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A review of the seismotectonics and some considerations on the seismic hazard of the Krško NPP area (SE Slovenia)

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ABSTRACT This paper gives short comments on the seismotectonic, seismological, and seismic hazard characteristics of the area of the nuclear power plant (NPP) of Krško (Slovenia). The plant was designed in the second half of the 1970s with no related probabilistic seismic hazard studies. The design was based on Regulatory Guides of 1973 with response spectra anchored to the peak ground acceleration of 0.30 g on the free field. The construction of a new NPP in the area is being taken into consideration by international investors. The Krško NPP is located inside a seismically active area, in which low-to-medium magnitude earthquakes have occurred in the last centuries. The greatest intensity felt near the NPP site was VIII for a local M_W 5.7 - 6.2 earthquake in 1917, and the strongest event in the region was the $M \approx 6.3$ Zagreb, 1880 event, whose epicentre was about 65 km from the NPP. The plant is close to some faults with unresolved neotectonic activity in the post-glacial epoch (18,000 years). Some stress test results from the 1990s would have suggested that 0.3 g were adopted at -20 m depth, corresponding to an effective value of 0.6 g at zero depth; this aspect is also commented. Finally, the difficult problem of estimating the maximum credible magnitude, M_{max}, for very long return periods is addressed, based on the geological evidence provided by Geomatrix Consultants Inc. in 2004. From an apparent rupture length of 40 km of the Orlica fault, an M_{max} of at least 7.2 could be hypothesized (1 st. dev. included). This hypothesis has anyway a low reliability, because the extent of the spatial continuity of the Orlica fault is still debated.

Key words: seismic hazard, NPP, Krško, Slovenia.

1. Introduction

The probabilistic seismic hazard map of Europe for the return period (T) of 475 years (thus, for *normal housing*, not for strategic facilities) is shown in Fig. 1 (Jiménez *et al.*, 2001; Giardini *et al.*, 2003), together with the nuclear power plants (NPPs) operating in Europe in 2012. The power of each reactor (proportional to dot size) is reported according to the International Atomic Energy Agency (IAEA, 2013). One can see that the Krško NPP, although small, is the only one in Europe built in a seismic area close to the contact between the African and Eurasian plates (see Fig. 1; also see the inlet in Fig. 2). There are, however, two more European NPPs close to

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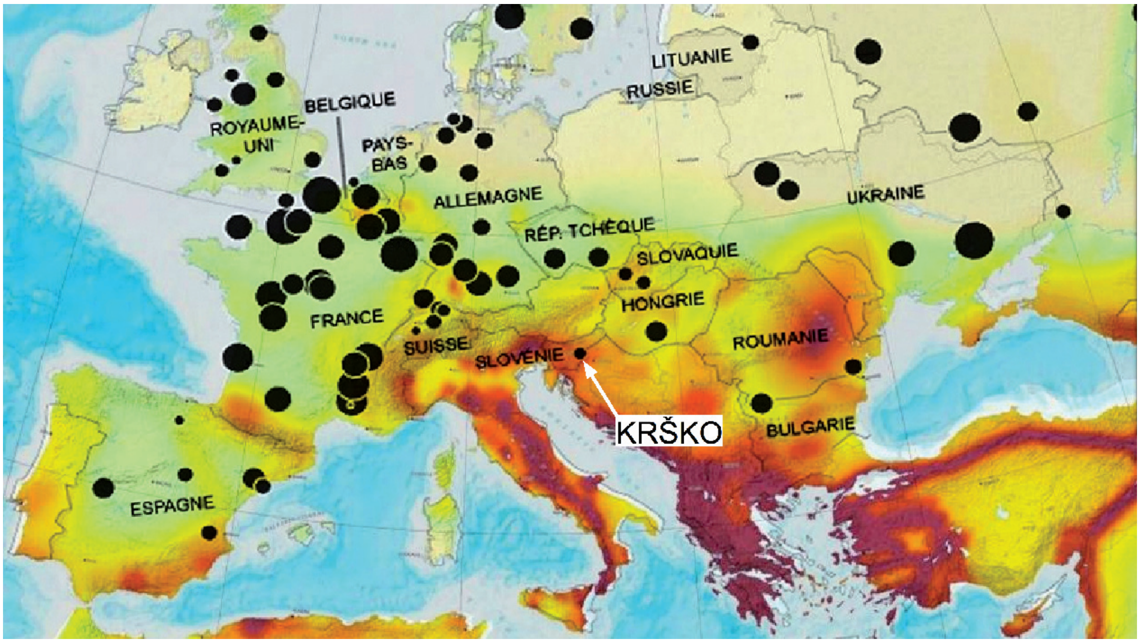

Fig. 1 - Probabilistic seismic hazard map of Europe from the EU project Sesame (Jiménez *et al.*, 2001; Giardini *et al.*, 2003). The nuclear reactors are reported from the IAEA Agency (see text).

seismic regions, one in Spain and one in Romania.

In this paper we discuss only some seismic safety issues of the Krško NPP, prompted by the examination of some data on both the seismotectonics and on the regional and local seismic hazard of the area in which the Krško NPP was built and is operating. This work is also timely, in view of the possible "doubling" of the plant (strictly speaking, the construction of a new NPP not far from the existing one).

The motivations for this paper also arise, on one hand, from knowing that the seismotectonic and hazard information at the time of the NPP construction is outdated and, on the other hand, from observing that some data on seismotectonics, seismology and seismic design and performance of the existing NPP, presently in use, seem to be at least questionable, if not contradictory.

The seismotectonic understanding of the region was recently improved by inverting for the source parameters the macroseismic data of the 1895 Ljubljana earthquake with a macroseismic magnitude (M_m) according to Ribarič (1982) of 6.1 and its M_m 5.0 aftershock of 1987 (Jukić *et al.*, 2011; Sirovich *et al.*, 2011). The 1895 event (approximately 75 km away from the NPP) is one of the strongest earthquakes contained in the Slovenian catalogue of the Agencija Republike Slovenije za Okolje (ARSO) whose data have been merged into the European Mediterranean Earthquake Catalogue (Grünthal and Wahlström, 2012) and it also affected the region NW of the Krško NPP. According to the Italian macroseismic database (DBMI11; Locati *et al.*, 2011) the 1895 event caused damage in Ljubljana of degree VIII (MCS-64 scale) and of degree VIII - IX (EMS-98) according to the Slovenian macroseismic database (ARSO, 2012).

Coming back to Krško, one of the principal question marks in cases of design or of verification of a NPP is the maximum credible magnitude (M_{max}) to be reasonably taken into

