Opinion

On the Seismic Hazard Regulations for NPP Sites in Europe: A Controversial Case in Slovenia

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Introduction

Unlike the United States, Europe lacks mandatory rules for the siting of all nuclear power plants (NPPs) and a regulatory body to monitor, for example, the technical quality of seismic hazard studies and to authorize the continuation of the activity of an existing NPP or permit a new construction. This situation stems from the same founding act of the European Union (EU).

We attract the reader's attention to seismic hazard studies of NPP sites in the EU and on some consequences of the lack of mandatory rules. The cases studied include the Krško-1 NPP and the planned, adjacent, Krško-2 plant, both in an area with medium–high seismicity in Slovenia.

The 2020 update of the European Seismic Hazard Model by Danciu *et al.* (2021, 2024) made the hazard curves available for a point 5 km southwest of the NPP (see Fig. 1a). The NPP is located just inside one of the areas of Slovenia with the maximum hazard (0.8*g* < PGA < 0.9*g* with an exceedance probability of 0.01 in 50 yr; Fig. 1b). From the hazard curve, we can determine how the peak ground accelerations (PGAs) obviously increase as the probabilities decrease toward values today considered adequate for an existing NPP (0.005 in 50 yr according to Western European Nuclear Regulators Association [WENRA], 2021); even more stringent safety expectations apply to newly built plants (WENRA, 2013). The stress tests on Krško-1 (SNSA, 2011) predict possible accidents above a PGA of 0.8*g* (see subsequent paragraphs).

The site of Krško was chosen at the end of the 1960s, when the former Yugoslavia did not even have a seismic network. There were no probabilistic seismic-hazard analysis (PSHA) studies, nor were they performed for the new NPP. After independence (1991), wanting to close the plant, the first Slovenian government asked the National Institute of Italy for Oceanography and Experimental Geophysics (OGS) for scientific support, which appointed one of the authors (L. S.) as an OGS researcher.

Since the Maastricht Treaty of 1992 leaves the member states free to self-regulate in the matter, the role of the International Atomic Energy Agency (IAEA) remained that of its 1956 statute both for old and new NPPs: "to establish or adopt standards of safety […] that States can apply [but they] are not legally binding on Member States" (IAEA Safety Standards, 2022; pp. 2, 7, 9).

Writers have been dealing with the hazard of Krško for approximately 15 yr (Sirovich, 2012; Sirovich *et al.*, 2012, 2014) and had the opportunity to present the situation to the Italian Senate (see Data and Resources) and to the European Parliament. In Italy, various representatives have questioned the government on the subject, always receiving essentially the same answer, such as "[…] According to the Slovenian Agency for Nuclear Safety, stress tests confirm that the Krško power plant is among the safest in Europe." In 2015, the European Nuclear Safety Regulators Group (ENSREG) wrote that "the assessments found that the safety standards of nuclear power plants in Europe were generally high" (ENSREG, 2015; p. 1). However, when the EU was specifically questioned on the Krško plant, the competent Commissioner provided a much less reassuring assessment: "The stress tests carried out in 2011–2012 […] demonstrated that the seismic safety margins of the Krško power plant were sufficient" (European Parliament, 2016). Note the shift in language: from "among the safest in Europe" to "sufficient." The Krško problem is known in Brussels but has had no follow-up actions.

In the 1970s, the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.60 was chosen for the earthquake resistance design of Krško-1 (PGA = 0.3*g* to anchor the "Newmark/Hall" design spectra). Subsequent regulations required higher values. Now, as shown in Figure 1a, a PGA of 0.3*g* corresponds to a probability of almost 1 in 50 yr, a hazard level considered inadequate even for simple residential buildings. It was known that on 9 January 1917 a destructive earthquake of magnitude ~6 caused a macroseismic intensity VIII close to Krško, but almost nothing was known about seismogenic sources or capable faults (*sensu* IAEA Safety Standards, 2022) in the region.

