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Time-Dependent Seismic Hazard Assessment Based on the Annual Consultation: A Case from the China Seismic Experimental Site (CSES)

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Abstract—We propose an interdisciplinary approach to Time-dependent Neo-deterministic Seismic Hazard Assessment (T-NDSHA) for the China Seismic Experimental Site (CSES) at a one-year time scale. The approach is based on the Neo-deterministic Seismic Hazard Assessment (NDSHA), with the "controlling earthquakes" (or "scenario earthquakes") as defined by the Annual Consultation on the Likelihood of Earthquakes. The Annual Consultation, organized by the China Earthquake Administration (CEA), has been an interdisciplinary practice since 1972, with the output of "alert regions" with increased probabilities of strong earthquakes, featured by real forward forecasting characteristics. We take the year 2014, in which there were four strong earthquakes in the CSES region, as a showcase example to illustrate how the T-NDSHA may be conducted and evaluated. Considering the alert regions provided by the Annual Consultation, the expected strong ground motion parameters and the macroseismic intensities are mapped by the NDSHA algorithms considering the regional Earth structures and the focal mechanisms of historical earthquakes. The estimated intensities are then compared with the observed intensities produced by the actual earthquakes. Evaluation of the performance of such annual seismic hazard assessment is performed using a confusion matrix and Molchan error diagram, respectively, indicating that the combination of the NDSHA and the annual forecasting provides the emergency preparation with a ready-to-use mapping of expected intensities which outperforms random forecasting. The proposed approach provides a substantial improvement to the Annual Consultation, and it can naturally be applied to other regions where intermediate-term middle-range earthquake forecasts are available and where the need for emergency preparation are duly considered.

Keywords: Time-dependent Neo-deterministic Seismic Hazard Assessment (T-NDSHA), China Seismic Experimental Site (CSES), Annual Consultation.

1. Introduction

The Annual Consultation on the Likelihood of Earthquakes (the *Niandu Dizhen Qushi Huishang* in Chinese, in which *Niandu* is annual, *Dizhen* is earthquake, *Qushi* is tendency or likelihood, and *Huishang* is consultation or panel discussion) has been organized by the State Seismological Bureau (SSB, now China Earthquake Administration, CEA) since 1972. The year 2022 is the half-century anniversary of this important practice of forward forecast employing a multidisciplinary approach. Several papers have been published for the introduction (e.g., Wu, 1997; Zhu & Wu, 2007), evaluation (e.g., Shi et al., 2001; Zhuang & Jiang, 2012), and development (e.g., Zhang et al., 2017; Zhao et al., 2010; Wu, 2021) of this comprehensive practice. To improve this practice, it might be necessary to combine the output of the Annual Consultation with reliable seismic hazard assessment (for a review see Panza et al., 2022) so that the annual forecast may play a significant role in the reduction of seismic disaster risk. In this paper we consider the China Seismic Experimental Site (CSES, see Li et al., 2022) with the annual scenario of 2014 as a showcase example to illustrate such a combination.

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2. *The Annual Consultation on the Likelihood of Earthquakes: Main Procedures and Principal Output*

The Annual Consultation Meeting, generally held at the turn of the year, is basically organized in a "matrix". On one hand, from the perspective of monitoring, the analysis of the precursory anomalies is divided into several categories according to different disciplines, namely seismology, geomagnetism/geo-electricity, ground deformation/gravity, underground fluid/geochemistry, and comprehensive analysis. On the other hand, the China Earthquake Administration (CEA) and its provincial earthquake agencies have deployed and have been operating a huge number of observational facilities, either mobile or permanent, monitoring changes in seismicity, deformation, geomagnetic/geo-electric field, and underground water level and water content, among others, with organized quality-control systems and consensus standard for routine data processing. Interdisciplinary discussion is conducted on a regional basis.

Annual earthquake tendency is also assessed in other countries/regions based on various approaches (e.g., Petersen et al., 2017). However, the Annual Consultation on the Likelihood of Earthquakes in China is characterized by its multidisciplinary framework and the role of experienced experts in the comprehensive analysis (Zhang, 2019; Zhu & Wu, 2007). In the consultation, the precursors under consideration are not intrinsically different from those studied in other countries/regions; statistical analysis is applied not only to seismicity but also to the space–time distribution of precursors/anomalies; a panel discussion of experienced experts plays an essential role at the decision-making stage determining the regions at risk for strong earthquakes at a one-year time scale; and case studies of earthquakes play an important role in the accumulation of experiences. The output of the Annual Consultation meeting is to be reported directly to the central government and local governments for engineering reinforcement, enhanced deployment of an earthquake early warning system (EEWS), hazardous objects (such as chemical plants) protection, and especially earthquake emergency preparation, among which the most important is the annual budget of financial and human resources. Considering the current limited capability of earthquake forecast, the report of the Annual Consultation is only for internal use and is kept classified for 3 years.

An example of the output of the Annual Consultation is provided in Fig. 1, which shows the result of the Annual Consultation for the year 2014 in the region of the China Seismic Experimental Site (CSES, Li et al., 2022). Three "alert regions" were identified with increased likelihood of strong to major earthquakes in the year 2014. Evidence leading to the identification of the alert regions includes the following[1]:

Region #1: Border of Sichuan and Yunnan, with expected magnitude of about 7. Inferred from identified anomalies of seismic gap, increase in micro-seismicity, clustering of small earthquakes, the "seismic response window",[2] anomalies in apparent stress and focal mechanisms, abnormal signals at several stations after the 2013 Lushan earthquake; abnormal signals revealed by mobile gravity and geomagnetic observation, GPS-revealed shear strain rate variation, "quasi-synchronization" of anomalies, and clustering of macro-anomalies;
Region #2: Northwestern Yunnan to the border of Sichuan and Tibet, with expected magnitude from 6 to 7. Inferred from identified anomalies including the end of the seismic quiescence, increase in the number of earthquakes above magnitude 3, abnormal deformation, and ground fluid variation;
Region #3: South of Yunnan to southwestern Yunnan, with expected earthquake magnitude of about 6. Inferred from identified anomalies, including seismic quiescence since 2011, activation of micro-earthquakes since 2013, and "response

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[1] China Earthquake Networks Center (CENC) eds., 2013. *Open File of the Annual Consultation on the Likelihood of Earthquakes for the Year 2014*, subject to the Panel Discussion in the Annual Consultation Meeting. Beijing: China Earthquake Administration, in Chinese.

[2] Some regions (i.e., the special "window" here, probably with a peculiar geological structure) in which the increase in seismicity is believed to indicate the increase in the probability of occurrence of bigger earthquakes within a much larger area.