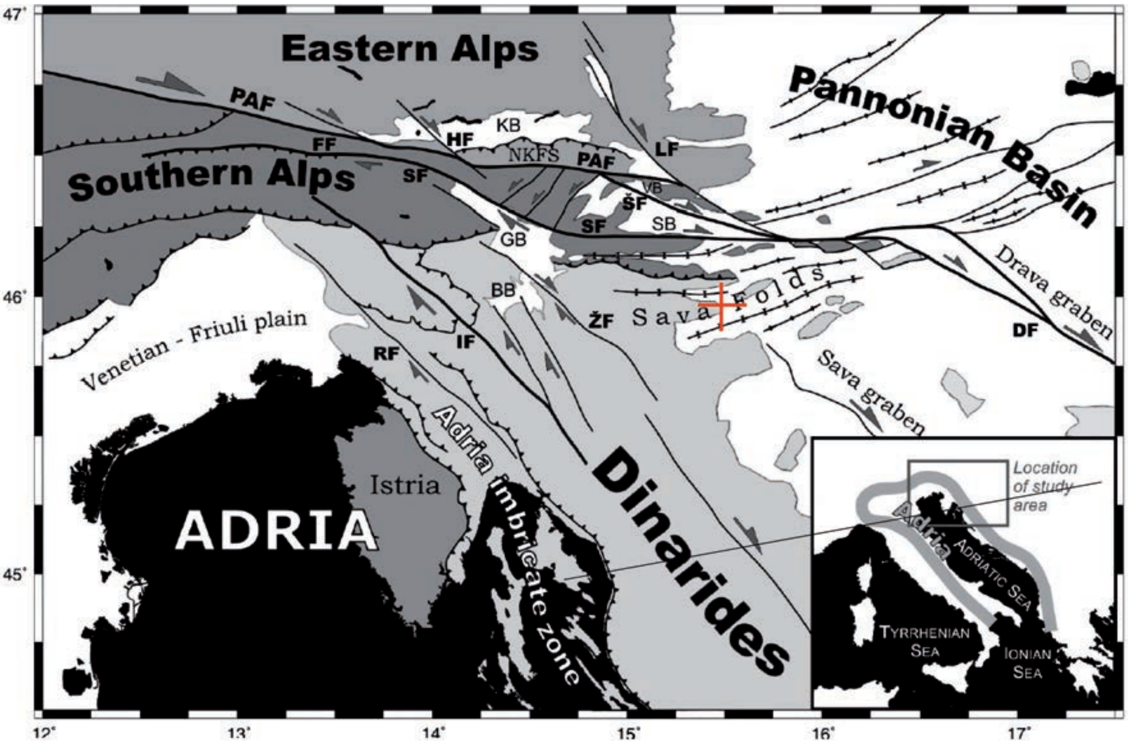

Fig. 2 - Simplified tectonic map of the north-eastern corner of the Adria - Europe collision zone (modified from Vrabec and Fodor, 2006). White: Neogene; IF: Idrija fault; PAF: Periadriatic fault; SF: Sava fault. The red cross is the Krško NPP.

account in the probabilistic seismic hazard analyses (PSHA). We present an attempt to estimate M_{max} for the Krško area, also in the light of the Safety Standards by IAEA (2010). For example, these standards prescribe that the assessment of seismic hazard by deterministic methods should include for each seismogenic structure, the maximum potential magnitude assumed to occur at the point of the seismogenic structure closest to the site area of the NPP, with account taken of the physical dimensions of the seismic source. When the site is within the boundaries of a seismogenic structure, the maximum potential magnitude should be assumed to occur beneath the site. In this case, special care should be taken to demonstrate that the seismogenic structure is not capable (IAEA, 2010).

The new PSHA studies of 2004 increased the reference free-field peak ground horizontal accelerations (*PGA*) to 0.56 g, i.e., almost twice the original design value of 0.3 g adopted in the 1970s (SNSA, 2011). The question of the acceptability of the 0.3 g value was long debated, and the value was accepted only after a number of discussions of the Professional Board of NE Krško and the reconciliation of the consultants' opinions (Geomatrix Consultants Inc., 2004). In fact, Fajfar (2011) explained that the amount and shape of the excavation (20 m deep) for the foundations of the NPP was sufficient to avoid amplitude doubling due to total wave reflection from the surface. Thus, the *PGA* = 0.3 g adopted at the free-field (at -20 m depth) at the end of the 1970s corresponded to an effective value of 0.6 g at zero depth, in accordance with the PSHA of 2004.

These two aspects further contributed to our writing of this paper.

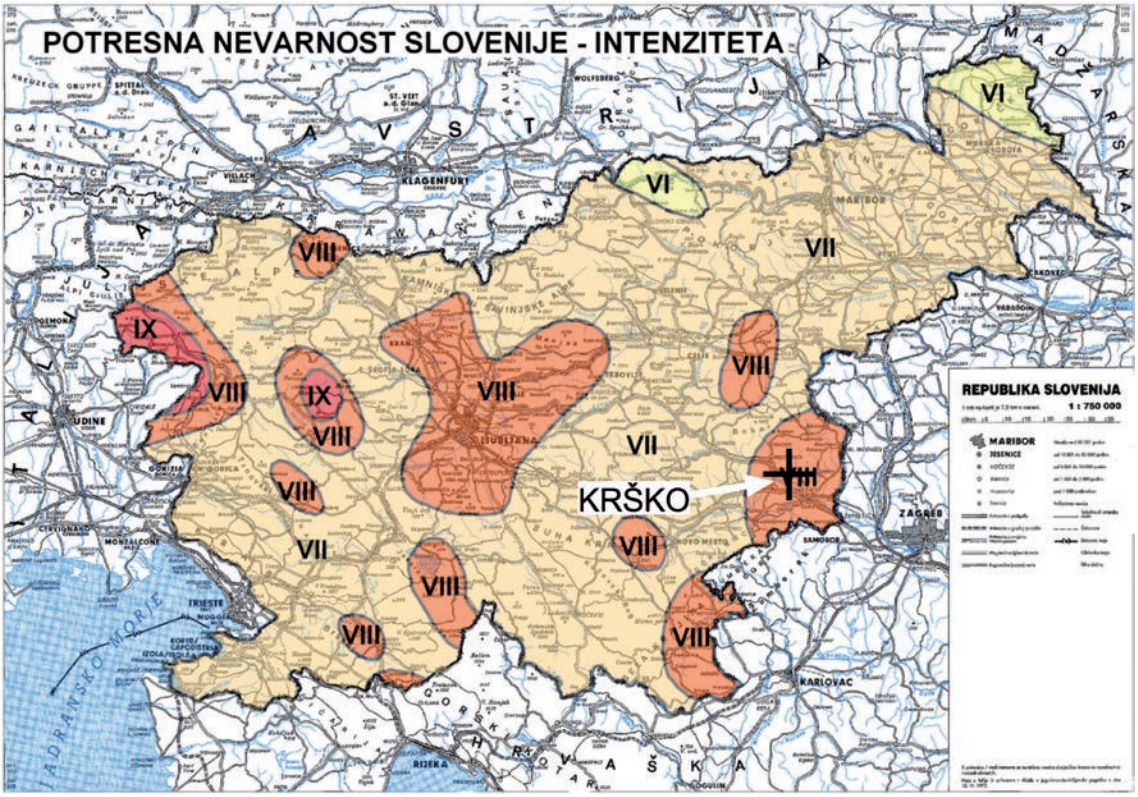

Fig. 3 - Maximum hazard for T = 500 years (intensity in MSK-64 scale) in Slovenia [Ribarič (1987); reproduced in Vidrih (2006): http://www.arso.gov.si/potresi/potresna%20nevarnost/].

In the international practice, the safety of existing and of future plants are considered with two different "philosophies", which do not derive only from the evolving of seismic rules, but are also conditioned by economic criteria. There are, in fact, different approaches when considering capable faults. When a new project is concerned, 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. Instead, in case of existing plants with capable faults found after construction, probabilistic methods analogous to and consistent with those used for the ground motion hazard assessment are suggested (IAEA, 2010).

Finally, according to Fig. 3 [Ribarič (1987); shown also in Vidrih (2006)], the NPP area has experienced in the last five centuries a maximum intensity VIII (MSK-64 and EMS-98 scales). Depending on one or the other of the many scales and relationships available, VIII could correspond very roughly to *PGA* spanning from 0.2 to slightly over 1 g (Wald *et al.*, 1999). Intensity VIII occurred in Brežice (Bavec, 2011), 6 - 7 km SE of the NPP during the January 29, 1917 earthquake. According to Ribarič (1982), its epicentre and magnitude were 45.900° N 15.567° E (approximately 5 km SE of NPP) and M_W 5.7. The Slovenian catalogue confirmed M_W 5.7 (ARSO, 2010), which was however re- estimated by Grünthal and Wahlström (2012) who increased it to M_W 6.2. Some examples of damage in Brežice are reported by Tornquist (1918).

