitude¹⁵. They also noted that the earthquake has not been investigated with up-to-date methodology (e.g., intensity-based source inversions to identify the ruptured fault), and that an $M_l=4.2$ earthquake occurred on 01. November 2015 in the same area (c. 10 km from Krško).

In the last part of their presentation Livio Sirovich and his co-authors stressed the importance to seismic hazard of the Orlica-, Artiče- and Libna faults in the vicinity of the Krško plant. In the discussion about the tectonic significance of

¹⁵ This is shown by close inspection of a seismicity map included in a presentation by GEN energija to the Slovenian Nuclear Safety Administration (SNSA) in January 2015. The presentation was published on the SNSA web page.

the observations made in the paleoseismological trench across the Libna fault they expressed strong doubts on interpreting the excavated Quaternary faults as the results of landsliding. They substantiated their doubts by the analysis of LIDAR-derived digital elevation data. Although this data confirms the existence of mass movements on the Libna hill, the direction of the landslide seems hardly compatible with the kinematics of the fault.

4 CONCLUSIONS

During the workshop it appeared that a common view of the experts exists on the seismotectonic boundary conditions of the Krško region¹⁶. Convergence across the geographic area under consideration is significant. GPS derived velocity fields suggests about 3 to 3.5 mm/year convergence between the Adriatic plate and stable Europe (M. Vrabec). Out of this general convergence about ~1 mm/year of N-S-directed shortening is currently accommodated by seismotectonic processes across the Sava Folds area (i.e., the region around Krško; M. Vrabec). N-S-directed compression causes seismic slip on NE-striking sinistral strike-slip faults, NW-striking strike-slip dextral faults, and N- or S-dipping thrust faults (M. Vrabec, B. Tomljenović, M. Živčić, V. Kastelic).

The most important faults in the region around Krško belong to these fault systems. Faults important for hazard assessment include the NE-striking Orlica and Artiče faults (M. Cline, S. Baize), which may be linked via a restraining bend and a blind thrust fault below the Artiče flexure (S. Baize), the NW-striking Libna fault, the NW-striking Hrastnik fault (V. Kastelic) and the Medvednica thrust (B. Tomljenović). It appeared that all experts generally agreed on the existence of these faults. All faults are located at close distances to the NPP site. Slip velocities of the faults are estimated to be in the order of magnitude of 0.1 mm/year (P. Jamšek Rupnik, M. Cline). Based on the dimensions of these faults maximum earthquake magnitudes of up to about $M_{max}=7$ may be expected (P. Jamšek Rupnik, M. Cline). Faults in the near-region of Krško are included in the database of active faults in Slovenia (except for the Libna fault; P. Jamšek Rupnik).

Dedicated paleoseismological studies were only presented for the Libna fault. According to the presentation by S. Baize paleoseismological trenching revealed evidence for a dextral strike-slip fault which was repeatedly active in the last 200.000 years. This interpretation of the trenching results was originally agreed by all members of the Consortium which included GeoZS (M. Bavec), BRGM and IRSN (S. Baize) in 2011 – 2012. The results were described in a common report.

After 2012, however, some experts (M. Bavec, M. Cline) did not further support the interpretation by the Consortium arguing that dating of the fault slip events is uncertain and the deformations observed in the trenches could be due to landsliding or other mass wasting processes. Paleoseismological investigations from other faults (Orlica, Artiče, Hrastnik etc.) have not been presented and it appeared that such investigations do not exist. During the workshop information was obtained that additional studies including a new PSHA are planned (M. Bavec, M. Cline).

During the discussion K. Decker and E. Hintersberger pointed out that the current paleoseismological information is not satisfactory due to the large uncertainties in the interpretation of the Libna fault and the lack of data from other faults. They argued that propagating the uncertainties of the interpretation of the Libna fault through a full-scope probabilistic seismic hazard assessment would likely lead to very large uncertainties of the resulting ground motion values. It should therefore be considered to acquire additional data and open more

¹⁶ Conclusions were reviewed by all contributing authors except Marko Vrabec.

trenches in order to arrive at a commonly accepted interpretation of the Libna fault. Paleoseismological investigations should be extended to other important faults such as the Orlica-, Artiče-, and Hrastnik fault. The acquisition of additional data has previously also been proposed by IRSN (S. Baize).

The importance of reliable fault data for probabilistic seismic hazard assessment was also stressed in the presentation of V. Kastelic. She pointed out that seismic hazard studies based on physical active fault models and geodynamic data enable predictions of the future seismicity. The major advantage of the approach is that it is widely independent from inaccurate or incomplete historical and instrumental earthquake records. This aspect of physical based hazard studies appears important given the short and incomplete earthquake records which are available from the area. For the Slovenian territory complete instrumental earthquake records are only available for about the last 50 years, and both locations and magnitudes of significant historical earthquakes are affected by large uncertainties (M. Herak, M. Živčič).

During the general discussion information was obtained that a new probabilistic hazard assessment for the site of the NPP Krško should be performed in the near future.

5 PARTICIPANTS

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6 WORKSHOP PROGRAM

09:30 **Andreas Molin, Rolf Holub (BMLFUW and Land Kärnten):** Opening of the Workshop

Kurt Decker (University Vienna): Introductory remarks - An Austrian perspective on seismic hazard, design basis values and seismic margins of the Krško NPP

Marko Vrabec (University of Ljubljana): Active tectonics at the Alps-Dinarides junction - Current data and ideas

Petra Jamšek Rupnik (Geological Survey of Slovenia): The Slovenian Active Fault Database

Stéphane Baize (IRSN): The potential for surface rupturing - the IRSN perspective

Miloš Bavec (Geological Survey of Slovenia): Seismotectonic characteristics of the Krško Basin in light of past and ongoing geologic investigations

M. Logan Cline, K. Michel Cline (RZZO Assoc.): Probabilistic fault displacement analysis for the Krško site

Wolfgang Lenhardt (ZAMG Vienna): Cross-border monitoring of seismic activity

Marijan Herak, Davorka Herak, Bruno Tomljenović (University of Zagreb): Seismicity and Neotectonics in the Greater Zagreb Area

Mladen Živčić (Slovenian Environment Agency): Seismicity of the Krško region

Livio Sirovich, Giovanni Costa, Franco Pettenati, Peter Suhadolc (University of Trieste): Questions and doubts on the seismic hazard of the Krško NPP site

Esther Hintersberger (University Vienna): Estimating paleo-earthquake parameters from multiple trench observations

Vanja Kastelic (INGV Roma): Contribution of active fault and geodynamic data to seismic hazard assessment

17:30 End of the workshop, transfer to hotels and social event

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