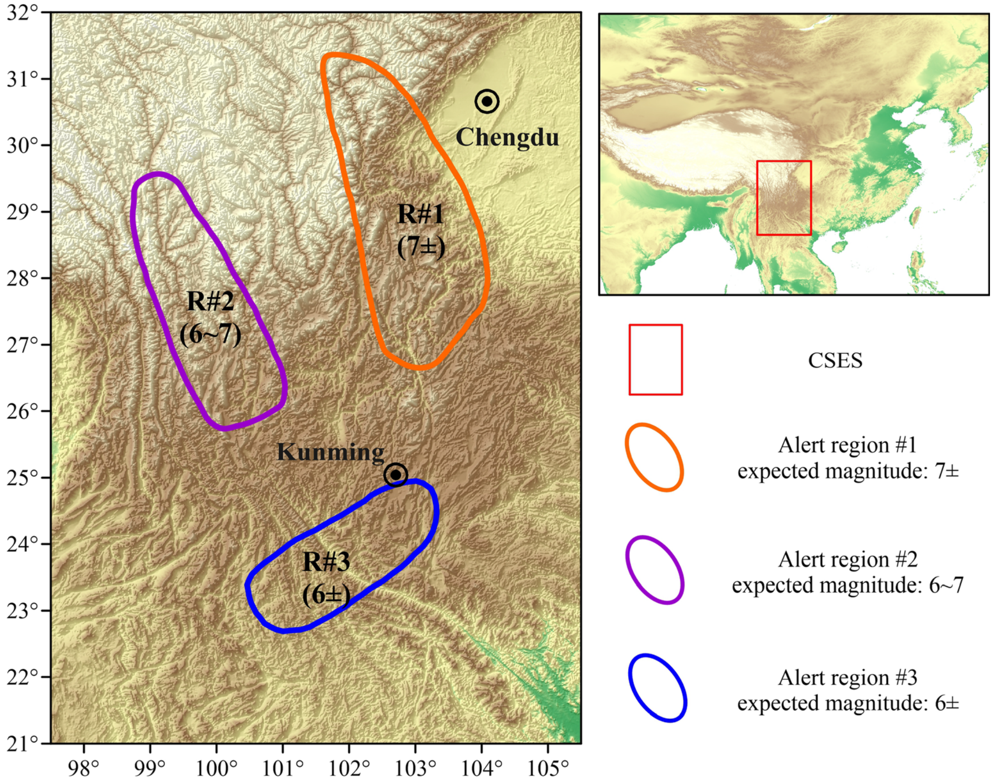

Figure 1
Alert regions identified by the Annual Consultation for the year 2014 within the geographical domain of the China Seismic Experimental Site (CSES, 97.5 °E–105.5 °E, 21 °N–32 °N). See text for more details

earthquakes”,[3] anomalies in mobile geomagnetic observation, anomalies in ground fluid, GPS and cross-fault measurement, “quasi-synchronization” of anomalies around 2012.

This evidence is subjected to a panel discussion at the Annual Consultation Meeting. The discussion may lead to differences in the final version from the initial version, and eliminate some unreliable/controversial/irrelevant evidences. From the list of evidence it may be seen that the approach is multidisciplinary, and the determination of the border of the alert regions (as well as the expected magnitude of earthquakes) based on multidisciplinary data is generally subjective (that is, a decision-making process using the experiences of experts as a “tool” for “data fusion”). For some of the considered years, probability is also presented qualitatively (e.g., “most likely”, “likely”, or “marginally likely”) or quantitatively (in percentile), but such probability is also subjective. Since 2015, the criteria for determining the regions of increased likelihood of strong to major earthquakes and the expected magnitude of the earthquakes have been formally defined and systematically applied (Zhang, 2019). Statistical evaluation showed that the Annual Consultation outperforms random guessing (see Appendix I).

Related to the Annual Consultation, there have been two issues in debate. Firstly, as introduced above, the predicted magnitude range (for example, expected magnitude 6–7) in one “alert region” identified by the Annual Consultation is empirical or even subjective, and is not necessarily related to a possibly quantitative assessment such as 6.5 ± 0.5,

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[3] Earthquakes occurring in some special time interval, in response to stress changes (such as tidal variation or change in Coulomb failure stress caused by other earthquakes), believed to indicate the increase in the probability of occurrence of bigger earthquakes within a larger area.

where 0.5 represents twice the average central value of magnitude global error (e.g., Båth, 1973; Bormann et al., 2007). In this case the target earthquakes will have an expected magnitude between 6 and 7, i.e. 6 $\leq M \leq 7$. If an earthquake occurs with $M > 7$ or $M < 6$, then it is not predicted. This fuzzy approach sometimes led to controversial conclusions when an earthquake occurred in the alert region but was smaller or larger than the "target" earthquake. And here another problem also contributes to the ambiguity: the uncertainty of the magnitude determination. The other controversial issue is that sometimes an earthquake occurred out of the alert region but very near the border, such as the 2013 Lushan, Sichuan, earthquake (Wu et al., 2014) and the 2014 Jinggu, Yunnan, earthquake (which is mentioned in Sect. 5). This case was sometimes noted (being controversial) as "marginally predicted". Because the prediction is not associated with distribution of probabilities, and is not associated with seismic hazard assessment, the evaluation of such forecast is sometimes ambiguous. Partly due to these controversial issues, the Annual Consultation was proposed to be cast in a probabilistic form and combined with seismic hazard assessment (Wu, 2021).

3. *Time-Dependent Neo-Deterministic Seismic Hazard Assessment (T-NDSHA): The Main Ingredients and the Principal Output*

As shown in Fig. 1, the output of the Annual Consultation consists, as a rule, of the set of "alert regions" with their annual seismic hazard (with specification of the sharp border of the regions and expected magnitude range of the "target" earthquakes, sometimes with probabilities). This output, although with considerable room for improvement, is a consistent scientific experiment distinguished by its real forward forecast nature and falsification possibility.[4] Such an experiment has been continuously conducted for half a century and provides an earthquake forecast study with a good (and to some extent, unique) sample for analysis.

What is important is that such an estimate of the increased likelihood of destructive earthquakes, in terms of "alert regions" and expected magnitude range of earthquakes, is not sufficient for people to take readily countermeasures for the reduction of seismic disaster risk. Partly due to this reason, the result of the Annual Consultation has never been published in "real time". One of the improvements to be considered is to reduce the interval between the Annual Consultation result and its release to society by introducing reliable seismic hazard assessment (RSHA) into the Annual Consultation.

The output of the Annual Consultation provides deterministic seismic hazard assessment (DSHA) with "controlling earthquakes" or "scenario earthquakes" (Reiter, 1990). In this paper, we use the Neo-Deterministic Seismic Hazard Assessment (NDSHA) approach, which has been applied in several places around the world (Panza et al., 2022). Building upon the familiarity and long experience of successful engineering practice with DSHA, NDSHA provides comprehensive physical knowledge of (a) the seismic source process, (b) the propagation of seismic waves, and (c) their combined interactions with site conditions, and thus effectively accounts for the *tensor* nature of earthquake ground motions and does not have to rely on the often questionable attenuation relations—these scalars are often identified as Ground Motion Prediction Equations (GMPEs). A recent example of the drawbacks introduced by ignoring the *tensor* nature (of earthquake ground motions) by resorting to scalar quantities is given by Dhakal (2021), who shows that the commonly used GMPEs in Japan may not sufficiently grasp moderate earthquake hazards. This is evidenced by the comparison of reported maximum intensity vs. calculated maximum intensity for 79 damaging moderate magnitude earthquakes in Japan (Dhakal, 2021). This result is not a surprise since it is natural that scalar quantities like GMPEs cannot grasp the *tensor* nature

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4FL01 4FL02 [4] Popper, K. R., 1962. *Conjectures and Refutations: The Growth of Scientific Knowledge.* New York: Basic Books.

of earthquake ground motion (e.g., Aki & Richards, 2009). The use of NDSHA provides realistic synthetic time series of ground shaking at a given location and exploits the best available distribution of the potential earthquake sources for scenario modeling.