The 1880 $M \approx 6.3$ Zagreb event, on the other hand, produced intensity VI to VII in the Krško area according to the UNESCO Atlas of isoseismal maps in the Balkan region (Cvijanović, 1974). Recently, Ivica Sović of the University of Zagreb proposed (personal communication, 2012) an intensity value VI - VII for the Krško village (45.969° N, 15.488° E) and VI for Brežice (45.905° N, 15.595° E).

2. Comparing PSHA maps of Croatia, Italy and Slovenia

We compare the PSHA maps officially adopted in Italy, Slovenia and Croatia in Fig. 4. For *normal housing*, all three countries have chosen, as usual (Reiter, 1990; Somerville and Moriwaki, 2003) and in accordance with Eurocode 8 (EN 1998-1, 2004), to refer to ground shaking parameters with a return period of 475 years, but the three maps were computed following different approaches. By the way, a homogeneous study of PSHA based on Cornell (1968), that encompasses also the Alps - Dinarides contact region discussed in this paper, was adopted by Slejko *et al.* (1999).

The national PSHA maps of Italy (Stucchi *et al.*, 2011) are based on the Cornell (1968) approach, which implies also the adoption of seismogenic zones based on seismotectonic

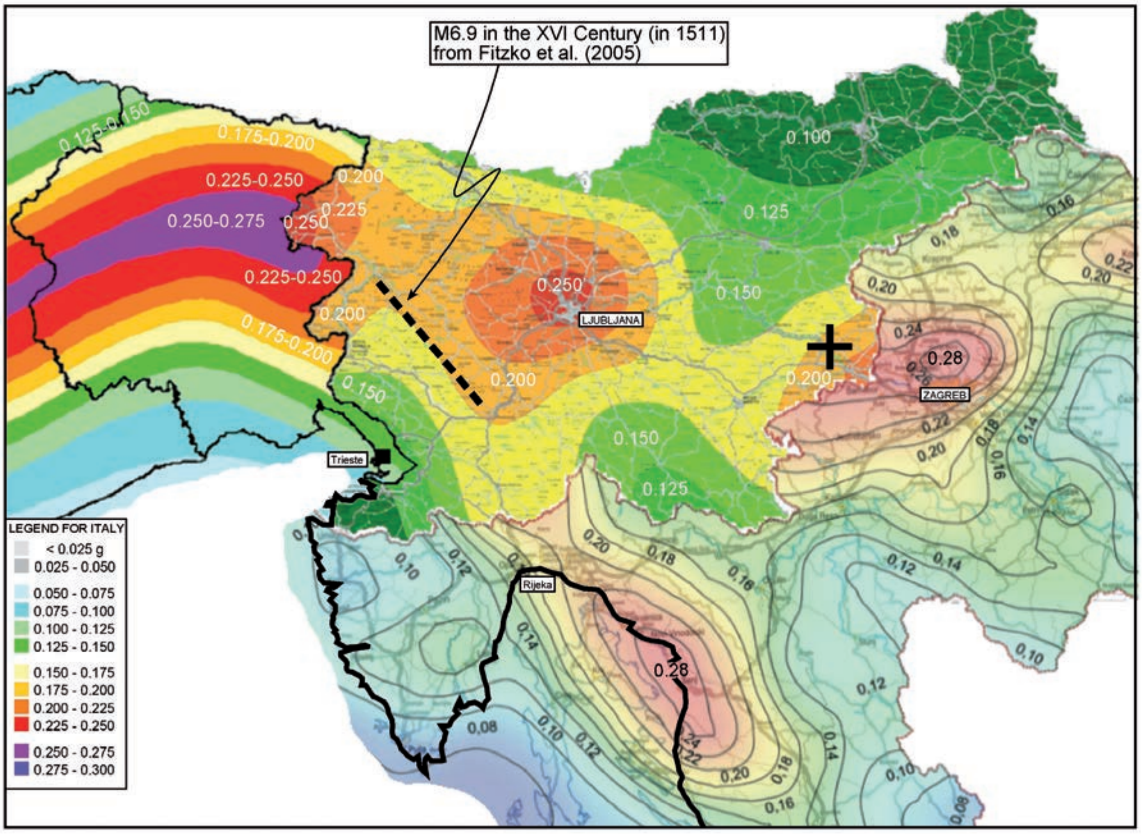

Fig. 4 - Comparison between the PSHA maps (see references in text) of Italy (Cornell approach), Slovenia and Croatia (two versions of the smoothed seismicity approach); black cross: the Krško NPP; dashed segment: the fault source of the M_W 6.9 - 7.0, 1511 earthquake according to Fitzko *et al.* (2005) (see text).

interpretation. In this sense, the Italian map tries to take somehow into consideration not only the events observed in historical times, but also the seismic potential of faults and structures having neotectonic and paleoseismological evidence. The map shown for NE Italy in Fig. 4 (INGV, 2012) is for hard soils (shear-wave velocity Vs > 800 m/s).

Slovenia adopted the smoothed seismicity approach (Frankel, 1995; Lapajne *et al.*, 1997). Its PSHA map is clearly related to the two strongest most recent earthquakes of the catalogue, that have taken place near the two largest cities (0.250 g for Ljubljana; 0.225 g towards Zagreb and 0.200 g for Krško), and to the Friuli earthquake of 1976 along the Italian-Slovenian border near Kobarid.

The new PSHA map of Croatia for *normal housing* (GFZ, 2011), released at the end of 2011 (see Fig. 4), was calculated by a zoneless, smoothed seismicity approach, with the stochastic Monte-Carlo simulation of 2,000,000 years of seismicity for six different seismicity models (Herak *et al.*, 2011; also see Markušić and Herak, 1999). In the computation, the spatial distributions of activity rates and of *b*-values were smoothed in three different ways. Again, as in the Slovenian case, only the historical catalogue was considered and the contribution of possible capable faults (which did not show seismic activity in the last centuries) on seismic hazard was not taken into account.

The crude comparison between the three maps of project accelerations (in terms of *PGA*) highlights the consequences of the different approaches followed by the three countries. The Cornell one results in a stripes-like pattern of the *PGA* in Italy (due to the seismotectonic constraint), whereas in Slovenia and Croatia the *PGA* pattern is patchy (dominant catalogue data, no seismotectonic assumptions).

Then, the Slovenian PSHA map for T = 10,000 years (Lapajne *et al.*, 2001; ARSO, 2013: figure not shown) attribute a *PGA* of about 0.40 - 0.45 g to the NPP area (the colorimetric scale is not easy to interpret). Such a value has been extrapolated, as usual in PSHA, on the basis of the catalogue that spans only a few centuries. This leads (e.g., Bommer *et al.*, 2004) to huge uncertainties of the estimated *PGA*. Note that some "stress tests" conducted after the preceding studies, assigned the value of *PGA* = 0.6 g at Krško (SNSA, 2011).

In Fig. 4 the tentative fault-source of the strongest earthquake recorded in the history of the Slovenia - Italy border area is plotted: the M 6.9, 1511 earthquake. Its fault-source was constrained in western Slovenia using quantitative seismological techniques, which treat the damage evidence at the beginning of the XVI century (Fitzko *et al.*, 2005); the result should be obviously verified also using the new intensities available, although most of the coeval information on damage related to the 1511 event are in the (present) Italian territory (Camassi *et al.*, 2011). This is not surprising, since in the XVI century the density of possible historical sources in Italy was much higher than in the neighbouring Slovenian regions. As can be seen from Fig. 4, the official PSHA map does not take the effect of the fault source by Fitzko *et al.* (2005) into account, nor the recent field evidence of activity of the Idrija fault (Cunningham *et al.*, 2006), since proposed (Lapajne *et al.*, 2001) years before this new information appeared.

