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NDSHA: A new paradigm for reliable seismic hazard assessment

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ABSTRACT

A New Paradigm is needed for Reliable Seismic Hazard Assessment RSHA, not only from consideration of (a) the huge human losses experienced in the many recently destructive earthquakes worldwide; but also from (b) theoretical considerations of seismic wave generation and propagation phenomena through often non-homogeneous media within the earth's crust, particularly when large and more complex fault ruptures occur. The Neo-Deterministic Seismic Hazard Assessment (NDSHA) method, proposed some twenty years ago, is found to reliably and realistically simulate the wide suite of earthquake ground motions that may impact civil populations as well as their heritage buildings. The scenario-based NDSHA modeling technique is developed from comprehensive physical knowledge of: (i) the seismic source process; (ii) the propagation of earthquake waves; and (iii) their combined interactions with site effects. Thus, NDSHA effectively accounts for the tensor nature of earthquake ground motions: (a) formally described as the tensor product of the earthquake source functions and the Green's functions of the transmitting (pathway) medium; and (b) more informally described as mathematical arrays of numbers or functions (indices) "that transform according to certain rules under a change of coordinates." Importantly, NDSHA therefore uses all available information about the spacial distribution of large magnitude earthquake phenomena, including: (a) Maximum Credible Earthquake (MCE) – which is based on seismic history and seismotectonics; and (b) geological and geophysical data. Thus it does not rely on scalar empirical ground motion attenuation models (GMPEs), as these are often both: (a) weakly constrained by available observations; and (b) fundamentally unable to account for the tensor nature of earthquake ground motions.

INTRODUCTION

Why a New Paradigm of Seismic Hazard Assessment?

It has now been more than 50 years since the original *creation* of the *concept* of Engineering Seismic Risk Analysis (Cornell, 1968). And since it is a "concept" — meaning different things in the minds of its different users, modifiers, practitioners and victims (Saxe, 1873; McGuire, 1976; Sauter, 1996; Newmark and Rosenblueth, 1971; Tall and Vinner, 1981; Bolt, 1991; McGuire, 1992, 1995; USGS PSHA – WGCEP, 1995; BSSC, 1998b; Hwang, 2000; BSSC, 2003a; Field et al, 2003; Fajfar and Krawinkler, 2004; McGuire, 2008; FEMA P-749, 2010; Kahneman, 2011; USGS PSHA, 2013b; Marzocchi and Jordan, 2017; and Mulargia et al., 2017), it was easily *transposed* and *transformed* into "Probabilistic Seismic Hazard Analysis" (*sometimes* "Assessment") or PSHA (McGuire, 1976; EERI PSHA, 1984; Reiter, 1991; Allen, 1995; Kramer, 1996; Sauter, 1996; USGS PSHA, 2013b; Wang and Cobb, 2013; and Stirling, 2014) where it then subsequently became the *benchmark standard* for determining earthquake-resistant design requirements in U.S. Building Codes, starting in 1988 (ATC 3-06, 1978; BSSC, 1985; USGS PSHA, 1986; Nat. Res. Council, 1988; Zacher, 1990; McGuire, 1995; Beavers, 2002; McGuire 2004, McGuire, 2008; and Ghosh and Henry, 2009), and subsequently in (too) many other countries worldwide (Giardini et al, 1999, 2003). Since, in these last *three decades*, not only most … but actually *all* of PSHA's *shortcomings* (and unfortunately also *fatal* drawbacks) have come to light worldwide (Kossobokov and Nekrasova, 2012) — for a recent review see Jia (2018) and references therein:

> ***A New Paradigm is needed, therefore, if Disaster Risk Mitigation is to actually succeed in fulfilling its very worthy goals!***

Echoing and amplifying the cautions and warnings of dozens of earlier papers (e.g. Grandori, (1991); Krinitzsky, 1993a, 1993b, 1995; Molchan et al, 1997; Castanos and Lomnitz, 2002; Krinitzsky, 2003; Wang and Ormsbee, 2005; Klügel, 2007; Wang, 2008; Mualchin, 2011; Nekrasova et al, 2011; Wang, 2011, 2012; ISSO, 2012; Panza et al, 2012, 2014; Bela, 2014; Klügel, 2015; Panza and Peresan, 2016) … most *recently* Geller et al, (2016) and Mulargia et al. (2017) have forcefully concluded: (1) that everyone involved in seismic safety concerns should acknowledge the demonstrated *shortcomings* of PSHA (Probabilistic Seismic Hazard Analysis); (2) that its use as the familiar,

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sacrosanct and unquestioningly-relied-upon *black box* standard for civil protection and public well-being must *cease*; and (3) that most certainly a *new paradigm* is needed!

The Neo-Deterministic Seismic Hazard Assessment methodology, NDSHA, developed at the end of the past millennium and described in detail by Panza et al, (1996, 2001, 2012), supplies a much more *scientifically-based* solution to the problems of *reliably* characterizing earthquake hazards.

These "acknowledged and demonstrated *shortcomings* of PSHA" persist, because (a) objective testing has *never* corroborated the validity of PSHA (Stark, 2017), which purports "to quantify the rate (or probability) of exceeding various ground-motion levels at a site (or a map of sites), given all possible earthquakes" (Field et al, 2003; Field, 2010); and (b) PSHA seismic hazard maps are *non-stable* over multiple derivations and result in "up-and-down" (*yo-yoing*) changes in engineering design codes (Beavers, 2002; Ghosh and Henry, 2009; USGS Project 17, 2015; USGS PSHA 2015a,b,c; Hamburger, 2016; Bruneau and MacRae, 2017).

"The PSHA Divergence Issue"

"It's difficult to make predictions, especially about the future."

The numerical/analytical approach for PSHA was *first* formalized by the late Allin Cornell (1938–2007) in 1968, very early in Cornell's career, as previously mentioned (Reiter, 1991; McGuire, 2008; Klügel, 2011); but it was *actually* titled "Engineering Seismic Risk Analysis" at that time. This was *later* "computer coded" by Robin McGuire in 1976 ("hence the so-called Cornell - McGuire PSHA" — Wang, 2012; McGuire, 1976).

Twenty-five years later, after just some 15 years of applied practice, a *review* of the "present-state-of-the-art" was conducted (by *necessity*) jointly by US Nuclear Regulatory Commission (NRC), US Dept. of Energy (DOE), and Electric Power Research Institute (EPRI) — because, they wrote, the current *state-of-the-practice*, "due to large uncertainties in all the geosciences data and in their modeling," meant (i) "multiple [hazard] model interpretations were often possible"; and further (ii) that disagreement among experts was resulting in "disagreement on the selection of ground motion for design at a given site." (NUREG-1488, 1993; SSHAC, 1997; Nat. Res. Council, 1997; and Hanks, 1997).

In regard to *everyday* engineering practice considerations, it was not until 1982 that the U.S. Geological Survey USGS had completed its only *second* PSHA hazard mapping attempt: "Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States", *U.S. Geol. Surv. Open-File Rep. 82–1033* (Algermissen, 1969; Algermissen and Perkins, 1976; Algermissen et al, 1982), now infused with monies resulting from the establishment of the National Earthquake Hazards Reduction Program NEHRP (under the Earthquake Hazards Reduction Act of 1977, Public Law (PL) 95–124.) — (Hanks, 1985; OTA, 1995; Smith, 2012) https://www.nehrp.gov/about/history.htm

"The Charleston issue"

"If you find a path with no obstacles, it probably doesn't lead anywhere."

When in that *same year* (1982) the USGS had announced to the US NRC "that an 1886 Charleston-size earthquake (MCE ≈ 7.5) could occur anywhere along the Eastern Seaboard in geologic/tectonic settings similar to that near Charleston, South Carolina" … according to Hanks (1997): (i) "the placement of a 'deterministic' M ≈ 7.5 earthquake anywhere in this seismotectonics terrain would impose *forbidding* demands on the design and construction of critical facilities along the entire eastern seaboard between Maine and Florida; therefore (ii) the only viable way of dealing with the *Charleston issue* was to treat it *probabilistically*, that is to recognize that while a Charleston-type earthquake *could* occur *anywhere* in this seismotectonics terrain, the *chances* of it occurring close to any nuclear reactor in the next 50 years or so are still *quite small*."