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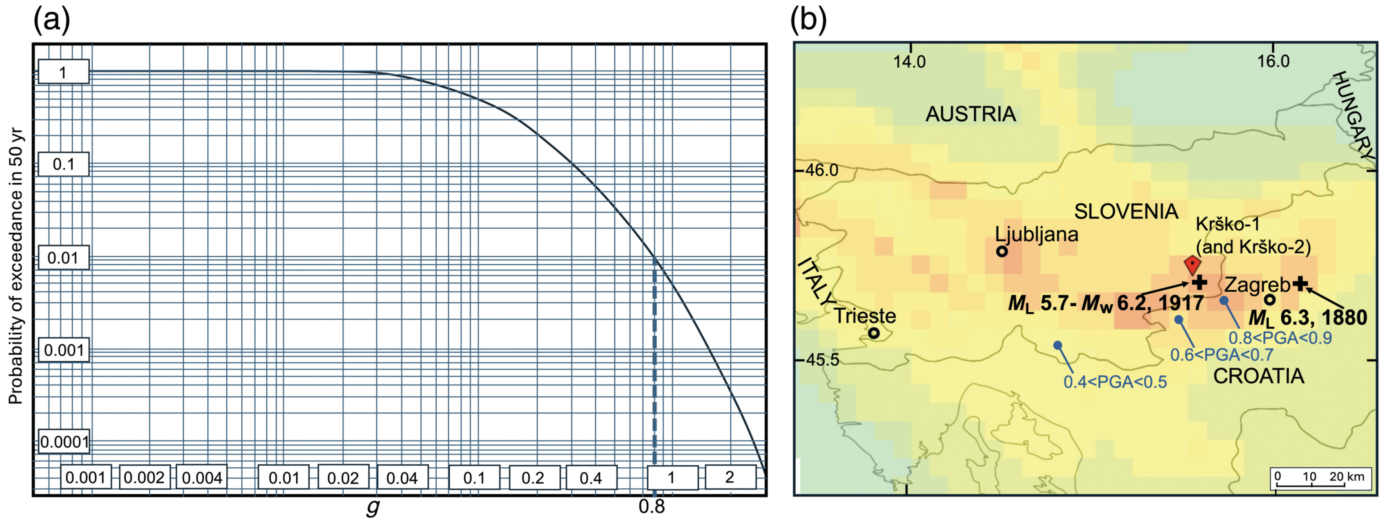

Figure 1. (a) Hazard curve of point (15.482° E; 45.900° N), 5 km southwest of the Krško nuclear power plant (NPP), from the 2020 update of the European Seismic Hazard Model (Copyright © 2020, ETH Zürich, produced under the Creative Commons Attribution 4.0 International License, CC BY; Danciu *et al.*, 2021, 2024; redrawn). (b) Peak ground acceleration (PGA; 5000-yr return period) from the 2020 update of the European Seismic Hazard Model (Danciu *et al.*, 2021, 2024, partim; Copyright © 2020, ETH Zürich, produced under the Creative Commons Attribution 4.0 International License, CC BY; redrawn; downloaded in August 2024, labels added). The lower vertex of the red symbol shows the Krško site; bold crosses: epicenters of the 1880 M_L 6.3 earthquake (Herak *et al.*, 2009) and of the 1917 M_L 5.7 (Ribarič, 1982)–M_w 6.2 (Grünthal *et al.*, 2013) earthquake; blue numbers guide you to the color legend (captions added).

The following points are discussed in this Letter: (1) the choice by the Slovenian Environmental Agency ARSO (for GEN Energija, see later) of macroseismic magnitude M_m for the 1917 earthquake instead of the local magnitude M_L, because here $M_m \ll M_L$; (2) the statement that a PGA of double 0.3g had been assumed for Krško-1 in the 1970s; and (3) the importance of capable and active faults for hazard assessment.

Magnitude of the 1917 Earthquake

Before the choice of the Krško site for the planned Krško-2 NPP, the 1917 earthquake was given a magnitude of 5.7–6.2 (e.g., M_L in Karnik, 1968, surface-wave magnitude MLH in Ribarič, 1982; moment magnitude M_w 6.2 in Grünthal *et al.*, 2013), which are disconcerting values for a nuclear site. In Grünthal *et al.* (2013), we read that the M_w 6.2 value for the 1917 earthquake was provided by ARSO to the Share European Earthquake Catalogue (SHEEC; Živćić, 1993).