Operationally, the NDSHA procedure includes the following steps (Panza & Bela, 2019; Panza et al., 2012, 2022):

Step 1: Preparation of all necessary seismological-geophysical-geological datasets, including earthquake catalogues, focal mechanisms, seismogenic zones, "seismogenic nodes" (Gorshkov et al., 2003; Gvishiani et al., 2020), and structural models.
Step 2: Discretization and smoothing of "effective sources" from earthquake catalogues, selection of seismic sources using seismogenic zones and "seismogenic nodes", determination of characteristic focal mechanisms in each seismogenic zone and node.
Step 3: Computation of synthetic seismograms based on the structural model and the input seismic sources, represented as a tensor at each predefined site. This is the kernel part in the NDSHA.
Step 4: Extraction of peak ground motion parameters (as well as other parameters of interest, including the macroseismic intensities deduced from these peak ground motion parameters) at each site.

4. *Annual Scenario of 2014 for CSES: A Showcase Example*

We consider the geographical domain of the CSES as an example. This experimental site, launched in 2018 as a continuation and extension of the West-Yunnan Earthquake Prediction Experimental Site (started in 1980) and the Sichuan-Yunnan National Experimental Site for Earthquake Monitoring and Prediction (started in 2014), has good observational facilities and scientific background for understanding the regional geodynamics and the mechanism of earthquake preparation and occurrence (Li et al., 2022). In this region some destructive earthquakes occurred, which were either predicted by the Annual Consultation (such as the 2014 Ludian earthquake, see Fig. 3) and "marginally predicted" by the Annual Consultation (such as the 2013 Lushan earthquake, see Wu et al., 2014) or not foreseen by the Annual Consultation (such as the 2008 Wenchuan earthquake, see Wu & Ma, 2012). Moreover, CSES provides a good database of Earth structure models, historical and instrumental earthquake catalogues with focal mechanisms of some earthquakes, and background data of active faults. Benefitting from these databases, Zhang et al. (2021a) computed NDSHA maps for CSES. In this paper we use the same dataset as Zhang et al. (2021a), with the only difference that "controlling earthquakes" or "scenario earthquakes" are those defined by the Annual Consultation.

We consider the year 2014 as a showcase example since in this year several strong earthquakes occurred in this region, and the macroseismic intensity maps can be used to evaluate the performance of the seismic hazard assessment. In the input of "controlling earthquakes" or "scenario earthquakes", one needs to consider not only the "expected earthquakes" defined by the Annual Consultation, but also the "background events", which are possibly out of the scope of the annual forecasting. In Yunnan and its surrounding areas, it was observed that magnitude 5 earthquakes exhibit a distributive and nearly random pattern (Su et al., 2001). In the computation, therefore, we introduce the "background events" falling in the "seismogenic zones" as discretized in Zhang et al. (2021a, b), with a fixed magnitude of 5.0 and focal mechanisms in accordance with the average focal mechanisms of the associated seismogenic zones. The used focal mechanisms for the three "alert regions" are as follows: *Region #1*: strike = 20°, dip = 46°, rake = 72°; *Region #2*: strike = 297°, dip = 58°, rake = 289°; *Region #3*: strike = 52°, dip = 90°, rake = 5°. The seismogenic zones are from the *Seismic ground motion parameters zonation map of China* (GB18306-2015), while the focal mechanism data are from the community database of the China Seismic Experimental Site (CSES, Li et al., 2022) and the GCMT catalogue.[5]

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[5] https://www.globalcmt.org/. Last accessed on March 1, 2022.