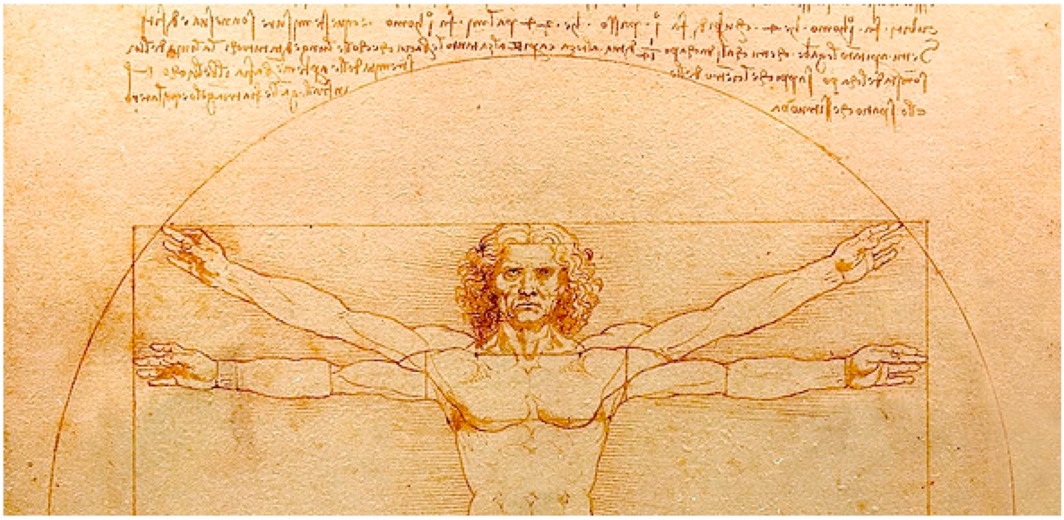
More specifically, within that time of various applications, most noticeably for *critical facilities* such as nuclear power plants, PSHA could still not be validated — because of its systemic "divergence issue" … i.e. *The Instability of the PSHA Process!*

"When the US NRC, the US DOE, and EPRI came together to co-sponsor the Senior Seismic Hazard Analysis Committee (the 'SSHAC Committee') in 1993, it was because there was a *crisis of confidence* in the field of probabilistic seismic hazard analysis (psha). This crisis had come about because two very prestigious, extensive, and very costly (multi-million-dollar) *multi-expert* PSHA studies, one sponsored by the US NRC and carried out under the leadership of experts at Lawrence Livermore National Laboratory and the other sponsored by EPRI, had come to *quite different overall conclusions* about the seismic hazard facing the several dozen nuclear power plant sites in the Eastern US. This difference occurred even though the two studies had [i] involved many of the same seismic hazard experts, [ii] had used similar technical and procedural methods to go about their work, and [iii] had been quite open about the 'boundary conditions' or 'rules' under which each of the two studies had been undertaken." (Budnitz, 2012).

The seven member Senior Seismic Hazard Analysis Committee SSHAC worked from early 1993 until late 1995, included Allin Cornell ("the brightest shining light in the group," Budnitz would write later), and was "supported by a large number of other experts" (SSHAC, 1997). Although the SSHAC committee *acknowledged* that "the most important and fundamental fact that must be understood about a PSHA is that the objective of estimating *annual frequencies of exceedance* of earthquake-caused ground motions can be attained only with significant *uncertainty*," they nevertheless *concluded* (without documentation) "that differences are due to procedural [elicitation and incorporation of *expert opinion*] rather than technical differences."

Subsequently, almost two decades later, following some workshops and other previous groundwork (Hanks et al, 2009) — "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies", NUREG-2117. Rev. 1, sought to *update* the original SSHAC report, "based on recent efforts to capture the lessons learned in the PSHA studies that have been undertaken using the SSHAC Guidelines." (Kammerer et al, 2012). The "Center, Body and Range of the Informed Technical Community" from NUREG NR-6372 (i.e. SSHAC, 1997) was *re-emphasized* as a key SSHAC concept, and "essential steps in SSHAC Level 3 and 4 Processes" were also clarified. However, none of these post-1997 "SSHAC Guideline" *psha evolutions* and *progress reports* could ever overcome the fact that PSHA still remained *more logic-tree art than science* — despite its (i) new SSHAC dogma (equating *expert opinion* with *data*); (ii) *esoteric* ("over-educated") vocabulary; and (iii) *elaborate* and *prestigious* committee structures and protocols!

Perhaps the most revealing illustration of this conundrum was the PEGASOS Research Project, SWISS NPP utilities' http://www.swissnuclear.ch/en http://www.swissnuclear.ch/en/pegasos-durchfuehrung.html planning efforts between 2000 and 2004 to *review* and *assess* the suitability for the Swiss nuclear power industry to "adopt the recommended use of SSHAC - procedures as a basis for the evaluation of the seismic hazard" at four Swiss Nuclear Power Plants — utilizing "the *highest* SSHAC Level 4 criteria for Seismic PRA without correction." (PEGASOS, 2004; Klügel, 2005 a,b,c; 2009).



The Center, Body and Range
"Leonardo da Vinci's Contribution to Science:"

"Patterns across disciplines can lead to great leaps in human understanding".

We are reminded *here* that it was Leonardo da Vinci's "ability to combine *art* and *science*, made iconic by his drawing of what may be himself inside a circle and a square, [that] remains the enduring recipe for innovation." (Isaacson, 2017)* While in 1490 Leonardo took *swipes* against "those who would cite *ancient wisdom* rather than make observations of their own," he "did not remain merely a disciple of experiments." "We can see in Leonardo a dramatic attempt to appraise properly the mutual relation of theory to experiment," wrote the twentieth-century physicist Leopold Infeld. (as quoted in Isaacson, 2017).

"Maybe you are searching among the branches, for what only appears in the roots."

And so PSHA's difficulties ("The PSHA Divergence Issue") and conundrums (i.e. *The Instability of the PSHA Process*) have nevertheless *persisted* (USGS PSHA, 1986 – "Workshop on Probabilistic Earthquake-Hazard Assessments"; Brune et al, 1996– "Precariously Balanced Rocks and Seismic Risk"; Reiter, 2003 – "NWTRB Perspective on Extreme Ground Motions [Results of the Yucca Mountain PSHA]"; PEGASOS, 2004 – "Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (PEGASOS Project)"; Pilkey and Pilkey-Jarvis, 2007 – "Yucca Mountain: A Million Years of Certainty:" *in* Useless Arithmetic: Why Environmental Scientists Can't Predict the Future; Panza et al, 2014– "Why are the Standard Probabilistic Methods of Estimating Seismic Hazard and Risk Too Often Wrong"; Stirling, 2014 – "The Continued Utility of Probabilistic Seismic Hazard Assessment"; and Stark, 2017– "Pay No Attention to the Model Behind the Curtain".)

"Do you need a number…
to see that it is a bad idea to put a nuclear site close to a major fault?"