This inconsistency is also due to the fact that the smoothed seismicity concept does not allow to take into account extended sources, capable faults or structures with activity evidence. So, from the applicative point of view, the map in Fig. 4 is not conservative, even for *normal housing*; not to mention the critical facilities, which need to be protected against earthquakes with extremely long return periods.

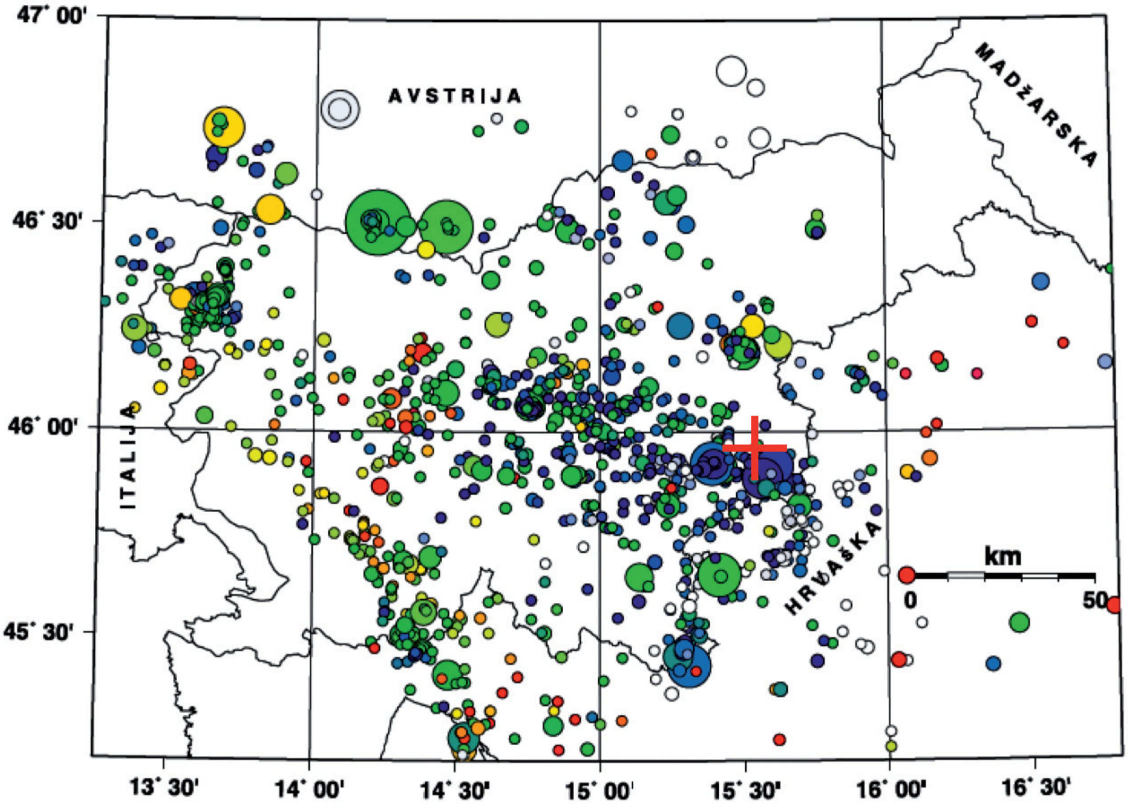

Fig. 5 - An example (referred to 2007) of the present Slovenian seismicity [modified from ARSO, (2010): http://www.arso.gov.si/potresi/poročila%20in%20publikacije/]; red cross: the Krško NPP.

The adopted PSHA map seems to reflect the fact that the seismicity in the wider Idrija region (e.g., Živčić *et al.*, 2011) continues to be quite low (Fig. 5) and that the 1511 epicentre was evidently assumed to have occurred in Friuli. In conclusion, the official PSHA map does not reflect the recent investigations on the biggest earthquakes in Slovenia and should be updated.

3. The Krško NPP

The NPP (see Fig. 2) is situated on the shore of the Sava River, about 35 km from Zagreb and 130 km ENE from Trieste (upwind of the prevailing winds). The plant (Westinghouse technology, operational since 1983) was planned at the end of the 1970s on the basis of the Regulatory Guide 1.60 (USNRC, 1973; NEK, 2011) of the U.S. Nuclear Regulatory Commission (USNRC). The regulations of that time anchored the response spectra “a la Newmark and Hall” to the *PGA* value of 0.30 g on the free-field. Successive regulations asked to choose this reference parameter from uniform hazard spectra with 10^{-4} or 10^{-5} annual probability, which lead to *PGA* > 0.30 g in the area in question. At the time, the anchoring frequency was 33 Hz assumed as corresponding to the soil *PGA*; since the paper of one of the authors of the Newmark and Hall technique (see: Levin *et al.*, 1983) values > 33 Hz are used.

According to a kind statement obtained from the NPP staff (personal communication, 2011), the construction was not preceded by a probabilistic study of seismic hazard. However, two studies were made later on, by two different groups. The first, at the beginning of the 1990s (Fajfar *et al.*, 1994), the second one coordinated by Geomatrix Consultants Inc. (2004). In this second study, only near regional sources (≤ 25 km) had been considered (Fajfar, private communication).

Since then, "stress tests" were conducted on the plant. The term refers to a walk-down (reconsideration), of the project and of the implementation of structures in order to verify the safety and performance of the whole plant. Note that the "stress test" concept is updated from time to time; the present one defines a "stress test" as a targeted reassessment of the safety margins of nuclear power plants in the light of the events which occurred at Fukushima (ENSREG, 2011).

However, the experts who performed the verification in question write that the PSHA made in 1994 increased the *PGA* to 0.42 g, whereas the 2004 PSHA study has further increased the seismic hazard to a *PGA* of 0.56 g (both values are considered in the free-field). Based on additional analyses using new seismic hazard data and a more advanced realistic model for soil structure interaction, it was concluded that the peaks in the floor response spectra corresponding to *PGA* = 0.6 g, i.e., twice the original design value, are similar to those obtained in the original design (SNSA, 2011). The favourable point on the side of safety seems to be the fact that, at the time of the construction, the 0.3 g *PGA* had been applied at the foundation level at -20 m depth.

It is worth citing here some results gained by the SNSA report of 2011, regarding some bad cases at high levels of seismic excitation. According to SNSA (2011) for earthquakes in the range of *PGA* exceeding 0.9 g, gross structural failures of spent fuel pool (SFP) cannot be excluded and it can be expected that fuel uncovery in the SFP would occur. It is considered that seismic levels at which core damage would be likely are at *PGA* range of 0.8 g or higher.

Furthermore, seismic events at which early radioactivity releases into the environment would be likely to occur are considered to be of *PGA* significantly exceeding 1.0 g; late radioactivity releases into the environment would be likely to occur in the range of 0.8 g or higher. Also, liquefaction cannot be excluded which would potentially fail buried structures and / or equipment (SNSA, 2011). No relevant improvements are introduced by SNSA (2012).

A new probabilistic study by Slovenian and non-Slovenian experts, coordinated by some French experts of the "Bureau de Recherches Géologiques et Minières" (BRGM) with the presence of the "Institut de Radioprotection et de Sûreté Nucléaire" of France (IRSN) is underway in preparation for a new power plant (at a nearby site) in the Krško area.

3.1. Geological and tectonic sketch of the Krško region

The interpretation of the geological and tectonic structure of Slovenia, northern Croatia and surrounding areas is evolving rapidly. A recent attempt of homogenizing the classification of 184 seimogenic sources in the Balkan region was done in the European SHARE (Seismic Hazard Harmonization in Europe) project (Kastelic *et al.*, 2011; Basili *et al.*, 2013). In the literature there is, however, no agreement either in the choice of the names of microplates, crustal blocks and units, or in the geodynamic and palinspastic reconstructions (*sensu* Kay, 1937). We introduce the reader to the matter in question using Fig. 2 (Vrabec and Fodor, 2006), albeit our description does not coincide with the one by the mentioned authors.