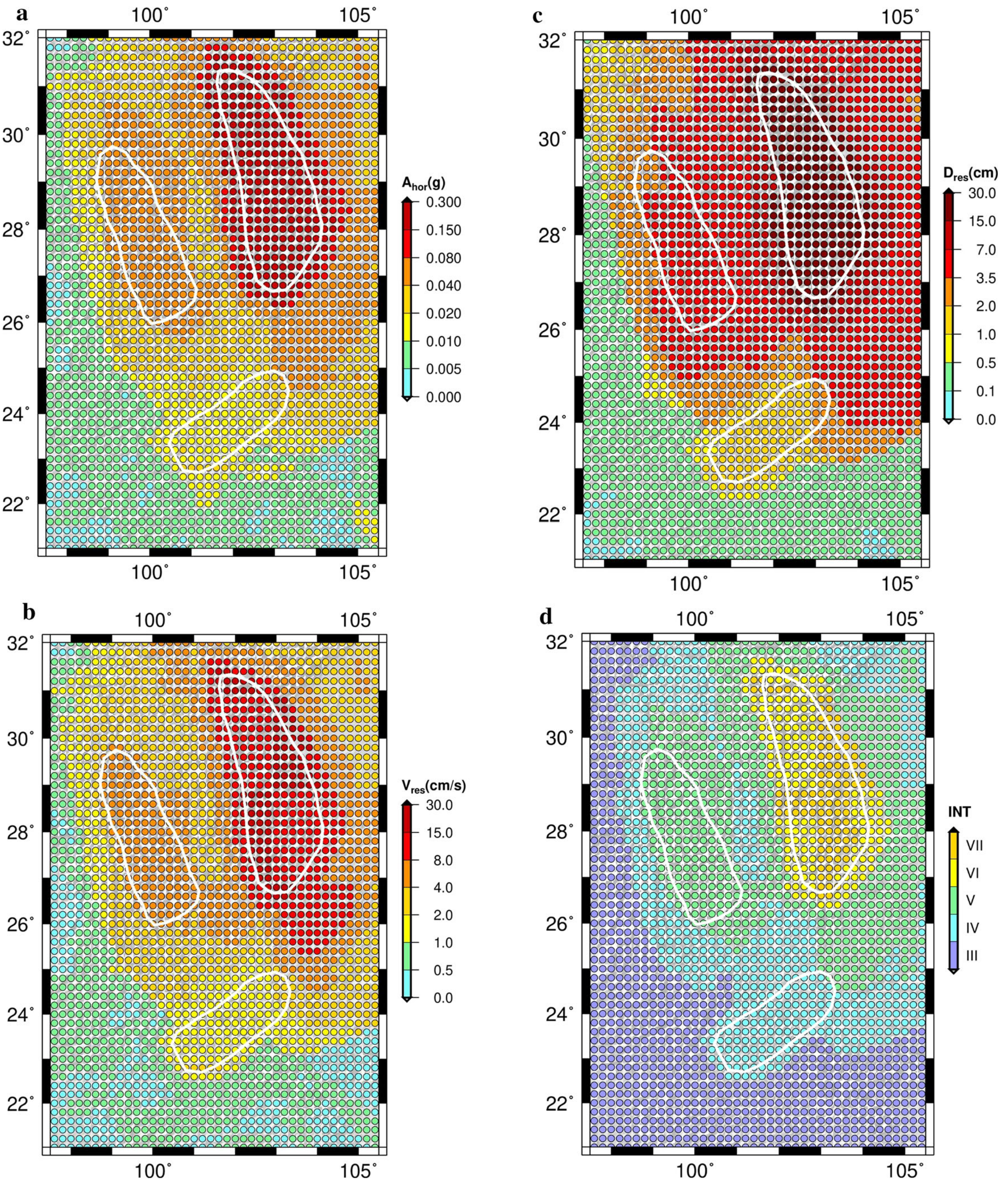

Figure 2

a T-NDSHA predicted maximum horizontal ground acceleration, represented by Design Ground Acceleration (DGA). The white irregular polygons refer to the alert regions shown in Fig. 1. **b** T-NDSHA resultant Peak Ground Velocity (PGV, horizontal component). **c** T-NDSHA resultant Peak Ground Displacement (PGD, horizontal component). **d** Predicted macroseismic intensity (MMI scale) deduced from the DGAs shown in **a**. See the text for details

Figure 2a–c shows the predicted maximum ground acceleration, Peak Ground Velocity (PGV), and Peak Ground Displacement (PGD), respectively, all being horizontal components of ground motions. As usual in NDSHA studies at regional scale (Panza et al., 2001; Panza & Bela, 2019; Panza et al., 2022), the synthetic Peak Ground Acceleration (PGA) is extrapolated to frequencies larger than 1 Hz as follows: (a) computing synthetic seismograms for $T > 1$ s; (b) matching the normative normalized response spectrum (e.g., *Eurocode 8: Design of structures for earthquake resistance*,[6] *Code for seismic design of buildings in China*, GB50011-2010) with the long-period portion of the synthetic normalized spectrum and obtain the "design response spectrum"; and (c) reading the value of the so-obtained "design response spectra" at $T = 0$ s as the Design Ground Acceleration (DGA). For more details, see Panza & Bela (2019). The macroseismic intensity is calculated accordingly with the relationship between PGA/DGA and the Modified Mercalli Intensity (MMI) scale (e.g., Wald et al., 1999), in which the range of predicted PGA/DGA is transformed to macroseismic integer degrees.

5. *Test of the Assessment by Actual Earthquakes*

In 2014, four earthquakes with magnitude greater than 6 occurred in the CSES region, causing varying degrees of destruction and disaster: the May 30, 2014, Yingjiang earthquake ($M_S = 6.1$), the August 3, 2014, Ludian earthquake ($M_S = 6.5$), the October 7, 2014, Jinggu earthquake ($M_S = 6.6$), and the November 22, 2014, Kangding earthquake ($M_S = 6.3$), dated according to the Beijing Time (BJT, UTC + 8 h.) with magnitudes being the fast report magnitude by the China Earthquake Networks Center (CENC), as shown in Table 1 and Fig. 3. In terms of official Annual Consultation, the Ludian and Kangding earthquakes were successfully predicted by the annual forecast; the Jinggu earthquake, with its epicenter about 18 km from the border of the "alert region", was (controversially) regarded as being "marginally predicted"; while the Yingjiang earthquake (probably due to its location near the border of countries where monitoring capabilities were relatively weak) was a failure to predict.[7]

Table 1

Strong earthquakes occurred in 2014 in the geographical range of CSES

Event	Date and origin time yy-mm-dd h:min:s (BJT, UTC + 8)	Place	Hypocenter		M_S
			Latitude, longitude (°, °)	Depth (km)	
1	2014-05-30 09:20:12	Yingjiang, Yunnan	25.03, 97.82	12	6.1
2	2014-08-03 16:30:10	Ludian, Yunnan	27.10, 103.34	12	6.5
3	2014-10-07 21:49:39	Jinggu, Yunnan	23.39, 100.46	5	6.6
4	2014-11-22 16:55:25	Kangding, Sichuan	30.26, 101.69	18	6.3

Data from the China Earthquake Networks Center (CENC) (https://www.cenc.ac.cn, in Chinese; last accessed on March 2, 2022)

It is worth noting here again that the output of the Annual Consultation is in an "alarm-based" form and gives a sharp delineation of the borders of the "alert regions", and that the evaluation of events occurring near the border of the "alert region" is ambiguous and controversial. Unlike the case of the Jinggu earthquake, in other cases, e.g., the April 6, 2009 L'Aquila (Italy) earthquake which occurred some 10 km outside of the identified alert regions, this earthquake was regarded as a failure to predict (Peresan et al., 2011). If, however, the "alert region" is represented by strong ground motion parameters defining seismic hazard, the prediction evaluation can be much more straightforward. As shown by Peresan et al. (2011), considering the case of the L'Aquila earthquake, when the epicenter of the target earthquake is located just outside the "alert region" (hence formally scoring as a failure to predict), the time-

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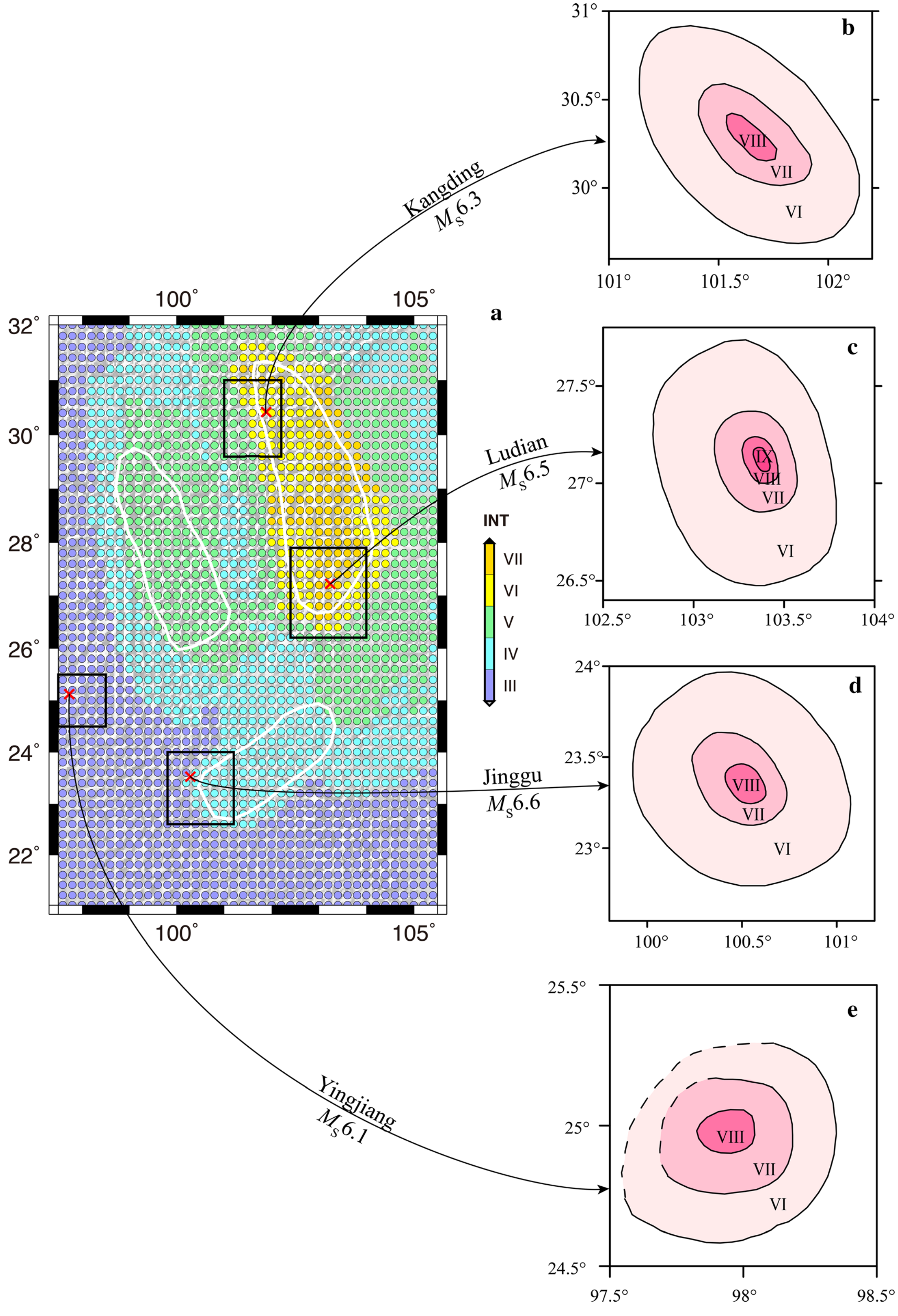
[6] https://eurocodes.jrc.ec.europa.eu/showpage.php?id=138. Last accessed on March 11, 2022.