- Mario Giampietro

Reflecting on the above now *three-decades-long* assortment, assemblage, mixed-bag and patchwork of PSHA's "tortured numbers", we believe PSHA's *potpourri of poor performance* derives from: (1) the inescapable conclusion that PSHA remains a *black box* (Mulargia et al., 2017) – whose continued reliance upon *paid experts* makes it also pretty much of a *black art* as well; (2) the *comingling* and use *interchangeably* of both "Hazard" and "Risk" (EERI PSHA, 1984; Peterson, 1988; McGuire, 1992, 1995; Fischhoff and Kadvany, 2011; and Kahneman, 2011) throughout its now long history has also added much *confusion* and difficulty; and (3) "Trust in Numbers" (Porter, 1996) is, as shown, "exactly wrong" (e.g. Feynman, 1986):

> "Drawing on a wide range of examples from the laboratory and from the worlds of *accounting*, *insurance*, *cost-benefit analysis*, and *civil engineering*, Porter shows that it is 'exactly wrong' to interpret the drive for *quantitative rigor* as *inherent somehow in the activity of science;* except –*where political and social pressures force compromise.* Instead, *quantification* grows from attempts to develop a *strategy of impersonality* in response to *pressures from outside* [i.e. *"The Charleston Issue"*]. Objectivity derives its impetus from cultural contexts [Saxe, 1873; Klügel, 2005b,c; Renault, 2009], *quantification becoming most important where elites are weak, where private negotiation is suspect, and where trust is in short supply."* https://press.princeton.edu/titles/5653.html

"When there's nothing else to trust, people trust numbers!"
Quantification by "scientists", publishing in presumed "scientific journals," mystifies the non-earth scientist, and one too soon *forgets* that they are still only just *numbers* … not nature! (See also Stark, 2017).

Combining all the above into one earthquake reality, in terms of *public safety* policy and *community resilience*, we are now simply and *unfortunately* quite literally "taking a chance on a guess!" And that's why PSHA's problems *are* and *remain* unsolvable! (Klügel, 2008).

Even although: (1) Panza et al, (2014) have recently proven PSHA to be *unreliable;* and although (2) their *comprehensive* evaluation has been (but *sadly* so) also corroborated by the more than 700,000 lives lost between 2000 and 2011, wherein *twelve* of the world's deadliest earthquakes have occurred *where* PSHA had predicted only *low* seismic hazard – Nevertheless, in spite of all the *scientific, mathematical* and *human suffering* arguments and objections against it, PSHA (*"the integration of earthquake characteristics and effects with probabilities, for the purpose of decision making in the face of uncertainty,"* per McGuire, 1992 and Somerville, 2000) has been widely used for now almost 40–50 years by governments and industry – when: (a) deciding safety criteria for *nuclear power plants*; (b) making official *national earthquake hazard maps*; (c) developing *building code* earthquake design standards – including now the derivative (and NEHRP supported) Performance Based Earthquake Engineering PBEE methodologies (May and Koski, 2004); and finally (d) when determining earthquake insurance rates from now yet *another* potpourri of similarly "black box" risk models! See…

PSHA – A Primer.

http://www.opensha.org/sites/opensha.org/files/PSHA_Primer_v2_0.pdf

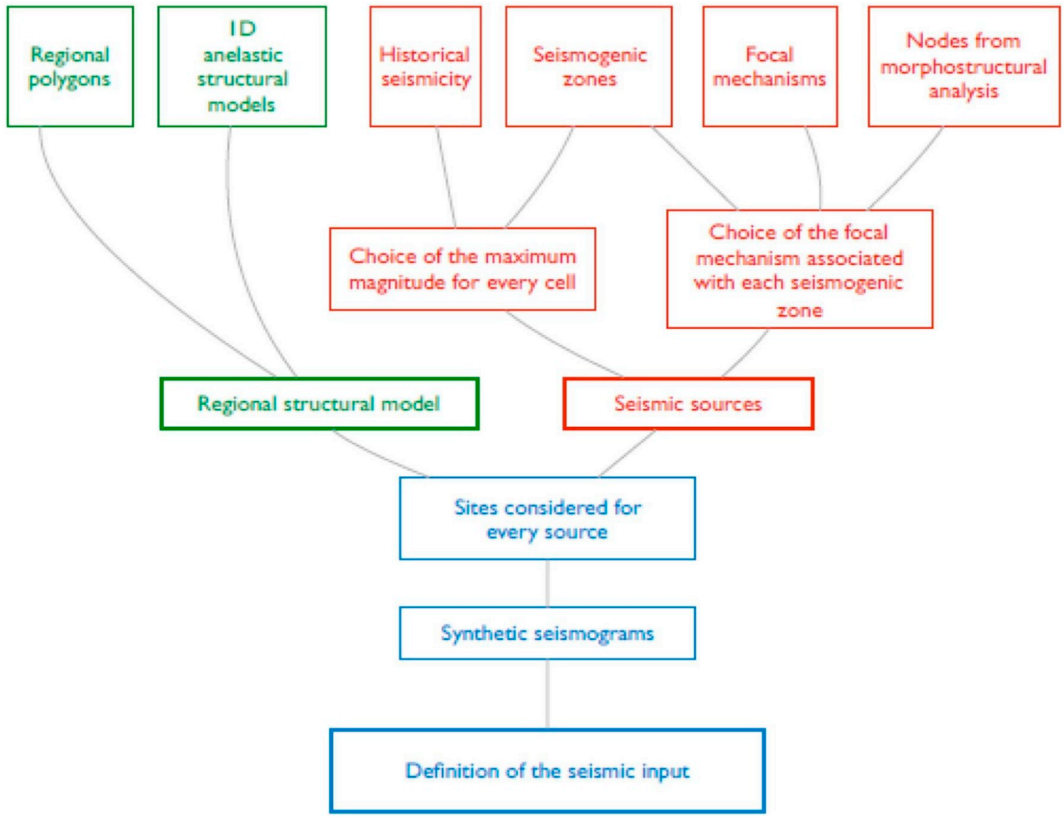


Fig. 1. Flow chart of NDSHA at regional scale.

California Earthquake Authority.
https://www.earthquakeauthority.com/California-Earthquake-Risk
GEM's Global Earthquake Model.
https://www.globalquakemodel.org/ and.
UCERF3 Uniform California Earthquake Rupture Forecast.
https://pubs.usgs.gov/of/2013/1165/

"Don't lose the moon while counting all the stars"

As in any branch of science and physics, theories of earthquake occurrence should be *tested* against observations; and they should also be *revised* in light of new data and experiences. In other words (per Kagan et al, 2012) "theories *unsupported* by observations and experiments must be either *corrected* or *rejected*, however intuitively appealing they might be!" For example, many widely held *beliefs* with respect to earthquake occurrence (including timing and magnitude), such as (a) Henry Fielding Reid's "elastic rebound" theory (Reid, 1911; USGS PSHA – UCERF 3, 2015b,c): that the 1906 San Francisco earthquake must have been caused by the sudden release of previously stored elastic stress); as well as the *Characteristic Earthquake Model*— unfortunately *disagree* with data (e.g. Hofmann, 1996; Kanamori, 1981; Molchan et al, 1997; Brune, 2003; Nekrasova et al, 2011; Kagan et al, 2012; Geller et al, 2016; Dolan et al, 2016; Stockmeyer et al, 2016; Bergen et al, 2017; Cowie et al, 2017; and Zinke et al, 2017). Therefore, the incorporation of *these* and other such *invalid* "implicit assumptions" into earthquake hazard models, which then make *probabilistic* statements about future near term seismicity, as is the case for USGS PSHA - UCERF 3 (2013) a; simply makes these models even more *untestable:* (i) on either a *local* scale; (ii) on a *regional* scale; and (iii) within a realistic *time* scale (e.g., "Dr. Who", 1963; Beauval et al, 2008; Panza et al, 2014). If you want *good answers*, you have to not only ask the *right questions*, but *scientific* questions as well; because large damaging and potentially deadly earthquakes will keep on occurring — and their occurrences will be decided by both *nature* and *science*, and *not just by belief* or *hazard models!* (i.e. "pi in the sky").

"History, despite its wrenching pain, cannot be unlived, but if faced with courage, need not be lived again."

PSHA, having too often delivered not only *erroneous* results, but also apparently unforecast *huge human losses* (Wyss et al, 2012; Bela, 2014); has been therefore both appropriately *debated* (ICTP Report 2010 (2011), p. 55) and repeatedly *challenged* over now many years (i.e. for *three decades*, as previously mentioned); and a sample of contributions is contained in the PAGEOPH Topical Volume 168, "Advanced Seismic Hazard Assessment" (2011) and references therein.