However, once the Krško-2 project started, two M_m values (4.9 and 5.0) were proposed by an NPP consultant (Baumont, 2010a,b) and by a Slovenian researcher of ARSO (Cecić, 2018). Furthermore, the existence of Baumont (2010a,b) and the secrecy surrounding it came out only during the Klagenfurt international workshop on Krško, in which GEN Energija, owner of the NPP, participated (Decker, 2017; p.19). In fact, when the A.D. 567 to 2013 catalog, prepared for the new PSHA studies, was presented—and it was noticed that the 1917 M ~6 was missing from the shown map of epicenters—the speaker (M. Živčić, of ARSO, the same researcher who provided the M_w data to the SHEEC catalog) explained that "M 4.9 had been used for the 1917 earthquake, from a Baumont restricted report" (it was not specified what type of magnitude it was; ed.). It later turned out that Baumont used only macroseismic data (see Discussion and Conclusions).

At the time, the map of the epicenters of the 567 A.D. 2013 catalog could be downloaded from the ARSO website and later from a Slovenian government website (see Data and Resources), but today all the documents have been removed, and we do not have permission to show the figure. Therefore, we use SHEEC 1900–2006 (Grünthal *et al.*, 2013) at least for a partial comparison. As shown in Figure 2, (1) the Krško site is located within the most seismically active area of the region (in accordance with Fig. 1b), and (2) the downgrading of the magnitude of the 1917 earthquake to M_m 4.9 (according to Baumont, 2010a,b) eliminated the strongest historical earthquake in the region (see the blue circle).

Afterward, a book chapter (in Slovenian) appeared (Cecić, 2018), which seemed to confirm Baumont (2010a,b); in fact, M_m 5 was calculated from the average radii of the isoseismals using unpublished and unavailable formulas. However, this calculation was performed after having decreased most of the 140 intensities reported in Croatia by "half degree or by whole degree, and sometimes more" (Cecić, 2018, p. 177). Our general opinion is that, when a magnitude calculated from instrumental measurements is available, it should be preferred to the magnitude obtained only from macroseismic intensity values. We kept this opinion even when we proposed an innovative technique for estimating magnitudes through geophysical inversion of intensities (and magnitude has proven to be one of the most stable parameters obtained; Gentile *et al.*, 2004; p. 1747). Note that in a recent article Cecić herself did not even

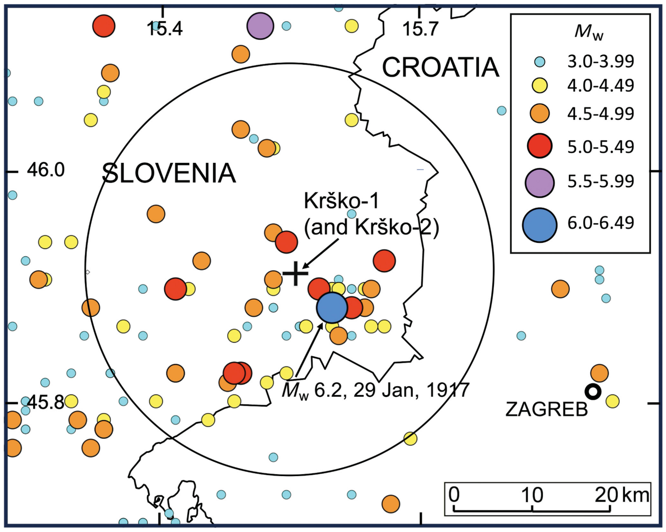

Figure 2. An excerpt from the Share European Earthquake Catalogue (SHEEC) 1900–2006 catalog (Grünthal *et al.*, 2013; moment magnitudes M_w). In the A.D. 567 to 2013 catalog, prepared by GEO-ZS and Paul C. Rizzo Associates, Inc., for the new probabilistic seismic-hazard analysis (PSHA) calculation for Krško-2, the 1917 earthquake (see the blue circle near the cross symbol that designates the location of the NPP) was downgraded to M_m 4.9.

mention the M_m value of 5, that she had obtained for the 1917 earthquake. In fact, in 2024, she wrote: "two historical earthquakes play an important role in the hazard calculation of the Krško NPP: 1880 (M_L 6.3, Herak *et al.*, 2009) and 1917 (M_{LH} 5.7, Ribarič 1982, who used eight stations)" (Pettenati *et al.*, 2024; p. 2). We conclude that the M_m values of 4.9 and 5.0 in 1917 should not have been included in the Krško-2 site hazard calculation.