[7] China Earthquake Networks Center (CENC) eds., 2014. *Open File of the Annual Consultation on the Likelihood of Earthquakes for the Year 2015*, subject to the Panel Discussion in the Annual Consultation Meeting. Beijing: China Earthquake Administration, in Chinese.


a
32°
30°
28°
26°
24°
22°
100°
105°
INT
VII
VI
V
IV
III
Kangding
M_s6.3
Ludian
M_s6.5
Jinggu
M_s6.6
Yingjiang
M_s6.1
b
31°
30.5°
30°
101°
101.5°
102°
VIII
VII
VI
c
27.5°
27°
26.5°
102.5°
103°
103.5°
104°
IX
VIII
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d
24°
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e
25.5°
25°
24.5°
97.5°
98°
98.5°
VIII
VII
VI

◀Figure 3
Strong earthquakes occurred in 2014, with macroseismic intensity maps published based on field investigations. In the intensity maps, intensity is determined according to *The Chinese seismic intensity scale* (GB17742-2008), a regional intensity scale that is similar to the MMI scale and takes into account the conditions of Chinese engineered structures (Chen & Booth, 2011). Dashed isoseismals in subplot (e) describe the extrapolation outside of the territory of China

dependent ground shaking-scenario associated with the prediction effectively assessed the related ground shaking. Accordingly, considering the forecasts in terms of ground motion parameters, rather than in terms of sharp space–time-magnitude windows, may facilitate the interpretation of results, and addresses possible issues associated with earthquake-related uncertainties.

Based on the field investigation organized by the China Earthquake Administration (CEA, according to the *Open Files of the Field Investigation* of these earthquakes as well as the related official news release[8]) macroseismic intensity maps (based on *The Chinese seismic intensity scale*, GB/T 17742-2008, which is quite similar to MMI both qualitatively and quantitatively) were published shortly after the earthquakes, as shown in Fig. 3b–e. In comparing the predicted and actual intensities, two issues have to be kept in mind. Firstly, due to the discrete nature of any macroseismic intensity scale, the error is not less than one unit, and therefore values can be considered really different when the difference is no less than two units. Since any intensity scale is defined as a sequence of natural ordinal numbers, i.e., a scale in which each number tells the position of something in a discrete scale of integers, such as I, II, III, IV, V, etc., we cannot locate any problem for which the artifact of introducing non-integer intensity values within combined experience until now, and the illusion of high precision does little to improve accuracy in the final product resulting from using this pre-instrumental system for recording the sizes of earthquakes as witnessed by their effects. For more details see Panza et al. (2022). Furthermore, the isoseismals naturally contain important information about the properties of earthquake sources, and the consideration, along with the unconventional (smoothing method) modified polynomial filtering (MPF), of the diffuse boundary (DB) method, which visualizes the uncertainty in the isoseismal boundaries, may improve, at the same time, the reliability of the verification tests (Kronrod et al., 2013; Molchan et al., 2002).

The spatial resolutions of the NDSHA map, on one side, and the macroseismic intensity map, on the other side, are different. Therefore, a reasonable comparison can be made only at some discrete sites. In fact, in the NDSHA map, the predicted values of ground motion are provided only at predefined discrete sites (in the standard NDSHA maps, the study area is discretized in cells of 0.2° × 0.2°). These are the sites considered for comparison, i.e., where the values are compared with the results of the actual isoseismals (see Tables 2, 3, 4, 5). Figure 4a shows the confusion matrix, a tool which has been widely used in the study on earthquake early warning (e.g., Minson et al., 2019), of predicted intensity versus actual intensity. From the confusion matrix, the quadrants of "true positive (TP)", "false negative (FN)", "true negative (TN)", and "false positive (FP)" provide a comparative evaluation of the seismic hazard evaluation. In the confusion matrix, the threshold for specific actions towards the reduction of seismic disaster risk is taken as intensity VI, since in actual earthquakes, intensity VI is the indication of slight damage, and the isoseismal of intensity VI borders the "seismically disastrous region" which requires the actions of emergency management—field investigation and emergency management in the relatively lower-intensity areas, and rescue (whenever needed) in the relatively higher-intensity areas. In all the observed intensity maps published, the intensity values lower than VI are not shown; therefore, in the confusion matrix, the FP and TN quadrants are obviously empty.

For each site at which T-NDSHA-predicted intensity and the actual intensity range are available, "successful prediction" and "failure to predict" can

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[8] https://www.cea.gov.cn/cea/dzpd/dzzt/370084/370085/35792857/index.html; http://www.gov.cn/xinwen/2014-08/07/content_2731360.htm; http://www.gov.cn/xinwen/2014-10/11/content_2762886.htm; https://www.cea.gov.cn/cea/xwzx/fzjzyw/5197042/index.html; all in Chinese; Last accessed on March 1, 2022.