But NDSHA, for already now *two-thirds* of those three decades of *conundrum*, provides both *Reliable* and *Effective* Seismic Hazard Assessment tools (RSHA) for not only *understanding* but also for *mitigating* earthquake risk.

"Conundrum" most descriptively characterizes the PSHA policy problem, which can be boiled down to: "We're not talking about whether it's *right* or not. .. it's *required!*"

"Beware of false knowledge. It is more dangerous than ignorance"

Unlike PSHA … NDSHA *could* be "falsified" by the global occurrence of earthquake events — however it has been, to the contrary, very effectively *validated* by all earthquake events so far which have occurred in regions where NDSHA Hazard Maps were already previously available at the time of the earthquake: (i) Emilia-Romagna (Peresan and Panza, 2012); (ii) Central Italy (Fasan et al, 2016); and (iii) Nepal (Parvez et al, 2017).

It should therefore be widely taken to heart, we advise, that the *continued* practice of implementing PSHA for *determining* earthquake resistant design standards for: (a) civil protection; (b) mitigation of heritage and existing buildings; and (c) community economic well-being and resilience… is unfortunately *still* in a *state-of-crisis!* And "alternative methods", which are already available and ready-to-use, like NDSHA, could and *should* be applied worldwide! The results, we believe, will then be threefold: (1) to extensively test these alternative methods; (2) to prove that they globally actually perform *more reliably* (safely) than PSHA; and (3) to make the "real earthquake" more *understandable* and more *tangible* to design professionals in their undertakings of more effective *earthquake-resistant* design considerations to protect civil populations, heritage buildings, and a more resilient infrastructure…

R.I.***PSHA!***

METHODOLOGY

"Simplicity is the ultimate sophistication."

– Leonardo da Vinci

The procedure for the Neo-Deterministic Seismic Hazard Assessment NDSHA (Panza et al, 1996, 2001, 2012; Panza et al, 2017) is based on the computation of realistic and physics-based *synthetic seismograms* (earthquake scenarios) – and the end products of NDSHA are therefore synthetic *ground motion* accelero-grams, veloci-grams and displacement-grams. In **NDSHA**, *seismic hazard* is defined as "the *envelope* of the values of earthquake ground motion parameters:" **(a) considering** a wide set of *scenario* events (including Maximum Credible Earthquakes MCE); and **(b) *calculated*** by means of physically-rooted models formulated using the available *physics-based* knowledge on earthquake *source* and *wave propagation* processes. NDSHA does not rely, therefore, on empirical *attenuation models* (GMPEs), as these are: (i) often weakly constrained by the available observations; and (ii) unable to account for the *tensor* nature of earthquake ground motions, which are formally described as the "tensor product" of the *earthquake source tensor* with the *Green's functions* of the transmitting medium (Aki and Richards, 2002).

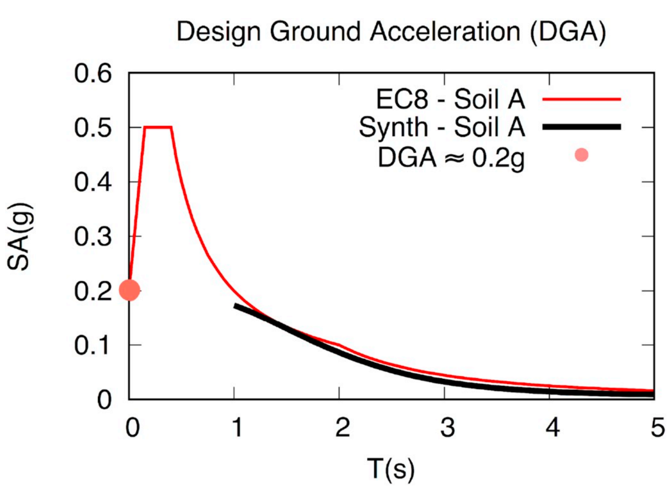


Fig. 2. Elastic Acceleration Response Spectrum. To obtain an estimate of PGA ≈ DGA ≈ EPA (Panza et al, 2004), overcoming the $T = 1$ s or 1 Hz cutoff (consistent with the available detail in the input data used for the modeling at national scale) the "shape" of any code design spectrum can be used. The thin (red) line represents the shape of the chosen standard seismic code normalized response spectrum (EC8 - Soil A), scaled here with the long period ($T > 1$ s) response spectrum, thick (black) line: determined with NDSHA computed time histories (Synth) at the site of interest (Panza et al, 1996). These approximations PGA ≈ DGA ≈ EPA hold as follows: (a) DGA = PGA for elastic Design Spectra; (b) DGA ≈ EPA at bedrock — although, importantly, it is also controlled by the *earthquake source* time history; EPA (although it is *correlated* with the real Peak Value) is then, as a rule, actually not "equal to", nor even "proportional to" it (Panza et al, 2003).

NDSHA (Fig. 1), employs *numerical modeling codes* that are based upon: (1) the physical description of the *earthquake rupture process;* and then upon (2) the *seismic wave propagation* pathways — to then reliably predict resulting ground motion parameters resulting from the many considered potential seismic sources (see Panza et al, 2001, 2012; Magrin et al, 2016a, 2016b; Panza et al, 2013 and the references therein).

Since these *scenarios* are determined consistent with: (i) the *available knowledge* about the *earth's structure* (through which seismic waves propagate); (ii) the *earthquake sources,* and (iii) all *previously known seismicity* of the study area – therefore it is possible to *compute* realistic synthetic seismograms for engineering applications. One can then quantify peak values of *Acceleration* (PGA), *Velocity* (PGV) and *Displacement* (PGD) or any other *ground motion parameter* relevant to seismic engineering, e.g. Design Ground Acceleration (DGA) computed consistently with the shape of any preferred Design Spectrum (Panza et al, 1996), as shown in Fig. 2.

Familiar scales of *moderate* to *strong* shaking intensity that can be felt by humans are often *not* very informative for the earthquake response of long-period structures, such as taller buildings and long span bridges, particularly during large magnitude earthquakes. For example, a shaking intensity of 30% g (0.3 g) is about the level of shaking that would make it difficult for you to walk down the airplane aisle without *holding onto a seat* during turbulence, because 30% of your *mass* is pushing you *sideways!* In the M 7.8 Nepal earthquake in 2015, the shaking intensity (PGA < 0.2 g) in Kathmandu was only moderate, but the strong motion records: (a) ≈ 0.5 g *spectral acceleration* at ≈ 5 s period (e.g. Pokharel and Goldsworthy, 2015); (b) seem to indicate that practically any modern high-rise building (say > 40 stories) would have been vulnerable to collapse in these long period motions. Although a *single* parameter is insufficient to completely describe an event, the *first* number any structural engineer should want to know is PGV (for at recorded levels greater than 50 cm/s, there is typically damage). The *second* number is PGD; for when greater than 1 m, then *tall buildings* are also likely to be in trouble!

The Design Ground Acceleration DGA is the "Spectral Acceleration" SA(g) anchoring the Elastic Acceleration Response Spectrum at a period of $T = 0$ s. This quantity is comparable to PGA, since an infinitely rigid structure (i.e. a structure having a natural period of 0 s) moves exactly like the ground (i.e. the *maximum acceleration of the structure is the same as that of the ground*, which is the PGA). Moreover, DGA is practically equivalent to Effective Peak Acceleration (EPA), which is defined as the "average of the maximum ordinates of elastic acceleration response spectra within the period range from 0.1s to 0.5s, divided by a standard factor of 2.5, for 5% damping" (Panza et al, 2004).