In the 1970s, Was a PGA Double That of the NRC 1.60 Guide Adopted for Krško-1?

Even with mildly conservative assumptions and short catalogs, the PSHA studies of 1994 (Fajfar *et al.*, 1994) and 2004 (Geomatrix Consultants Inc., 2004) gave PGAs of 0.42*g* and 0.56*g*, respectively, for the Krško site on the free field. Is this still acceptable for existing NPPs? Is the site suitable for Krško-2? The position of the NPP operator (NEK) and its owner (GEN Energija) has always been that everything is OK with the project's PGA because 50 yr ago, the 0.3*g* PGA was applied not to the free field but at the foundation level (at −20 m depth) and that this allows the doubling to 0.6*g* for the free field (due to total reflection). However, this type of statement is usually made verbally in informal forums and in the mass media. There are few written statements in this regard to be found in technical texts that are available to the public. Incidentally, Geomatrix Consultants Inc. wrote that it took "numerous discussions of the Professional Board of NE Krško and the reconciliation of the consultants' opinions" to reach an agreement (Geomatrix Consultants Inc., 2004; p. 2.5–66).

Referring to the 0.42*g* and 0.56*g* values, the (in-house) 2011 stress test stated that "based on additional analysis […], it was concluded that these values are similar to those obtained during the original design" (SNSA, 2011; pp. 1–2). Among attendees at the 2011 30th Congress of the Italian National Solid Earth Geophysics Group, GNGTS, there was a certain expectation for intervention by P. Fajfar of the University of Ljubljana, coauthor of the 1994 PSHA studies, because he wrote that the 0.3*g* of the NRC Regulatory Guide had been applied to the free field (Lapajne and Fajfar, 1997; p. 215). Instead, during the congressional session "Seismic Hazard of Complex Plants," P. Fajfar claimed that the 0.3*g* value had been applied at the foundation level of the excavation bottom (−20 m) and thus that the new PGA of 0.56*g* was compatible with the 0.3*g* of 1973 because of the total reflection from the topographic surface. However, no details on the modeling that supported this explanation were given.

At the end of the session, the press had scheduled an interview with only one of the two copresidents of the session, P. Fajfar (presented as a scientist and not as a consultant to the plant). Therefore, only his statements that everything was OK reached the public (see interviews in the newspapers Il Piccolo and Il Gazzettino, 17 November 2011). Afterward, for the proceedings of his session, P. Fajfar published an abstract mentioning an almost doubling of the PGA from −25 m to the free field, obtained with the Shake calculation code, but without any calculation details (Fajfar, 2011; slide number 16).

However, in a technical-popular report (Jamšek, 2024; p. 16), the GEN group has recently and officially reaffirmed their confidence in the doubling of the PGA from 0.3*g* to 0.6*g*. This report was made available at the end of September 2024 through a website specifically set up to inform Slovenian citizens in view of a national referendum on the construction of Krško-2 (referendum decided by the Slovenian Parliament on 11 October 2024, then annulled on 9 November 2024 following a new vote by the same Parliament after an appeal to the Constitutional Court).

Stress Tests

The NPP has always passed checks by the Slovenian Nuclear Regulator (SNSA, 2011, 2012). Unfortunately, only the PGA was chosen in communications to the public; thus, any detailed verification is impossible (think of the numerous NPP components important to safety). In the 2011 stress tests, we read that (1) "above a PGA of 0.8*g*, damage to the reactor core would be probable, with releases of radioactivity" and that (2) "sand liquefaction in the foundations cannot be excluded" (SNSA, 2011). As shown in Figure 1a, this value still corresponds to a rather high-exceedance probability in 50 yr (0.01).

Active Faults

The IAEA Safety Standards (2022; §5) states that "If a capable fault is identified in the site proximity of an existing nuclear installation, the site shall be deemed unsuitable if the safety of the nuclear installation cannot be demonstrated," and the situation is worse for a planned NPP: the "new site shall be considered unsuitable" (ibidem).