Krško is situated in the Sava folds area, where the principal structures are oriented in the WSW-ENE direction (folds but also important transcurrent - mainly sinistral - faults). The Sava folds area is a transition zone between (clockwise description) the eastern offshoots of the Southern Alps in contact with the Pannonian Basin, the Sava Graben area - often addressed to as the Balaton zone - with modest present-day seismic activity, and the Dinarides. The latter are subdivided (Placer *et al.*, 2010), from east to west, into three zones: i) the internal Dinaric thrusts (the closest to the Krško region from the SE side), ii) the external Dinaric thrusts (west of the region of the plant), iii) the chain of the external thrusts with an imbricated structure (Dalmatian coast and islands). In the internal and external Dinarides the presence of strike-slip or transpressive, dextral, big faults is important, with some of them showing present-day seismic activity. In particular, one of them (not one of the largest), the Ravne's fault was responsible for the two Bovec earthquakes of 1998 (M_W 5.7) and of 2004 (M_W 5.2). On the other hand, several authors attribute an earthquake with M_W 6.9 - 7.0 in 1511 to the Idrija fault (Ribarič, 1979, 1982; Fitzko *et al.*, 2005). Such structures do represent a high seismic potential.

Unfortunately, GPS measurements are still scarce in the region. From the GPS-derived motions by Weber *et al.* (2010) it is seen that the Adriatic microplate is moving northwards, but one cannot discriminate what is going on in the transition region under study.

The seismotectonic vision that inspired the designers at the end of the 1970s followed the structuring views of the 1950s - 1960s, according to which geodynamics is mainly due to vertical (gravitational) movements (Beloussov, 1970). In this sense, some old seismotectonic charts of the Krško region show a division in "blocks", in uplift or in subsidence, divided by a grid of vertical or almost vertical faults; a structuring that belongs now to the history of science.

As concerns the modern views on the seismotectonics of Slovenia, and in particular of the area around Krško, the consulted literature and some project documents suggest that there are some recent good-quality papers (es: Poljak *et al.*, 2000; Vrabec and Fodor, 2006; Placer *et al.*, 2010; Jamšek *et al.*, 2011) but there is still much work to be done to obtain a comprehensive picture.

Coming back to the Southern Alps, their eastern limit is debated, but they appear at present to overthrust on the Dinarides (this Alps-Dinarides contact is not always traced with certainty). In this context, according to Vrabec and Fodor (2006), the region of the Sava folds (at which centre the Krško area lies) is dominated by E-W to ENE-WSW trending synclines of Neogene strata. Synclines formed between pop-ups of pre-Tertiary basement, uplifted along moderately dipping reverse faults.

3.1.1. Close-up of the site

It is thought that the most recent phase of folding in the NPP area began at the end of the Pontian (uppermost Miocene); in fact, all Neogene strata exhibit uniform thickness (Bavec, 2011). Evidences of neotectonic activity were found a few kilometres from the NPP (see Fig. 6), and prompted geophysical investigations. Fig. 7 presents the suspected Quaternary-active faults in the Krško region according to Geomatrix Consultants Inc. (2004). The most impressive tectonic feature is the Orlica fault (same orientation of the Sava folds), which is classified as sinistral, strike-slip (Geomatrix Consultants Inc., 2004) or transtensive (Comerci, 2000). As seen in Fig. 7, the Orlica fault is intersected by sections KK01-99 and KK02-99 performed by Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) in the Krško area (Persoglia,

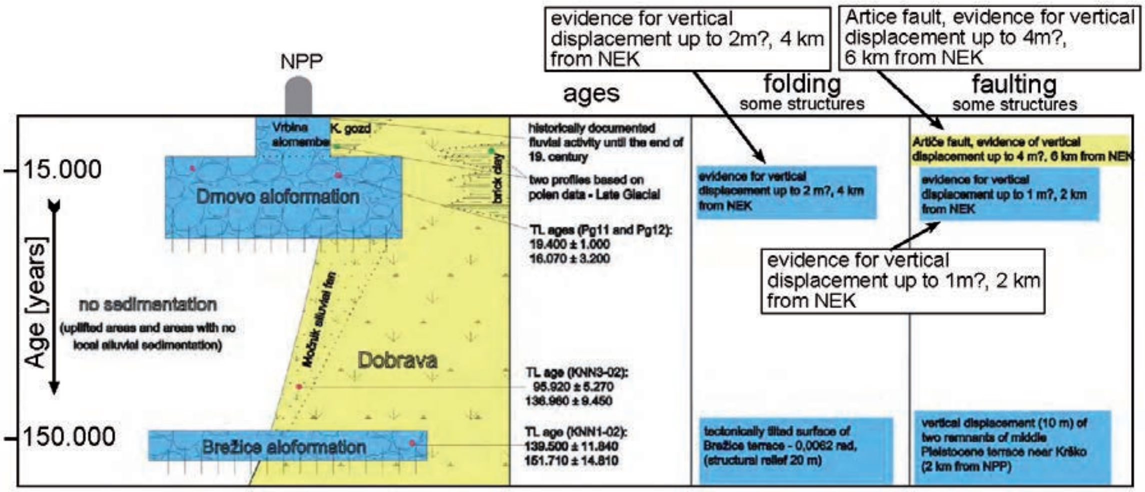

Fig. 6 - Evidence of folding and faulting activity in the post-glacial epoch in the area of the Krško NPP. Yellow: "System of local alluvial input"; blue: "Sava River alluvial system"; the bases of the "Drnovo and Brezice aloformations" are "distinctive erosional boundaries" [modified from Fig. 2.5-9 of Geomatrix Consultants Inc., 2004 (rev.14)].

2000), not by section KK03-99. This interpretation by Geomatrix Consultants Inc. agrees with that by OGS (Persoglia, 2000).

The time section of the WSW-ENE trending line KK01-99, almost parallel to the so-called Krško syncline, is shown in Fig. 8; the supposed intersection with the Orlica fault is on the left. As seen from the figure, the syncline is dissected by younger faults. The NPP is 1.1 km to the north of the section of Fig. 8.

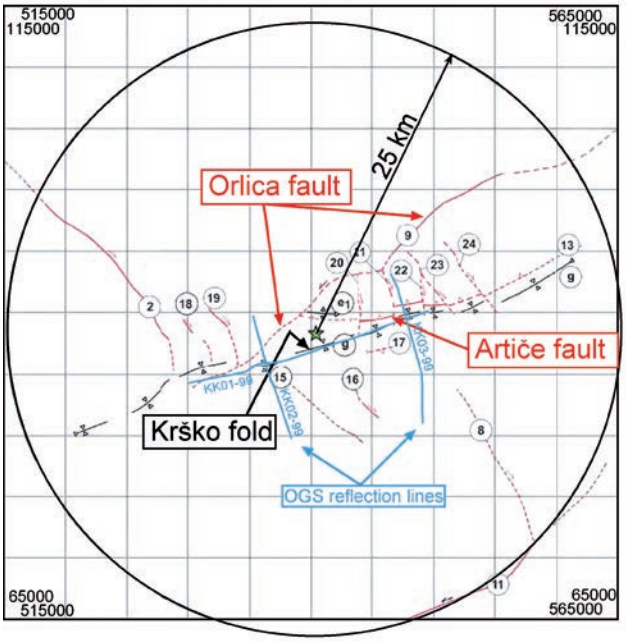

Fig. 7 - Known or suspected Quaternary-active faults in the near region of the Krško NPP (25 km radius); the star indicates the NPP [modified from Fig. 2.5-38 of Geomatrix Consultants Inc., 2004 (rev.14)]. Traces of three OGS reflection lines from Persoglia (2000).