Importantly, as a rule, the *computations* of time history accelerograms containing accelerations at *short periods* ($T < 1$ s) require a level of knowledge of earthquake *source processes* and wave medium *pathway* that so far is unattainable; but accelerogram computations that are reliable at *long periods* may be extended to T < 1 s by using *elastic acceleration response spectra*. In absence of *normalized* spectra derived from specific regional recorded signals, the recommended procedure is to use "Code spectral shapes", e.g. Eurocode 8 (EC8, 1993; 2008), which defines the *normalized elastic acceleration response spectrum* of the ground motion for 5% critical damping. Thus, it is possible now to obtain DGA by: (i) computing the response spectrum for each *synthetic accelerogram* computed for periods of 1 sec. and longer; and (ii) by then *extending* this spectrum to shorter periods using any normalized elastic acceleration response spectrum of the ground motion (e.g. corresponding to soil A, as in Fig. 2). DGA estimation (computed at national scale) has been described and validated by Panza et al, (2001), and later also applied to many cases worldwide, e.g. Egypt (Hassan et al, 2017) and India (Parvez et al, 2017).

The *normalized* code elastic response spectrum method, although rooted in structural dynamics, is by nature of its origin from many *different* earthquakes and the required *smoothing* of data, *not* precise!

The smoothed shapes of standard Code Elastic Response Spectra (which prescribe strength base shear requirements for *new* structures) are obtained, as a rule, through a demanding statistical processing of signals obtained under quite *different earthquake conditions,* and they cannot always be considered the "best tool" to assess structural behavior.

These limitations result from, among other things: (a) our *inability* to duly consider both the wavelength *phases;* and also (b) the *durations* of the recorded earthquake signals. However, it is still today the most frequently used method for application in seismic design codes, because of its relative ease in estimating the *peak* or *maximum elastic response* of a building, which forms the basis for calculating the "forces" that a structure must be designed to resist. For engineering purposes, the *seismic hazard* is still today defined by a code prescribed *normalized elastic design response spectrum*, which perhaps takes indirectly into account the variability of the possible signals. These response spectra, however, have *national* shapes and no true direct links to the site under examination. Malhotra (2015) *found* that the latest empirical ground motion prediction equations (GMPEs) do not always preserve the shape of the normalized response spectrum and he recommends: (i) that ground motion prediction models should *only* be developed for PGA, PGV and PGD; and (ii) that the response spectra for various damping ratios should be generated from PGA, PGV and PGD by using the normalized response spectrum.

In NDSHA, as a general rule: (a) a *regular grid* (usually $0.2^\circ \times 0.2^\circ$) is placed over the study region; (b) the *earthquake sources* are centered in the grid cells that fall within the adopted *seismogenic zones*, while the *computation sites* are placed at the nodes of a grid that is staggered by 0.1° with respect to the sources' regular grid; (c) a *smoothing procedure* for the definition of *earthquake location* and *magnitude* M is then applied to partly account for spatial uncertainty, catalogue incompleteness and for earthquake source extension; (d) after smoothing, *only the cells (earthquake sources)* located within the seismogenic zones or within a seismogenic node are retained; (e) a *double-couple point source* is placed at the center of each cell, with a representative *focal mechanism*, which is consistent with the *known present-day dominant tectonic regime* of the corresponding seismogenic zone (cellular source): (i) to *define the magnitude of each source* (cellular magnitude), the NDSHA procedure makes use of information about the space distribution of large-magnitude earthquakes (M > 5), which can be defined from historical, instrumental and geological observations; and (ii) the *source depth* is taken into consideration as a *function of magnitude*, in agreement with literature (e.g. Caputo et al, 1973; Molchan et al, 1997; Doglioni and Panza, 2015). A complete description of the NDSHA methodology can be found in Panza et al, (2001), and its *updates* and *validations* in Panza et al, (2012), Fasan et al, (2016), Magrin et al, (2016a, 2016b), Fasan (2017) and Hassan et al, (2017). More specific 3D NDSHA applications can be found in Lamura et al, (2011), Gholami et al, (2013) and Panza et al, (2013).

In addition, NDSHA permits (if really necessary, as claimed by PSHA *addicted practitioners* fearful of "overdesign" because a damaging earthquake is *unlikely*) an "accounting" for earthquake *occurrence rate* (Peresan et al, 2013 and references therein): *first* the characterization of the *frequency-magnitude* relationship for earthquake activity in Italy is performed, according to the "multi-scale seismicity model" (Molchan et al, 1997; Kronrod, 2011*), such that a robust estimated occurrence rate is *associated* to each of the NDSHA modeled sources; *second,* the *occurrence rate* assigned to the source is thus *associated* to its pertinent synthetic seismogram, coherently with the physical nature of the problem. Accordingly, then, *two separate maps* are obtained: (1) one for the "ground shaking;" and (2) another for the corresponding perceived "average occurrence rate."

Since, in policy decisions to *protect* civil populations, the authors believe that the engineering use of these "average occurrence rates" (per Cornell, 1968) is not only *questionable*… but also both *unsafe* and *unsound*; they can neither recommend nor even suggest their use! Therefore, "in policy decisions to *protect* civil populations" — (a) when considering two sites prone to earthquakes with the *same* Earthquake Hazard M, given that all the remaining conditions are the same; (b) the parameters for seismic design *must be equal* at the two sites — since the magnitude we have to *defend* against is the *same* M, independently from the *sporadic* nature (i.e. perceived *likelihood*) of the earthquake's occurrence!

The Flow Chart that describes the NDSHA procedure for *regional scale* analysis is shown in Fig. 1. When *available knowledge* may sometimes permit reliable accelerogram computations comprising frequencies >1 Hz (*higher* frequencies at *shorter* periods *less than* the standard $T = 1$ s cutoff), such accelerograms can be considered. Remembering: (a) $T = 1/f$; and (b) building period can be approximated at 0.1 s per story — the *physics-based* ground motion modeling is however, as a rule, *limited* within the frequency range from 1 to 10 Hz, because any estimates of ground motions at *higher* frequencies (*shorter* periods) would require a comprehensive knowledge of: (i) *source heterogeneity*, (ii) *physical properties* of the rock/soil, and (iii) *ground motion attenuation parameters*— all with a resolution realistically not attainable!

This is well in agreement with Aki's (2003) conclusion: results about (i) the source-controlled f_{max}; (ii) non-linear soil response; and (iii) the studies of seismic attenuation from borehole data — all indicate that there is *no* need to consider frequencies *higher* than about 10 Hz in strong motion seismology! In fact, the *quality of the results* obtained by physics-based ground motion modeling depends on the *quality of the input data.* The NDSHA procedures allow for *sensitivity analyses* to evaluate evidence and also to address the *uncertainties* using *different input data* and *varying levels of knowledge* about seismic sources and attenuation *velocity structural models*. Proper presentation and evaluation of *uncertainties*, associated with the ground motion computation, will help the potential users determine how much confidence to place on the NDSHA computed seismic hazard map!

Further insight into the hierarchical interrelationships of NDSHA procedures considers the following: (a) the *strength of the source* is determined as the maximum between a *lower bound* and the *magnitude* defined by the smoothing procedure. The lower bound for magnitude inside the seismogenic zones is M = 5, that *also* is conventionally (D'Amico et al, 1999) taken as the *lower bound* magnitude of damaging earthquakes; (b) the lower bound of earthquake magnitude within the *seismogenic nodes* is the *magnitude threshold* identified for that node by the *morphostructural analysis* (Gelfand et al, 1972); (c) the *orientation of the double-couple point source* is the one representative of the parent seismogenic zone or seismogenic node; (d) *hypocentral depth*, in fairly good agreement with existing literature, is taken as a discrete *function of magnitude* f (M) = (10 km for M < 7) (15 km for 7 ≤ M < 8) and (25 km for M ≥ 8). More and updated details about the NDSHA methods and procedures can be seen in Parvez et al, (2017).

NDSHA: TRUE OR FALSE?