In 2000, for the first time, high-quality independent geophysical surveys were carried out on the Krško site and its surroundings under the framework of a European Commission technical assistance project (Persoglia, 2000); several buried structures likely to be active or capable faults were identified. For more than 20 yr, many geophysical campaigns were subsequently conducted under the direction of GEN Energija, mainly on possible capable faults. Little was done to better define some large primary active faults that affect the ground-shaking hazard. Paleoseismological research was initiated by a consortium of the Slovenian Geological Survey (GeoZS), the French Geological Survey (BRGM) and the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN). However, in 2012, interpretative disputes arose between the French and Slovenians on the possible "capability" of some faults, deduced from trenches on the Libna hill, about 1–2 km north of the site. The French identified "clear evidence" of "coseismic and recurrent" fault offsets in the postglacial era (in the Holocene; Baize, 2017), confirming preliminary conclusions by Geomatrix Consultants Inc. (2004). However, in 2011, during the 30th GNGTS Congress, the Slovenian geologist "manager of the recent geological project in Krško for GeoZS" spoke out against the same 2004 estimates of Geomatrix. He announced that his group had performed a "new expertise that will reduce or even eliminate" some results by Geomatrix (the displacements of 1–10 m in the postglacial era at faults on the Libna hill, 6–2 km from the site). The new results "however, could not be made available to the conference" (Bavec, 2011) "and the client must also remain unknown" (M. Bavec, oral presentation, 30th GNGTS).

However, these assessments were contradicted by another—contemporary—study in an EU scientific context, carried out in part by the same people, coordinated by the same geologist in a UNESCO project, where we read: "This UNESCO report was focused on the paleoseismological study that was executed on the Libna hill, Krško Basin, including excavation, logging and interpretation of three paleoseismological trenches (the same as the other study; ed.) [the] survey revealed that all seismic deformation on Libna pre-dates the iron age" (Slovenian IGCP Committee, 2012).

At the end of 2012, interpretative differences became irreconcilable. On 9 January 2013, the general director of the IRSN (Jacques Repussard) wrote to his client (GEN Energija):

> *"this new and serious finding (of capable faults near the site; ed.) does not allow concluding in a favorable manner as regards the suitability of the Krško II sites (two study sites, adjacent to the existing NPP; ed.) for the implantation of a new nuclear power plant. (…) IRSN believes that GEN should reconsider revising its strategy for the Krško II project and further examine the possibility to search for an alternative site". "IRSN considers that it is of utmost importance that the possible implications on the safety of the existing plant of this fault capability, as well as its potential structural relationship to nearby faults be addressed without delay. I understood—continues Mr. Repussard—that GEN felt concerned about this issue and was willing indeed to inform Krško 1 plant operator (Nuklearna Elektrarna Krško - NEK) as well as the Slovenian Nuclear Safety Administration (NSA) about this finding. I would be very grateful if you could confirm that this has been actually done, since I do envisage drawing NSA's attention on this issue, considering the potential safety implications it may have at national and international level" (Repussard, 2013).*

In April 2013, the consortium dissolved, and Paul C. Rizzo Associates Inc. entered the field. These new consultants presented their preliminary technical position on the presence of any capable faults (mainly the Libna fault) near the site. They wrote that the current interpretation by IRSN was premature because there was no professional consensus even on the presence of the Libna fault on Libna Hill. They added that "the offset observed in the Libna Hill trench is either completely or partially related to mass wasting and karst development" and that the age of the observed offset "may have been pushed artificially younger due to bioturbation" (Paul C. Rizzo Associates Inc., 2013a).

The IAEA Safety Standards (2010, 2022) suggests calculating the maximum magnitudes for various seismogenic zones or structures. In 2012, a maximum potential magnitude of approximately 7.2 (including 1 standard deviation) was estimated for the entire Orlica fault (Sirovich *et al.*, 2012). For the northern segment of the same fault, Paul C. Rizzo Associates Inc. (2013b; its table 6) adopted maximum M_w 6.7 (highest weight) but also included M_w 7.0 (with low weight). Note that, after considering the two reference fault lengths, the estimates by Sirovich *et al.* (2012) and by Paul C. Rizzo Associates Inc. (2013b) substantially agree.