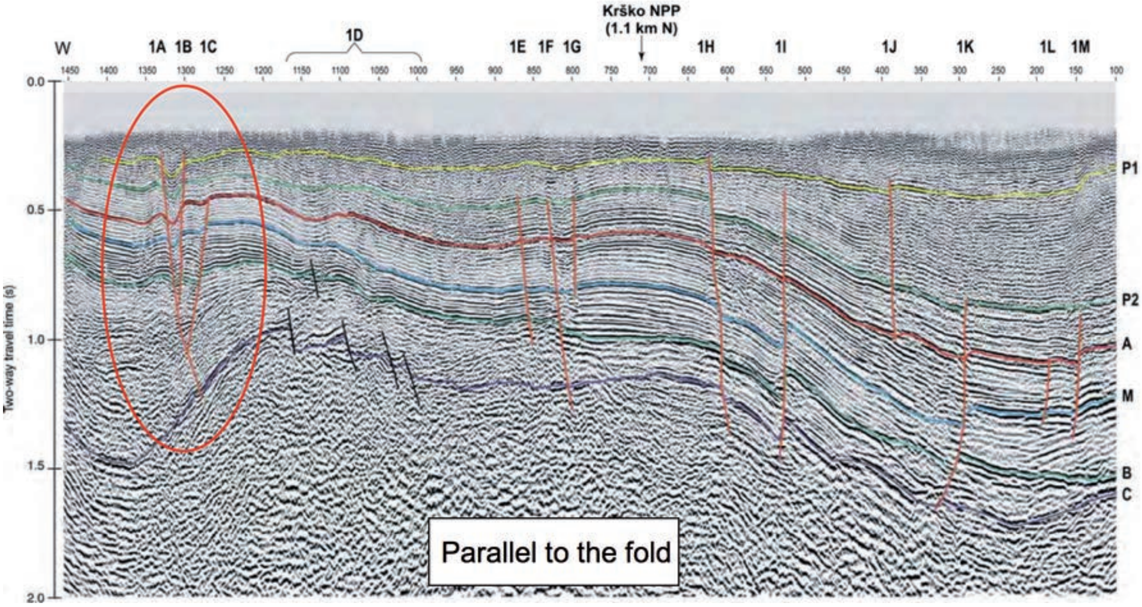

Fig. 8 - Reflection line KK01-99 by OGS [Persoglia (2000); see its trace in Fig. 7] almost parallel to the fold with Plio-Quaternary and Middle Pleistocene sediments called Krško syncline (for the conventional zero in the vertical scale, see Section 3.1.1) [modified from Fig. 2.5-14 of Geomatrix Consultants Inc., 2004 (rev.14)].

At this point, before commenting the aforementioned intersections between the Orlica and the lines KK01-99 and KK02-99, we must explain that OGS (Persoglia, 2000) adopted two different conventional references for the zero of the two-way travel time vertical scales in the A3 size (like the one reproduced in Fig. 8) and in the approximately 2.5 m long paper sheets. Then, a third conventional zero was adopted by Geomatrix Consultants Inc. (2004). Therefore, it is difficult to understand how close the faults approach the free surface. However, a clear indication is given by the depth migration of the line KK-02-99 performed by OGS (Persoglia, 2000; Accaino *et al.*, 2001), which was improved by using the staggered method (Vesnaver and Böhm, 2000). From this depth migration it is seen that the tectonic line in question reaches approximately a 35 m depth; for technical reasons, the 0 - 35 m depth range is mute.

Under the NPP area, the Krško syncline with Plio-Quaternary and Middle Pleistocene sediments [perhaps of "Riss" age according to Geomatrix Consultants Inc. (2004)] would have been levelled by the erosion of the Sava River (and Krka River close by), that went on till very recent times (also see Verbič, 2004, 2005).

In fact, the same excavation done in the 1970s to prepare the foundations of the NPP showed that: i) the tilted strata of Neogene have uniform thickness; ii) the present alluvium is horizontal and 8 - 10 m thick (Geomatrix Consultants Inc., 2004). Besides, for all these structures of the Krško region, recent data regarding neotectonics and/or paleoseismology seem not to be available, and it is therefore difficult to draw convincing conclusions in terms of their seismic potentials, useful for the calculation of seismic hazard for projects purposes. It seems that in the last decade trenches for paleoseismologic study on presumed faults have been dug for the new plant, but the data are not yet public.

3.1.2. Neotectonic questionable clues

According to Geomatrix Consultants Inc. (2004), both fault systems (i.e., the NW-SE and NE-SW trending strike-slip faults and the E-W trending reverse faults) have been locally reactivated in response to the present N-S compressional tectonic regime. Fig. 6 (modified from Geomatrix Consultants Inc., 2004) is part of the original figure and shows the neotectonic offsets of post-glacial age found on the Artiče reverse fault, whose location is reported in Fig. 7. As seen, vertical displacements from 1 to 4 m (the question marks are in the original figure), about 2 to 4 km from the NPP, seem to have been found in 2004 on the southern flank of the Libna hill, NE of the NPP, and close thereby.

During the conference of the Italian Group for Solid Earth Geophysics (GNGTS) in 2011, it was explained that some preliminary geological results, retrieved from the ongoing studies for the new NPP in the area (new geological trenches included), suggest that the new expertise will reduce, or even eliminate, the values mentioned in Fig. 6 (Bavec, private communication). It is anyway worth mentioning that a total cancellation of these neotectonic offsets of post-glacial age located NE and ENE of the plant would be in conflict with what another working group - but sharing some participants - has already reported in the IGCP Project No 567 of UNESCO on Earthquake Archaeology and Archaeoseismology (Slovenian IGCP Committee, 2012). 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 main trench was excavated within an archeologically protected area of iron-age (Hallstadt). Therefore, an extensive archeological study accompanied classical paleoseismological work. Three iron-age houses were excavated and the settlement was dated to 500 - 800 years B.C. by archeological findings. Archeological survey also revealed that all seismic deformation on Libna pre-dates the iron age (UNESCO, 2012). The area in question is on the road past Libna from Krško to Brežice with almost 14 hectares of prehistoric settlements (Krško, 2013). From the above, one understands that paleoseismological seismic deformations (displacements, or offsets) exist on the Artiče fault, but that they are elder than 2500 - 2800 years b.p.

Finally, no reliable paleoseismological details are available for the Orlica fault which, however, has a greater regional relevance than the Artiče one. In fact, it could represent the NE boundary of the Balaton structural zone, which exhibits most of the present geodynamic deformation along the SW-NE oriented faults (Bavec, 2011). We can only mention the following hints coming from a graduate thesis in geology (Comerci, 2000). In the area of the Krško village, the interpreted track of the ENE-WSW trending Orlica fault is located in the eastern part of the inhabited centre, close to the western limit of the Libna hill, approximately coinciding with the course of the Potočnica stream which flows from NNE to SSW. Two corresponding erosional surfaces (terraces) of middle Pleistocene were observed there by Verbič (1993) on the two sides of the fault. Both were produced by the Sava River, are almost horizontal and exhibit calcareous pebbles. According to Comerci (2000), the terrace on the side of the Libna hill is 8 m higher than that on the side of the village. It is worth noting that the aforementioned terrace displacement could be compatible with the fault movements visible on the left side of the reflection line in Fig. 8. The short visit of the site for the present work, was not sufficient to draw a reliable conclusion on its throw entity and on its possible anthropic causes (or concomitant cause), also because the age of the terraces has not been confirmed by dating methods (see also Geomatrix Consultants Inc., 2004). Remember that in the analysis of Comerci (2000) the Orlica fault is classified as transtensive sinistral and this could explain the vertical throw.