— *Validations by the facts*

NDSHA, *unlike PSHA*, is falsifiable, and therefore it can be tested! Since PSHA is *false*, it is *not* falsifiable and it *cannot* be tested! A detailed review of the traditional PSHA method (besides just *errors* in its implementation, e.g. Frankel, ca 1996 and Thenhaus, 2012) revealed most strongly that the *method* itself is inadequate to describe the *physical process* of earthquake occurrence, because of its built-in and required *assumption* of a "memoryless" stochastic process – Poisson process (e.g. Ferraes, 1967). It is obvious that strain and stress renewal *needs time,* and therefore the process of rebuilding the conditions for the next earthquake is "time-dependent" (Kanamori, 1981; Cisternas et al, 2017). Furthermore, the locations of earthquakes (even at and along the *same* faults) are *changing with time,* as well as are fault strength *mechanical properties*, in particular *after* each event. Each magnitude range of earthquakes (M 5 – M 5.9) (M 6 – M 6.9) (M 7 – M 7.9) and (M 8 or

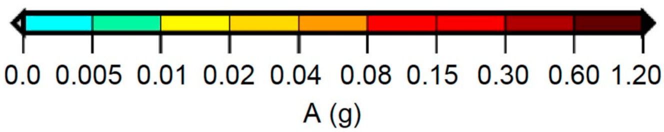


Fig. 3. Typical discrete ranges of hazard values (units of g). Shown in geometrical progression (close to 2×), consistent with the real resolving power of the worldwide available data (e.g. Cancani, 1904; Lliboutry, 2000).

greater) is *modifying* the boundary conditions for the next one! This means that a *mathematical probabilistic model* has to be at least *bivariate*, and probably also *bimodal.* This is outside of the scope of human knowledge due to: (a) *lack* of data; and (b) also the *shortness* of human observation time in comparison with *geological* time scales.

As does any physical earthquake model, NDSHA must deal with *uncertainties* intrinsic in the basic model input data, here chiefly coming from: (a) earthquake catalogs; and (b) lack of satisfactory theories about earthquake source (slip distribution at initiation of rupture, and slip distributions in cascading *multi-fault ruptures*). For this reason the hazard values at *national/regional* scale supplied by NDSHA are given as *ranges over areas*— whose values are consistent with the information content of the basic data. Typical values are displayed on a grid mesh of about 25–50 km spacing, and hazard values are *color-coded* in discrete ranges of geometrical progression close to 2× (Fig. 3). More specific hazard estimates can be obtained at local scale by means of ad hoc studies, as shown, for example, in Rugarli et al, 2019.

In the original formulation of NDSHA (Panza et al, 2001, 2012), *physics-based* computer computation was; (i) combined with a comprehensive geologic and geophysical overview of the *regional tectonic setting* and *earthquake history* to: (ii) solve, in a *first approximation*, the fundamental problems posed by an adequate description of the physical process of earthquake occurrence (which in the real earth is a *tensor* phenomenon). It examined the *largest* scenario event physically possible, usually termed Maximum Credible Earthquake (MCE), whose cellular magnitude M_{design} at a given site can be tentatively, until proven otherwise, set equal to the *Maximum* observed or estimated earthquake magnitude M_{max}, plus some *multiple* of its accepted global standard deviation σ_M. In areas where information on faults and other input data are sparse, the *historical data* and *morphostructural analysis* are relied upon to estimate this Maximum Magnitude, M_{max}.

For estimating specifically, no more than $1/k^2$ of a distribution's values can be more than k standard deviations away from the mean (or equivalently, at least $1–1/k^2$ of the distribution's values are within k standard deviations of the mean). If $k = 2$, then at least 75% of the values fall within $2\sigma_M$; and if $k = 3$, then at least 89% of the values fall within an interval of $3\sigma_M$ centered on the mean. The factor k can be considered a "*tunable* safety factor" that may be applied systematically with the *other* safety factors that are used in structural engineering, e.g. γ_{EM} (EM = Earthquake Magnitude). So $M_{design} = M_{max} + \gamma_{EM}\sigma_M$— where it is currently assumed $\sigma_M \approx$ 0.2-0.3 (Båth, 1973, p. 111, Rugarli et al, 2019), and it is proposed to use γ_{EM} = 1.5-2.5. Since the design value M_{design} is determined by adding a further tunable increment to the *maximum* estimated value M_{max}, it must be considered an *envelope*— evaluated at the best of our present day knowledge. This choice is *consistent* with *Chebyshev's theorem*: "for a very wide class of *probability distributions*, no more than a certain fraction of values can be more than a certain distance away from the mean" (but here a Maximum estimated M value, M_{max}, is used).

> *"Everything that happens* once *can never happen again. But everything that happens* twice *will surely happen a third time."*

As an example of NDSHA's global applications: (i) when considering the upper limit of $\gamma_{EM}\sigma_M$; and then (ii) applying this "*tunable* safety factor" to the Maximum observed M ($M_{max} = 7.5$) in southern California within the time interval 1932-2011 (Chiou and Miao, 2013); we can then determine here that $M_{design} = M_{max} + \gamma_{EM}\sigma_M = 7.5 + 0.7 = 8.2$; this result is *well in agreement* with Kijko (2004), where $M_{max} \approx 8.3$; and with Field et al, (1999), wherein $M_{max} \approx 8.0$.

Since NDSHA's computations supply a bounding or *envelope value* (in other words, *a value that should not be geologically or seismologically exceeded* in nature) —*this* value is immediately falsifiable: (1) *if* an earthquake occurs with a magnitude M_{eq}*larger* than that indicated by NDSHA's M_{design} ($M_{eq} > M_{design}$), then $\Delta M = M_{eq}- M_{max} > \gamma_{EM}\sigma_M$ and γ_{EM} should then be increased (Rugarli et al, 2019). Given the way M_{design} is defined, however, this is expected to be a rare circumstance!

The tunable increment to M_{max}, γ_{EM}, could *similarly* be increased, should recorded peak ground motion values (e.g. PGA, PGV, or PGD) on the bedrock (at the occurrence of an earthquake M_{eq}*after* the compilation of NDSHA maps) *exceed*, within error limits, those values given in these same maps. By way of improving usefulness and applicability of future strong ground motion recordings, this would suggest targeting installation of additional strong motion network stations over *stiff soils*, so as to avoid the *local amplifications* due to site effects — since the majority of the strong ground motion stations of the Italian strong motion network are sited upon *soft* soils (Rugarli et al, 2019).

While the selection of the multiplier γ_{EM} to be applied to σ_M cannot be derived by equations (indeed, it would be misleading to try), today it is partly *heuristic*, or "rule-of-thumb" *learned from experience*. Nonetheless, should this heuristic be *falsified* by natural experiments, this multiplier can be gradually reset to the new *minimum* safe value. This is what has already been done with all the already *safety factors* used in engineering: (i) the 1.5 safety factor for material limit stresses was used well before the availability of reliable statistical measures; and (ii) the semi-probabilistic methods used in structural engineering are de facto tuned to confirm these already *validated-by-experience* values (Rugarli et al, 2019).

STUDY CASE HISTORIES

— *Egypt*

In the last century, Egypt experienced earthquakes with magnitudes ranging from m_b 5.8 to Mw 7.3. The most current update on the seismic hazard maps available for Egypt incorporated the results of many recent studies, including: (i) revised historical earthquake catalogs; (ii) morphostructural zonation data (MSZ); (iii) revised focal mechanism solutions; and (iv) revised mechanical models of the lithospheric structure — and was all completed within the framework of the Neo-Deterministic Seismic Hazard Assessment (NDSHA) procedure (Hassan et al, 2017). The set of relevant *scenario earthquakes* considered provided a large dataset of *synthetic seismograms*, particularly important for the areas like Egypt that suffer from an endemic lack of useful strong motion time histories; and these comprise the basis for completing more detailed and comprehensive seismic *microzonation* studies in the future. A *sensitivity analysis* based on the different scenario ground motion maps, which were computed by adopting different: (a) models for the *earthquake source process*; (b) *mechanical models* of the crust; and (c) mapmaker's preconceptions (e.g. *different seismotectonic models*) — helps clearly communicate the possible *uncertainties* and thereby provides potential users with an adequate range of choices for Egypt's significant earthquake hazards. The availability of a wide spectrum of hazard maps is an important prerequisite in making available the valuable information necessary for the significant improvements to *current practices* in seismic engineering codes.