Table 2

Predicted versus actual intensities at specific sites: the Yingjiang earthquake

Sites	Latitude (°)	Longitude (°)	Predicted	Actual
1	24.8	97.6	III	VI
2	25.0	97.6	III	VI
3	24.6	97.8	III	VI
4	24.8	97.8	III	VII
5	25.0	97.8	III	VII
6	25.2	97.8	III	VI
7	24.6	98.0	III	VI
8	24.8	98.0	III	VII
9	25.0	98.0	III	VIII
10	25.2	98.0	III	VI
11	24.8	98.2	III	VI
12	25.0	98.2	III	VI
13	25.2	98.2	III	VI

Table 3

Predicted versus actual intensities at specific sites: the Ludian earthquake

Sites	Latitude (°)	Longitude (°)	Predicted	Actual
1	27.2	102.8	VI	VI
2	27.4	102.8	VI	VI
3	26.8	103.0	VII	VI
4	27.0	103.0	VII	VI
5	27.2	103.0	VII	VI
6	27.4	103.0	VII	VI
7	27.6	103.0	VII	VI
8	26.6	103.2	VII	VI
9	26.8	103.2	VII	VI
10	27.0	103.2	VII	VII
11	27.2	103.2	VII	VII
12	27.4	103.2	VII	VI
13	27.6	103.2	VII	VI
14	26.6	103.4	VI	VI
15	26.8	103.4	VII	VI
16	27.0	103.4	VI	VII
17	27.2	103.4	VII	VIII
18	27.4	103.4	VII	VI
19	27.6	103.4	VII	VI
20	26.6	103.6	VI	VI
21	26.8	103.6	VI	VI
22	27.0	103.6	VI	VI
23	27.2	103.6	VI	VI
24	27.4	103.6	VII	VI

Table 4

Predicted versus actual intensities at specific sites: the Jinggu earthquake

Sites	Latitude (°)	Longitude (°)	Predicted	Actual
1	23.2	100.0	III	VI
2	23.4	100.0	III	VI
3	23.6	100.0	III	VI
4	23.0	100.2	III	VI
5	23.2	100.2	III	VI
6	23.4	100.2	IV	VI
7	23.6	100.2	III	VI
8	23.8	100.2	III	VI
9	23.0	100.4	IV	VI
10	23.2	100.4	IV	VII
11	23.4	100.4	IV	VII
12	23.6	100.4	IV	VII
13	23.8	100.4	III	VI
14	22.8	100.6	IV	VI
15	23.0	100.6	IV	VI
16	23.2	100.6	IV	VII
17	23.4	100.6	IV	VII
18	23.6	100.6	IV	VI
19	23.8	100.6	IV	VI
20	23.0	100.8	IV	VI
21	23.2	100.8	IV	VI
22	23.4	100.8	IV	VI
23	23.6	100.8	IV	VI
24	23.0	101.0	IV	VI
25	23.2	101.0	IV	VI
26	23.4	101.0	IV	VI

be defined as follows. If a data point falls into the TP quadrant, then it is a "successful prediction"; otherwise, if a data point falls into the FN quadrant, then it is a "failure to predict". In the evaluation, not only hits but also false alarms must be considered. In the Molchan error diagram, this is represented by the fraction of alarm areas versus the total area. In our evaluation, if at a site the predicted intensity is higher than VI, we have a "prediction". It may be seen from Fig. 4b that on one hand, the T-NDSHA outperforms random guessing to some extent. On the other hand, because the "target events" defined in this case, namely the sites with predicted and actual intensity, are correlated with each other—that is, for one earthquake we may have several sampling points—the assessment of the confidence level based on the number of "target events" is still an open problem that will be the subject of future investigations. Or simply speaking, the diagonal is naturally correct, but the dashed lines representing the confidence levels from 1%, 5%, 25%, and 50% to about 100%, respectively, are questionable.

Considering that the error of macroseismic data is not less than one unit, in the Molchan error diagrams

Table 5

Predicted versus actual intensities at specific sites: the Kangding earthquake

Sites	Latitude (°)	Longitude (°)	Predicted	Actual
1	30.4	101.2	V	VI
2	30.6	101.2	V	VI
3	30.8	101.2	V	VI
4	30.0	101.4	V	VI
5	30.2	101.4	V	VI
6	30.4	101.4	V	VI
7	30.6	101.4	VI	VI
8	30.8	101.4	VI	VI
9	29.8	101.6	V	VI
10	30.0	101.6	VI	VI
11	30.2	101.6	VI	VII
12	30.4	101.6	VI	VIII
13	30.6	101.6	VI	VI
14	30.8	101.6	VI	VI
15	29.8	101.8	VI	VI
16	30.0	101.8	VI	VI
17	30.2	101.8	VI	VII
18	30.4	101.8	VI	VI
19	30.6	101.8	VI	VI
20	29.8	102.0	VI	VI
21	30.0	102.0	VI	VI
22	30.2	102.0	VI	VI
23	30.4	102.0	VI	VI

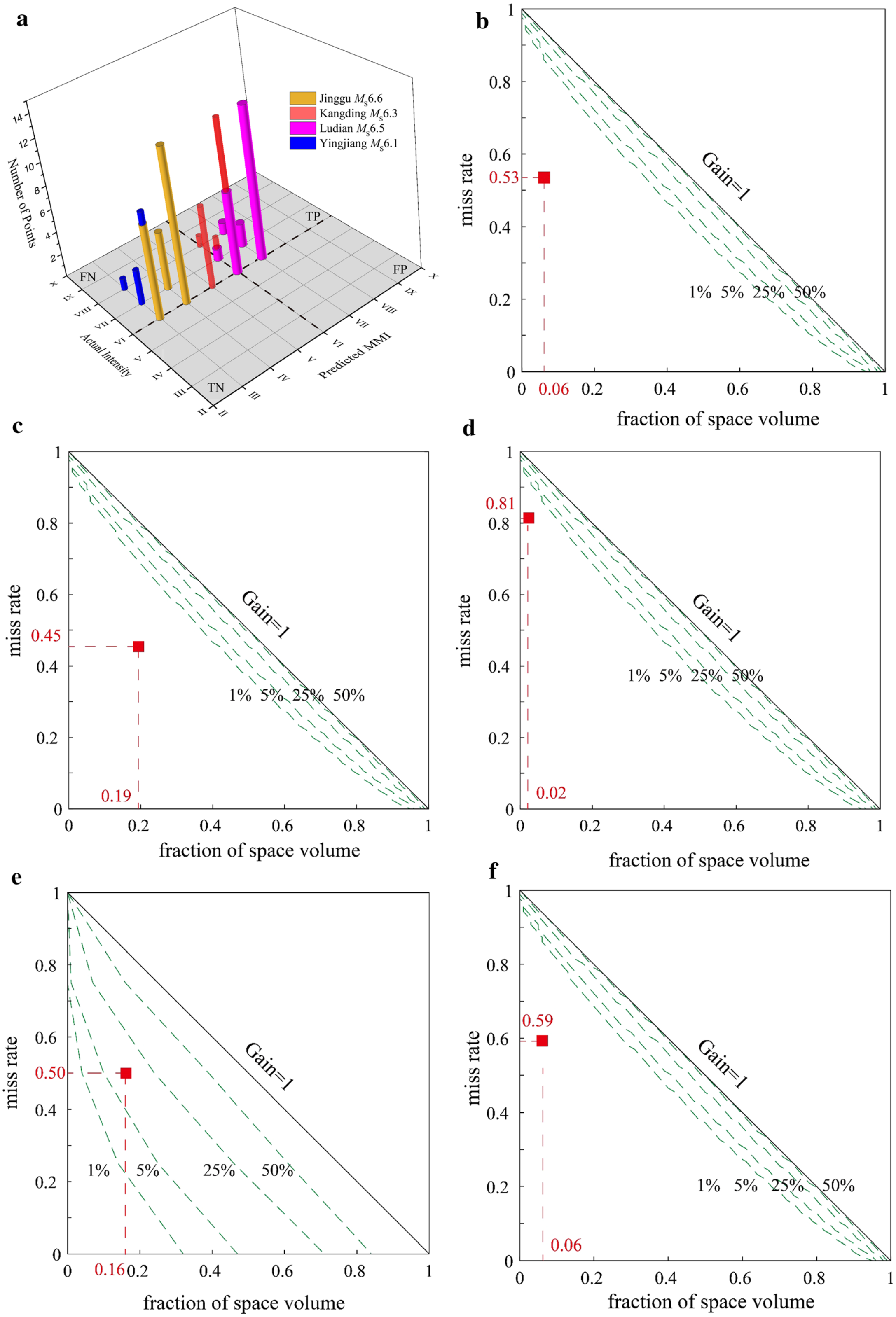
shown in Fig. 4c, d we also consider the "best case" (i.e. all the T-NDSHA-predicted intensities plus one unit) and the "worst case" (i.e. all the T-NDSHA-predicted intensities minus one unit). For reference, the Molchan error diagram in Fig. 4e shows the performance of the Annual Consultation itself (that is, the prediction of the earthquakes) for the year 2014. It can be seen that the performance of the T-NDSHA (with total error of 0.59) is near, and slightly better than, that of the Annual Consultation (with total error of 0.66). On the other hand, however, the "best case" and the "worst case" as discussed here (indicated by the predicted ground motion parameters or intensities) are not necessarily related to the "best case" or the "worst case" of prediction. As a matter of fact, when considering the performance of prediction, we have to consider not only the miss rate but also the fraction of space volume.