Finally, one comment on capable faults in the area: given the approximate location of the epicentre of the 1917 earthquake [Ribarič, (1982): M_S 5.7; Grünthal and Wahlström, (2012): M_W 6.2], both the Orlica and the Artiče fault stand as candidates for that event.

3.2. The present seismicity

The Krško basin is in one of the most seismically active areas in the territory of Slovenia (Ribarič, 1982; Geomatrix Consultants Inc., 2004; Smolar and Macek, 2011). Regarding the present seismicity, the epicentres of 1999 - 2010 confirm that the Krško area is active (see an example in Fig. 5). The biggest events reach magnitudes between 3 and 4, however.

As regards strong motion evidence, we can see in Table 1 that the mechanical accelerometers installed from 1981 to 1989 near the NPP [managed by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) of Skopje] recorded six quakes with meaningful accelerations. In particular, on December 28, 1989, an M_L 3.9 event occurred very close to the plant giving high-frequency acceleration peaks of about 0.4 g on both the horizontal components (Lapajne and Fajfar, 1997).

According to Geomatrix Consultants Inc. (2004): i) 21 local earthquakes were recorded on the free-field at the NPP with modern digital strong-motion instruments during 1994 and the first half of 1995; ii) the analysis of the three strongest earthquakes of the 1995 series indicated that earthquake hypocentres were located approximately 2 km west of the NPP at depths of 1 to 3 km. However, no records would have been obtained on the NPP premises, because the trigger threshold of the accelerometers, fixed at 0.01 g, would have never been exceeded (NPP staff, personal communication).

Table 1 - *PGA*s recorded by mechanical instruments near the NPP from 1981 to 1989 (Fajfar *et al.*, 1994).

date	time	M	peak ground acceleration (cm/s^2)			reference (IZIIS)
			horizontal		vertical	
6.10.81	02:10		213.6	126.4	29.9	81-121
11. 3.84	11:55	4.2	20.2	17.7	18.6	91-04
30. 6.85	14:44	3.1	72.1	40.0	36.0	91-04
28.12.89	20:51	3.9	418.9	423.6	105.5	90-12
28.12.89	22:52	3.4	107.8	119.9	71.0	91-04
28.12.89	22:56	3.3	110.4	91.1	48.9	91-04

We are obviously aware that *PGA* is poorly correlated with damage, especially when carried by high frequencies, as in the case of the 1989 event; we recall these data only as evidence of an ongoing local seismic activity.

3.3. Maximum credible earthquake

Both seismotectonic uncertainties and questionable project constraints prompted us to look at the question of which could be a reasonable maximum earthquake (*M* and distance) for the

Krško plant. At the time of the Krško project (the end of the 1970s), there were no hypotheses on the maximum credible earthquake in the area.

We start from the Regulatory Guide 1.165 (USNRC, 1997: Appendix B), which prescribes that for NPPs an annual probability exceedance of 10^{-5}, corresponding to a T of 100,000 years, is to be considered. Beyond this value, the probabilistic assessment, also due to very large uncertainties, predicts unrealistic large ground motions. See on this the discussion in the case of the Yucca Mountain nuclear waste repository (e.g., Gonzales *et al.*, 2006) and the thorough discussion conducted in the framework of the Pegasos Project (Abrahamson *et al.*, 2002). In practice, these very long return periods imply that one has to include in PSHA also the largest possible earthquake(s) that could possibly affect the NPP.

The scientific community is aware that the exact definition of M_{max} for such a long T is almost an impossible challenge, not to mention the inconsistency of theoretical (dislocation theory) and empirical relationships between the length of the source at depth and the moment magnitude, M_W. Note that Wells and Coppersmith (1994; in the following: WC94) call the length of the source at depth subsurface rupture length (RLD). Most of the uncertainties are, however, due to the insufficient seismotectonic knowledge.

One geological source of inaccuracy is the progressive obscuration of displacements and surface rupture length (SRL) (*sensu* WC94) by erosion and weathering, so that SRL systematically underestimates M for historical earthquakes. This is the reason why Stirling *et al.* (2002) treated instrumental and historical earthquakes separately when developing their qualified empirical relationships. So, according to these authors, if you assume, e.g., SRL = 21.6 km you obtain a corresponding value of M 6.7 for instrumental earthquakes and M 6.9 for historical earthquakes. However, most empirical relationships for thrust faults have a low statistical reliability, and rupture areas scaling is more reliable than SRL (but rupture areas are unknown in our case).

During the aforementioned GNGTS conference, an opinion was expressed that a new earthquake like the M 6.4 Friuli in 1976 would not cause problems to the Krško NPP even if its source were under the reactor, i.e., in near-field conditions (Fajfar, private communication).

However, following the surveys by Geomatrix Consultants Inc. (2004) (see Figs. 6 and 7) new, preliminary, estimations of M_{max} for the NPP of Krško are feasible. In the interpretation by Geomatrix Consultants Inc. (2004), the sinistral strike-slip (or transtensive) Orlica fault seems to be potentially more hazardous than the Artiče reverse fault, because it has a regional significance and is at least 40 km long, whilst the Artiče one is segmented and short. The interpretation by Geomatrix Consultants Inc. (2004) is based on the regional geology and field surveys and also on the seismic lines mentioned in section 3.1.1.. The hypothesis of the simultaneous rupture of the 40 km-long segment of the Orlica Quaternary fault cannot be ruled out.

Thus, we adopted the regression equation for all faults in Table 2A of WC94, st. dev. included, and obtained a mean M_{max} of approximately 6.9 ± 0.3, with preference for the upper value (also see: Sirovich *et al.*, 2012) because we have seen before that SRL provides underestimates for magnitudes of historical earthquakes (Stirling *et al.*, 2002). By using the same SRL and the WC94 equation for strike-slip faults, almost the same value is obtained. Then, the relationships by Stirling *et al.* (2002) give M 7.1 in the case of an instrumental earthquake and M 7.4 for a historical one (and we are in the latter case).

We also use the work by Anderson *et al.* (1996), who included the slip rate in the WC94 relationships. We estimate the slip rate from the 1 m displacement data by Geomatrix Consultants Inc. (2004) along the Artiče fault, and use both the maximum time span of 15,000 years (the last retreat of glacers) and the minimum one (the iron age, i.e., 2,800 years), as reported in Slovenian IGCP Committee (2012). The two combinations give slip rates of 0.07 to 0.40 mm/year (from 1,000 mm/15,000 years to 1,000 mm/2,800 years), respectively. As an independent reference, Kastelic *et al*. (2011) suggest that our study area is inside a region with slow slipping faults (slip rate < 0.3 mm/year). So, if one uses a slip rate of 0.3 mm/year for the area of Krško, the M_{max} obtained from Anderson *et al*. (1996) is approximately 7.1.

Coming back to the smoothed seismicity approach of Fig. 4, for a site some kilometres east of Krško, Smolar and Maček (2011) propose the increase of M_{max} with increasing T as shown in Table 2.

Table 2 - Increase of M_{max} with increasing T calculated by Smolar and Maček (2011) for the region of Krško according to the smoothed seismicity approach.

Return period T (years)	200	475	1,000
Maximum credible magnitude, M_{max}	5.60	5.80	6.25

Incidentally, Herak (personal communication, 2012) and Cizelj (2012) share the opinion that the worst possible earthquake in the region of Krško would have $M_{max} = 7.0$.