— *India*

NDSHA Maps, expressed in terms of PGD, PGV and DGA, have been prepared (on a regular grid of 0.2° × 0.2°) over the entire country (Parvez et al, 2017). India's highest seismic hazard, expressed in terms of DGA (0.6 g - 1.2 g), is mainly distributed: (a) in Western Himalayas

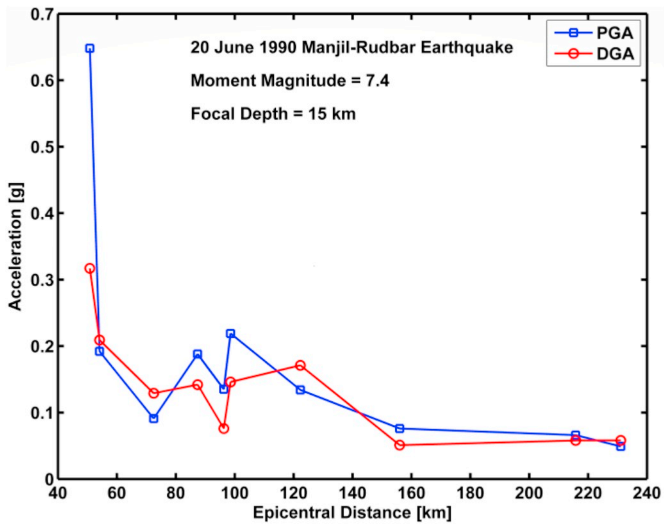


Fig. 4. Alborz region, Iran, 20 June 1990 Mw 7.4 Manjil-Rudbar earthquake. Plot of recorded PGA and estimated DGA versus epicentral distance. Apart from the closest station (which is at near source condition), the DGA and PGA values are well aligned (modified from Rastgoo et al, 2018b).

and Central Himalayas along the epicentral zone of the Mw 7.8 or M_s 8.1 Bihar Nepal 2015 earthquake; (b) in a portion of NE India and (c) in the Gujarat (Kachchh region). A similar pattern has been found for the Peak Velocities and Peak Displacements in the same regions. For the same earthquake event, using the conversion from ground shaking acceleration to EMS intensity measures (Lliboutry, 2000), the NDSHA results have been compared with the maximum *observed* intensities reported in EMS scale by Martin and Szeliga (2010): where observations are available, the modeled NDSHA intensities are rarely exceeded (2% of the cases when $\gamma_{EM} = 0$) by the maximum observed intensities.

– ***Iran***

Seismic hazard maps for both the Alborz region (northern Iran) and adjacent areas have been compiled accordingly with NDSHA procedures (Rastgoo et al, 2018b). To accomplish this, the study area was *zoned* according to different geophysical structural models – delimited at the surface by *polygons* (used to define the mechanical properties of the *source-to-site paths*). The *velocity structures* rely upon both: (a) the joint inversion of the P-Wave Receiver Functions (PRF); and (b) surface wave dispersion (Rastgoo et al, 2018a). The *input data set* then consists of: (i) *attenuation-velocity structural models* (representing bedrock conditions); (ii) *seismogenic zones*; (iii) *focal mechanisms*; and (iv) the *catalogue* of past seismicity. The seismic hazard, as expressed in terms of PGD, PGV and DGA, is mapped on a regular grid of 0.2° × 0.2° over the entire region. The results of this first order NDSHA mapping effort indicate a *high seismic hazard* in the Alborz region, and this may represent an important fundamental knowledge basis –*moving towards* more detailed and comprehensive seismic microzonation studies in the future.

A *validation* of our NDSHA results has been made against the records of the 20 June 1990 Mw 7.4 Manjil-Rudbar earthquake, which occurred in the Alborz region; and which was both an *unexpected* left-lateral strike-slip motion on a *previously unknown fault*, and also the *most destructive* documented earthquake in Iran in the last century (Fig. 4).

– ***Northern Italy: the Emilia Earthquake Crisis in 2012***

Currently, the PSHA map produced by the *Gruppo di Lavoro, Redazione della mappa di pericolosità sismica, rapporto conclusivo, 2004*, that can be downloaded at: http://zonesismiche.mi.ingv.it/mappa_ps_apr04/italia.html, is the official reference *seismic hazard map* for Italy, and this shows bedrock PGA values that have a 10% probability of being exceeded in 50 years (i.e. once in 475 years). The Emilia 20 May 2012 Mw = 5.9 and 29 May 2012 Mw = 5.8 earthquakes occurred in a zone that was defined at *low seismic hazard* by the Italian building code based on PSHA: PGA Map ("return period" 475 yr.) < 0.175 g; observed PGA > 0.25 g. The NDSHA map published in 2001 (Panza et al, 2001), which expresses shaking in terms of Design Ground Acceleration, DGA, equivalent to peak ground acceleration, PGA, (see Zuccolo et al. 2011), predicted values in the range 0.20 g - 0.35 g, in good agreement with the observed motion that exceeded 0.25 g. Seismic Hazard Maps are *most informative* when they seek to predict the *shaking* that could actually occur; and therefore what occurred in Northern Italy supplies a strong motivation for *proactively* using NDSHA or similar deterministic approaches – and also with the aim to *minimize* the *necessity to revise hazard maps* with time. In this view, public buildings and other critical structures *should be designed to resist future earthquakes!* Contrary to what is implicitly suggested by PSHA, *when* an earthquake with a given *magnitude* occurs, it causes a *specific ground shaking* that certainly does not depend on how *sporadic* (rare or not) the event is! Hence *ground motion parameters* for seismic design should be *independent* of how *sporadic* (infrequent) an earthquake is, as they are so treated with NDSHA (Peresan and Panza, 2012 and references therein).

– ***Central Italy***

The L'Aquila 2009 event

"Italy is a beautiful country, but that can change all of a sudden."

The fatal 6 April 2009 Mw 6.3 earthquake disaster that occurred in the Abruzzi region of Central Italy, killing more than 300 people and wrecking the medieval heart of the city, had been preceded by a swarm of earthquake activity beginning October 2008. Even though it occurred in a zone defined at *high seismic hazard*, as charted on a map – high *vulnerabilities* combined with *major failures* in Disaster Risk Mitigation (INTRODUCTION) to produce both the *tragic large losses* and an ensuing *legal earthquake:* "The L'Aquila Trial," as explained in more detail below.

Since many buildings had been *cracked* and *weakened* already during the months of preparatory shocks and tremors, when the observed acceleration values exceeded those predicted by the Italian building code based on PSHA: PGA Map ("return period" 475 yr.) 0.250 g - 0.275 g; observed PGA > 0.35 g – their damaging effects were amplified! The NDSHA map predicts values in the range 0.3 g - 0.6 g and this implies that *future* events may cause peak ground motion values *exceeding* those already recorded in 2009. As far as we know such *obvious* caution is *not* explicitly and duly considered in the ongoing reconstruction efforts, still ongoing!

"The L'Aquila Trial" was the unprecedented prosecution (for charges of *professional negligence* in adequately warning of risks) of six scientists and one government official, all participants of a controversial meeting on 31 March 2009 of the Grand Risk Commission, *convened* "under the auspices of the Italian Department of Civil Protection". (Imperiale and Vanclay, 2018) These authors, drawing heavily "on a *document analysis* of trial materials, which amounted to over 1,100 pages," as well as on "a review of academic and media commentary about the trial," found the following: (i) "Disaster Governance was inadequate and not informed by the disaster risk reduction paradigm or international guidelines;" (ii) "Risk Assessment was carried out only in a techno-scientific manner;" with (iii) "little acknowledgement of the Social Issues influencing risks at the local community level;" and (iv) "there was no inclusion of Local Knowledge or Engagement of Local People in transformative disaster risk reduction strategies." See also Alexander (2014) and Cocco et al, (2015).