The T-NDSHA based on the annual forecast is mainly focused on the annual countermeasures such as the emergency plan; therefore, the evaluation of T-NDSHA is different from that of the NDSHA, which mainly focuses on engineering purposes. In the NDSHA case, as we know, if the predicted intensity is no less than the actual intensity, the prediction is a "success"; otherwise, if the predicted intensity is less than the actual intensity, the prediction is a "failure". Finally, if the predicted intensity is no less than a prescribed intensity (for example larger than VI) but the actual intensity is less than this intensity threshold, the prediction is a "false alarm". Simply, but not exactly, the evaluation at the annual time scale is a kind of *sensu lato* evaluation, and the evaluation at a longer time scale (say 50 years) is a kind of *sensu stricto* evaluation. But they are both useful in practice, when SHA is estimated in a reliable way. The only difference lies in their practical purposes. As a reference, Fig. 4f presents the Molchan diagram of the *sensu stricto* evaluation, with a clear feature of the increase in the miss rate.

Despite that the overall assessment of seismic hazard has a good performance in terms of either the confusion matrix or the Molchan error diagram, as discussed above, it has to be noted that for some cases there are still large discrepancies between the predicted intensity and the actual one, such as in the case of the Yingjiang earthquake which is not predicted by the Annual Consultation (Table 2). This is a natural consequence of the fact that, similar to all the DSHA approaches, NDSHA belongs to the class of algorithms known as "garbage-in/garbage-out", and therefore it is dependent on the "controlling earthquakes". In the case discussed in this work, the "controlling earthquakes" are the possible impending earthquakes defined according to the Annual Consultation.

6. *Discussion and Conclusions*

Characterized by its multidisciplinary organization and by the role of a panel discussion of experienced experts, the Annual Consultation on the Likelihood of Earthquakes has been organized by the SSB (now CEA) for 50 years. The output of the Annual Consultation is, as a rule, the identification of "alert regions" with their annual seismic hazard (with clear specification of the border of the regions and


a
Jinggu M_S6.6
Kangding M_S6.3
Ludian M_S6.5
Yingjiang M_S6.1
Number of Points
2
4
6
8
10
12
14
FN
TP
FP
TN
Actual Intensity
Predicted MMI
II
III
IV
V
VI
VII
VIII
IX
X
b
miss rate
fraction of space volume
0.53
0.06
Gain=1
1%
5%
25%
50%
0
0.2
0.4
0.6
0.8
1
c
miss rate
fraction of space volume
0.45
0.19
Gain=1
1%
5%
25%
50%
d
miss rate
fraction of space volume
0.81
0.02
Gain=1
1%
5%
25%
50%
e
miss rate
fraction of space volume
0.50
0.16
Gain=1
1%
5%
25%
50%
f
miss rate
fraction of space volume
0.59
0.06
Gain=1
1%
5%
25%
50%

◀Figure 4

a Confusion matrix for T-NDSHA as compared with the actual cases of earthquakes. TP is “true positive” and refers to “correct alert” (or “successful hit”), i.e., both the predicted and actual macroseismic intensity exceed a threshold (in this paper, we take VI as the threshold); FP is “false positive” and refers to the case that the predicted macroseismic intensity is larger than VI but the actual intensity is smaller than VI; FN is “false negative” and refers to “failure to predict”), i.e., the predicted macroseismic intensity is smaller than VI but the actual intensity is larger than VI; and TN is “true negative” and refers to the case that both predicted and actual intensities are smaller than VI. Generally, the published intensity maps do not include the intensities smaller than VI, therefore the FP and TN quadrants are obviously empty. **b** Molchan error diagram of the T-NDSHA for the year 2014. See text for details. **c** Molchan error diagram of the T-NDSHA for the year 2014: the “best case”. See text for details. **d** Molchan error diagram of the T-NDSHA for the year 2014: the “worst case”. See text for details. **e** Molchan error diagram of the annual forecast for the year 2014 during which four earthquakes occurred (fraction of space volume: 0.16, miss rate: 0.50). See text for details. **f** Molchan error diagram of T-NDSHA for the year 2014: the *sensu stricto* evaluation. See text for details

expected magnitude range of the “target” earthquakes). This scientific product outperforms random guessing and is potentially useful for the reduction of seismic disaster risk. The potential usefulness of this scientific activity is to be further excavated by making use of the cutting-edge achievements of modern seismology.

For improving the application of the Annual Consultation, we propose combining the output of the annual earthquake forecast with a reliable seismic hazard assessment, like NDSHA. As a showcase example to illustrate such a combination, we consider the CSES in southwest China. We focus on the year 2014, a time interval during which strong earthquakes occurred in Yingjiang, Ludian, Jinggu, and Kangding, respectively. The T-NDSHA uses the “controlling earthquakes” (or “scenario earthquakes”) that are the result of the Annual Consultation plus the “background events” based on the characteristics of background seismicity. Such an approach may make the Annual Consultation results readily useful for engineering reinforcement, hazardous object protection, and earthquake emergency preparation, among others. It can be expected that with more and better data coming in (such as site condition and exposure data), especially when the spatial resolution of the data is enhanced, the proposed T-NDSHA based upon the Annual Consultation-NDSHA combined approach may play an increasingly important role in the enhancement of seismic disaster resilience.