Some seismic rules (e.g., France) cut the Gordian knot by assuming M_{max} to be 0.5 units greater than the maximum M of the catalogue, which in our case is $M \approx 6.3$, referred to the Zagreb November 9, 1880 earthquake, located however about 65 km from Krško (Herak *et al*., 2009). This would lead to an $M_{max} = 6.8$ for the Krško region.

In general, we know that the calculation of magnitude is not very accurate; we have an example of this also in the study case: the M_W of the Brežice earthquake of 1917 (early instrumental era) being 5.7 according to Ribarič (1982) and 6.2 following Grünthal and Wahlström (2012). Even greater uncertainties are expected for pre-instrumental events. Thus, in our opinion, when the estimation of M_{max} is dealt with, adding a +0.5 unit is non conservative.

Finally, consider that the authors of Fig. 7 explain that the dashed parts of the Orlica fault exist but are approximately located, and the minimum distance from the NPP is about 2 km. In conclusion, the spatial continuity of the Orlica fault seems to be reliable in the area under study, but its seismic "capacity" (*sensu* capable of generating earthquakes) remains questionable. Therefore, our present speculation on M_{max}=7.2 has a low reliability.

4. Discussion and conclusion

In general, it is worth noting from Fig. 4 that in Italy the *PGA* values are strongly conditioned (perhaps too much) by the geologic interpretation of the active faults; on the contrary, in Slovenia and Croatia the *PGA* values are conditioned by the locations of the historical earthquakes, which could be affected by systematic errors due to the origin of the related historical documentary sources (often concentrated in monasteries and important cities).

As regards the reliability of *PGA* = 0.40 - 0.45 g assigned by the Slovenian official cartography to the NPP region for *T* = 10,000 years, we agree with Cáceres and Avidsson (2000) according to whom prediction of ground motion for *T* longer than, say, twice the length of the catalogue provides highly unreliable results. Thus, we think that this value should not be used as a hazard reference for a NPP; not to mention that more hazard-related engineering parameters should be taken into account, such as peak ground velocity effective peak acceleration, response spectra and so on.

Moreover, we are still faced with two intriguing questions regarding: i) the most relevant shock of the past for the hazard in the area of the NNP, and ii) the nature of the local seismic activity.

Regarding the first question, in the absence of a specific study of disaggregation of hazard [in the Cornell (1968) approach] one cannot understand whether the hazard in Krško is dominated by the November 9, 1880, Zagreb $M \approx 6.3$ earthquake or by the M_W 5.7 - 6.2 local shock of 1917. Furthermore, from the point of view of the local shaking in the NPP area in the past, the intensity VIII caused by the M_W 5.7 - 6.2 local earthquake in 1917 is anyway more relevant than the 423.6 cm/s^2 carried by high frequencies in the 1989 M_L 3.9 shock (see Table 1).

Regarding the second question, the small local earthquakes of 1989 and of the 1994 - 1995 sequence could be compatible with the epicentre proposed for the earthquake of 1917 (Ribarič, 1982). This would confirm that under the NPP site, or very close to it, there are faults that can produce damage, at least to non - aseismic constructions.

Few things can be said, on the other hand, on the local seismic response at the NPP site. The 1880 intensities at Krško (VI - VII) and Brežice (VI) by Ivica Sović (personal communication) could perhaps suggest either a slight amplification at Krško or a deamplification at Brežice, because Brežice is closer to the 1880 epicentre than Krško. Note, however, that the site of the NPP is approximately 2 km away from the Krško village and located in different geomorphological and geotechnical conditions and, therefore, the intensity in the village is not totally valid for the NPP. Amplifications up to three were found for the area of the Krško NPP for frequencies between 0.2 and 3.0 Hz, especially on the radial and vertical component of motion, considering 2D site effects (Čarman, 2006), from both observational and synthetic modelling. A seismic source about 24 km from the NPP was considered.

Finally, on local seismic effects, the reasoning on the absence of amplitude doubling for the total wave reflection at the foundation level under the NPP is, in our opinion, premature. New recordings from the existing accelerometers located on the free-field and in a borehole at -20 m depth, along with new modellings of the entire excavation and of the existing NPP structures would greatly help in this respect.

We come now to the crucial point of the paleoseismological data on the regional faults which cross, or pass close to, the area of the NPP. By the way, the reference USNRC rules were updated on August 22, 2012 (USNRC, 2012). Paleoseismological evidence would contribute to the classification of one, or some, of these faults as faults capable to produce destructive earthquakes of a certain magnitude (e.g., up to *M* 7.2 for the Orlica fault). It is well known that coseismic slips are irregularly distributed on an activated fault plane and that reliable M_{max} are estimated from mean slip. Instead, when very few slip measurements along a km-long outcropping rupture are available, it is impossible to understand if we are dealing with maximum, minimum or intermediate values. Thus, in the study case, many more trenches should be dug to quantify the capabilities of the Artiče fault and, above all, of the Orlica one. Judging the M_{max} of a capable fault from very few slip measurements would be misleading. For example, these concepts were repeated in the most recent, and striking, state-of-the-art-paper by McCalpin (2012), who also called for prudence in this kind of speculations «since we are still in the infancy of paleoseismology (…) not to mention the frequent surprises we have from unknown faults».

In the light of what we have seen here, we think that the working hypothesis of postglacial offsets on the Artiče reverse fault is reliable. Since they are elder than 2,500 - 2,800 years b.p., they could be perhaps ignored for the seismic design of normal housing, but not for critical facilities, that ask for protection against earthquakes with very long return periods.

No clear paleoseismological evidence is available for the Orlica fault, but: i) there is consensus on its regional relevance and activity in Quaternary (which was confirmed in 2004 also by the consultants of the present NPP) and ii) its shape in the seismic section of Fig. 8 could be compatible with the presumed vertical offset of the terrace in the eastern part of the Krško village. Thus, in general, both Orlica and Artiče - and related structures - could be responsible for the ongoing seismic activity and/or be capable of producing future earthquakes.

In this general framework, one can understand how delicate the definition of M_{max} is. Following the French approach (see section 3.3), the $M \approx 6.3$ Zagreb November 9, 1880, earthquake located about 65 km from Krško (Herak *et al.*, 2009), could be an empirical reference for the M_{max} estimate, but - in our opinion - it would lead to a non-conservative assumption.

Consider also that the aforementioned SHARE Project: i) assigned potential $7.0 > M > 6.5$ to three seismogenic sources trending WSW-ENE in the Krško region (Basili *et al.*, 2013), for both fast and slow slipping faults (Kastelic *et al.*, 2011), and ii) decided, for normal housing, to assume M_{max} 0.5 - 0.9 units greater than the maximum M of the catalogue (Woessner *et al.*, 2012). By the way, we do not know the reliabilities of the M assignements to each fault, but agree with M increments > 0.5. Thus, in conclusion, an M_{max} value of 6.9 ± 0.3 seems to be a reasonable working hypothesis for the study area insofar critical facilities are concerned.

In our opinion, the aforementioned results of the stress test (SNSA, 2011) report, regarding for example the consequences of $PGA > 0.8$ g, should be weighed in the context of both the presently known relatively high accelerations due to moderate-magnitude earthquakes, and of the seismotectonic setting of the area. As an example of the former, consider that the M_W 5.9 (Piccinini *et al.*, 2012) earthquake of May 20, 2012 in the Po Valley, Italy, produced $PGA = 0.9$ g on the vertical component at frequencies of engineering interest (De Nardis *et al.*, 2014) and widespread liquefactions (Malagnini *et al.*, 2012). Regarding the latter, the statement reported in the SNSA (2011) «at the end, it needs to be pointed out that seismic events with PGA higher than 0.8 g were estimated to be very rare events at the Krško NPP site. Based on the revised PSHA and SPSA (seismic probability safety assessment), the return period for such an event is considered to be larger than 50,000 years» is in our opinion, not yet demonstrated.

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