Finally, geological and paleoseismological investigations, performed to update the national seismic hazard map, confirm the existence of these likely active faults in the near region of the NPP: Artiče, <5 km from Krško; Orlica, <5 km from Krško; Dobrovec-Hrastnik fault system, approximately 10–20 km from Krško; Orehovec-Poštena vas, >7 km from Krško; and the eastern strand of the Dinaric fault system, approximately 25 km southwest of Krško with 1–2 mm slip per year (Atanackov *et al.*, 2021, fig. 10; Becker *et al.*, 2022). It appears that none of the mentioned faults have been adequately considered until now in existing seismic hazard models.

Discussion and Conclusions

It was not possible to see the "restricted" M_m calculation for the 1917 Krško earthquake by Baumont (2010a,b), despite many written requests and even a registered mail to GEN Energija d.o.o. Note that the secret is put simply on a characteristic of the region, something like keeping classified the width of a river over which a bridge should be built.

On 8 March 2017, Andrej Stritar, the then director of the Nuclear Safety Administration of Slovenia (which oversees the stress tests)—formerly the 2007–2011 chairperson of the ENSREG conference (which issues the standards for the stress tests themselves)—granted an interview with the Italian television network "La7" (journalist Lorenzo Caroselli in "Tagadà": see Data and Resources). To the question, "director, should we hope that a M 7 earthquake, as the experts predict, never occurs?," Stritar bangs his knuckles on the table and says: "knock on wood!"

The Krško-1 696 MWe (electric Megawatt) NPP entered service in 1983; its operation window has been extended to 2043, but it is expected to operate until 2063. For many years, the Slovenian government and GEN Energija have been studying the possibility of building a 1000–1650 MWe (electric Megawatt) Krško-2 alongside Krško-1, for an investment of 9.3–15.4 billion euros, and they seem determined to build the new plant, which would be operational for 60–80 yr.

For many years now it has also been known that the 2004 PSHA study would be updated in view of the construction of the new reactor. The new PSHA was expected by the end of 2025, but is now expected to end March 2027, with the construction decision to be made in 2028.

In our modest opinion, from the point of view of the seismic hazard, the in-house checks were not sufficient either to seriously evaluate the opportunity to continue the operation of Krško-1 for 60 or 80 yr or to inform the design of Krško-2. This is an indirect result of the 1992 Maastricht Treaty, which did not establish a body with the authority to check the quality of hazard studies and to issue and revoke permits. However, it is advisable not to contradict the IAEA's suggestions, even if they are not binding. In the United States, the NRC created by Congress in 1974 has the power to license and supervise NPPs, and their designers and operators must make natural hazard studies, measurements and monitoring data available to the public, though some reports might be restricted for security reasons.

The cost of decommissioning the Krško NPP would be roughly on the order of 1.5×10^{-2} of the gross domestic product (GDP) of tiny Slovenia (2.1 million inhabitants). (By comparison, it would represent approximately 3.1×10^{-4} of the GDP of France.) A rational way out should include the participation of the EU because the issue clearly is of common interest. Slovenia could be helped in determining another suitable site and/or the EU could partially bear the costs of decommissioning the current NPP.

Finally, the authors would like to point out that they and their past coauthors have never taken a position on the civil use of atomic energy.

Data and Resources

All the data and information used in this article were obtained from published and unpublished sources listed in the references. Senate of the Republic is available at https://bit.ly/4drychn. Map of the epicenters of the A.D. 567 to 2013 catalog could be downloaded from www.ursjv.gov.si/si/info/posamezne_zadeve/o_potresni_varnosti_nek/. Lorenzo Caroselli in "Tagadà" is available at https://bit.ly/3SOY7Y3. According to the Slovenian Agency for Nuclear Safety, stress tests confirm that the Krško power plant is among the safest in Europe can be found (in Italian) in the parliamentary records, for example here https://www.camera.it/leg17/410?idSeduta=0640&tipo=atti_indirizzo_controllo; see the replies to Members Prodani, Rizzetto, Pellegrino and Rosato. All websites were last accessed in March 2026.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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