The advantage of the combination of NDSHA with the Annual Consultation can be evidenced by the following “detail.” [illegible]he whole paper, the magnitude of earthquakes appeared repeatedly. In general in seismological observations, for strong to major earthquakes and for smaller earthquakes, surface wave magnitude Ms and local magnitude M_{L} are instrumentally measured, respectively (Båth, 1973). For recent major to great earthquakes, moment magnitude M_{W} is instrumentally determined. In the general discussion, the simple word “magnitude” is used in all these cases, with some consideration of the transfer from one magnitude to the other. In earthquake forecasting, specific rules should be defined to univocally identify the operating magnitude of the target events (e.g. magnitude type, agency, conversion rules. See Peresan et al., 2005), In the Annual Consultation, however, the difference between different magnitudes, as well as the errors introduced by the magnitude conversion, is not considered. Therefore, for some earthquakes it is difficult to judge whether they are successfully predicted by the forecasting considering only their magnitude, such as the Yingjiang M_{S} 6.1 earthquake (see Sect. 5). The introduction of NDSHA makes it possible to compare the intensities and even strong ground motion parameters (whenever feasible), and largely avoids the problems caused by the uncertainties of magnitudes.

NDSHA takes advantage of the synergy between to-date available pattern recognition of earthquake-prone areas (PREPA), intermediate-term earthquake prediction (ITEP) of different spatial accuracy, scenario-based seismic hazard analysis (SSHA), Unified Scaling Law for Earthquakes (USLE, Kossobokov & Mazhkenov, 1994; Nekrasova et al., 2020; Parvez et al., 2014) that accounts for the fractal distribution of seismic occurrence, and Geodetic Data Analysis (GDA) of GPS and other determinations (Panza et al., 2022). In this paper, we illustrate how the Annual Consultation as a specific approach to intermediate-term earthquake prediction may be combined with NDSHA. Since NDSHA, unlike traditional SHAs, provides comprehensive physical knowledge of the seismic source process, the propagation of seismic waves, and their combined interactions with site conditions, and thus effectively accounts for the tensor nature of earthquake ground motions (Aki & Richards, 2009; Bela & Panza, 2021; Panza & Bela, 2019), it is naturally suitable for region-specific emergency preparation. In this perspective, NDSHA, combined with intermediate-term middle-range earthquake forecasting, could enhance the emergency response and not be limited to academic study.

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Appendix

Appendix I: Statistical evaluation of the Annual Consultation

Up to now, only a few results of the Annual Consultation have been published in widely accessible academic journals (especially in English). Therefore, the results, methodology and philosophy of this approach are still not well known among the international seismological communities. Statistical evaluation of the Annual Consultation has been conducted since the turn of the century (e.g., Shi et al., 2001; Zhang et al., 2002). In this appendix we recapitulate and discuss some of the important results of the statistical evaluation of the Annual Consultation.

In the work of Shi et al. (2001) and Zhang et al. (2002), the evaluation uses the R-value (Xu, 1989), that is, hit rate minus false alarm rate. In a similar perspective to the receiver operating characteristic (ROC) test (Swets, 1973), if the R-value is positive, then the prediction outperforms random guessing. In fact, the R-value corresponds to the vertical axis minus the horizontal axis in the ROC diagram for a specific prediction in the "alarm-based" form. Since the beginning of the twenty-first century, the performance of the Annual Consultation, in terms of the R-value, has been stable, with a slight increase (about 0.194 from 1990 to 1999, about 0.345 from 2000 to 2007, and about 0.353 from 2005 to 2015, Zhang, 2019). Therefore, the result of Shi et al. (2001) and Zhang et al. (2002), although not to date, is reproducible and representative.

Table 6 lists the original data used by Zhang et al. (2002), sampled by binning the whole territory of China (without considering the Tibetan plateau and Taiwan island, which were not covered by the Annual Consultation in due time) into 931 rectangular boxes. The evaluation can also be implemented by the Molchan error diagram (Molchan, 2010), as shown in Fig. 5.

Table 6

Data used in Zhang et al. (2002) for the evaluation of the Annual Consultation with parameters used in the Molchan error diagram added

Year	Number of predicted earthquakes	Total number of earthquakes	Number of cells with alarms	Total number of cells	*R*-value	Miss rate	Fraction of space volume	Total error
1990	2	12	66	931	0.097	0.83	0.071	0.90
1991	5	19	118	931	0.139	0.74	0.127	0.86
1992	3	10	102	931	0.193	0.70	0.110	0.81
1993	3	14	89	931	0.121	0.79	0.096	0.88
1994	1	10	60	931	0.036	0.90	0.064	0.96
1995	5	18	104	931	0.170	0.72	0.112	0.83
1996	5	11	110	931	0.340	0.55	0.118	0.66
1997	4	11	95	931	0.265	0.64	0.102	0.74
1998	3	7	77	931	0.349	0.57	0.083	0.65
1999	4	13	86	931	0.228	0.69	0.092	0.78
2000	5	9	84	931	0.470	0.44	0.090	0.53
Total	40	134	991	10,241	0.205	0.70	0.097	0.80

Note: the first six columns of data are from Zhang et al. (2002). The last three columns of data are deduced from the original data of Zhang et al. (2002) for the test by the Molchan error diagram (Molchan, 2010). Total error is calculated by the sum of the miss rate and the fraction of space volume. The case that the total error is equal to 1 corresponds to a random guess. The lower the total error, the better the forecasts (see Peresan, 2018)

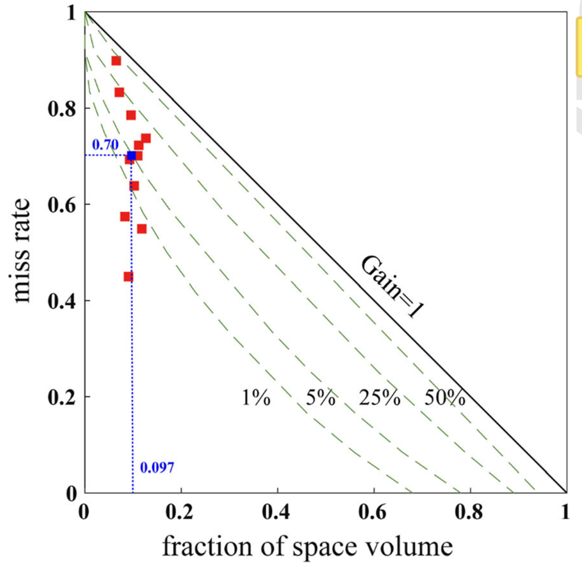

Figure 5
Molchan error diagram of Annual Consultation results from 1990–2000 in Table 6. The point in blue indicates the total

Similar to the concept of "Seismic Roulette" (Kossobokov & Shebalin, 2003; Kossobokov et al., 1999), "gambling score" is also used for the evaluation of the Annual Consultation (e.g., Zhuang & Jiang, 2012), which shows that the Annual Consultation outperforms random guessing to some extent; meanwhile, such a performance relies to a large extent on the seismicity. However, as pointed out by Molchan et al. (2017), such gambling score may underestimate the performance when the forecast is in "alarm-based" form.

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