The Earthquake Crisis starting in 2016

The 24 August Mw 6.1 and 30 October Mw 6.5 earthquakes occurred in a zone defined by the Italian building code as *high seismic hazard*, but the observed acceleration values exceeded those predicted by the code standards, based on PSHA: PGA Map ("return period" 475 yr.) 0.250 g - 0.275 g; observed PGA > 0.4 g (a value that is larger than the one recorded at L'Aquila in 2009!) Alternatively, the NDSHA map predicts values in the range 0.3 g - 0.6 g. Following this Earthquake Crisis, beginning with the August 24, 2016 Mw 6.1 event, *"The Lesson"* unfolded… illustrating in dramatic example the familiar English proverb: "you get what you pay for!" … and maybe even also another lesson: "a little bit of knowledge is a dangerous thing!" Both provide *wisdom* and are as described in the following section: *The Lesson.*

− ***The lesson***

After these recent and very damaging earthquake events many civil engineers, designers and practitioners *complained* about the fact that the accelerations given in the Italian building code standard hazard maps (based on PSHA) are *distorted downwards* and therefore that they are *misleading*. Their voiced concern for a *due revision* of these maps, therefore, to coincide with *real earthquake* experiences, however, encounters *strong and blunt resistance*; particularly regarding the *methodological* concepts and practices of PSHA. However, more than just these methodological aspects, it is also necessary to *seriously* consider the contrast between the very real *benefits* of risk reduction, as against simply the "building costs" increment of a higher standard - if *more reliable* and *robust* Risk Coefficients are considered − ones *consistent* with the Magnitude size (M_{max}) of *possible* future events, like these just recent ones! Beyond the untold human toll, *a posteriori* retrofitting costs about 30× times *more* than the upgrading of earthquake-resistant design standards at the time of *new* construction (here to the more realistic and therefore more stringent *earthquake-resistant* measures as identified by M_{design} in NDSHA).

Thus it seems, again, very *appropriate* always to remember the wisdom of the ancient Greek teachings, as well as of our more modern everyday sayings and proverbs: "adequate prevention is better than cure!" − as Hippocrates said about 2500 years ago … (a *wisdom* "return period" ~ 2475 yrs); and the old English phrase or proverb "you get what you pay for!" A most dramatic example of this both *ancient* and *modern* wisdom is provided by the city of Norcia. Perhaps, in *this case* we could also add *Caveat Emptor*, or "Buyer Beware!"

Norcia had been retrofitted after the Umbria-Marche Earthquake Crisis (a long sequence of earthquakes, six between M 5 – M 6) that began September 26, 1997. All reconstruction works used as a *benchmark* the PSHA map ("return period" 475 yr.) on which the Italian building code seismic requirements were based. Those maps proved totally *misrepresentative* and *erroneous* upon the occurrence of the 30 October 2016 Mw 6.5 earthquake, where in Norcia the earthquake ground motion was *much larger* than what had been predicted by PSHA. The resulting damage was large, corresponding to I_{MCS} = IX. Instituto Nazionale di Geofisica e Vulcanologia *reports* I_{MCS} = VIII – IX.

http://www.afs.enea.it/poggif/amatrice/docs/QUEST_rapporto_15nov.pdf But it should be kept in mind that any Intensity Scale is *discrete*, having *unit* incremental steps; and therefore *intermediate* values are not defined. On the NDSHA map, the hazard value indicated is slightly above the experienced ground motion generated by the 30 October 2016 earthquake. In all likelihood, if the *reconstruction* and *retrofitting* that followed the 1997 Umbria-Marche earthquake crisis would have been undertaken in due account of the NDSHA demand estimates, the damage would have been, very likely, much less (if not negligible), when compared with that *actually observed* after the 30 Oct. 2016 M 6.5 event.

To have simply and *blindly* followed PSHA designated design strength and detailing requirements for new buildings, while at the same time neglecting the fact that the Italian seismic code *further* provides:

> "*L'uso di accelerogrammi generati mediante simulazione del meccanismo di sorgente e della propagazione è ammesso a condizione che siano adeguatamente giustificate le ipotesi relative alle caratteristiche sismogenetiche della sorgente e del mezzo di propagazione.*" (NTC, 2018 chapter 3.2.3.6)

"The use of accelerograms generated simulating source mechanism and wave propagation is allowed provided the hypotheses about the seismogenic characteristics of the source and the properties along the pathway are duly justified."

… while (1) following this PSHA *concept* certainly allowed some (marginal) cost saving during the reconstruction and retrofitting following the 1997 events, when compared to the higher *earthquake-resistant* requirements indicated under NDSHA; nonetheless (2) any apparent "savings" has been *unrealized* and ultimately *seismologically frustrated* by the 30 October 2016 Mw 6.5 earthquake − and *now* it is necessary to consider in the *reconstruction* and *retrofitting* the NDSHA values, which were unwisely *ignored* after the 1997 earthquakes. … We believe that Francis Bacon had *The Lesson* right as well: "A prudent question is one-half of wisdom!" In other words, it is not the "last" earthquake that should concern us, but *rather* the earthquake that comes *after* the next one!

Lastly to be considered as a lesson (but by no means the least), *before* the occurrence of the 30 October 2016 Mw 6.5 event, when Norcia was almost completely destroyed:

(a) Fasan et al, (2016) did show that the *spectral accelerations* for the 30 October 2016 Mw 6.5 event, with magnitude M_{eq} close to the Maximum M (M_{max}) ever *historically* observed in the area, were in *very good agreement* with what had *earlier* been predicted, based on NDSHA ground motion simulations; and.

(b) Panza and Peresan (2016) had issued the *warning* that the 24 August 2016 Mw = 6.1 earthquake did not necessarily generate the *largest possible ground motion* in the area: since *historically* the area had been previously hit by the 14 January 1703 M 6.9 Valnerina earthquake. They *further* had warned that, *in the ensuing reconstruction and retrofitting activity, engineers should take into account as well that, in the future, seismic source and local soil effects may lead to ground motion values exceeding the NDSHA value of 0.6 g (predicted at the bedrock).*

Therefore many now believe that it is both *well validated* and also scientifically *justified* to claim that NDSHA is not only a *more reliable* but also a *ready alternative* to the presently widespread use of PSHA (for not only practical but also more *realistic* and Reliable Seismic Hazard Assessment RSHA), particularly since PSHA's continued use has been so widely *proven* in the professional journals and publications to be a *totally unjustified and unreliable* procedure, i.e. a *fabulation dependent upon magical realisms* (e.g. Saxe, 1873; Krinitzky, 1993a,b,c, 1995, 2003; Klügel, 2008; PAGEOPH Topical Volume 168, 2011; Mualchin, 2011; Wang and Cobb, 2013; Klügel, J-U, 2015; Fasan, 2017; Mulargia et al., 2017; and Stark, 2017).

PSHA and NDSHA − The Similarities are Different!

> *"The difference between the 'almost right word' and the 'right word' is really a large matter—'tis the difference between the lightning bug and the lightning."*

(I) PSHA seeks a biased *advantage* towards lowering *first costs* of construction (McGuire, 1992; Hanks, 1997; Somerville, 2000;

Rugarli, 2019); and it both easily and *familiarly* fits within the standard business model, whereby: (a) the focus is on *production* of products and services by *fast*, *efficient* and *repeatable* protocols; (b) the *details*, science, validity and truth underlying these methods, as well as any accountability for using them, are *not* as important, if even considered at all; and (c) the decisions made are, therefore, not always either *error-free*, consistent with past practices, or actually the *best* decisions! (Egan, 1989; Kahneman, 2011). It is, therefore, *not* surprising to us, that the code writers maintaining the now institutionalized *regional* and *global* dominance of PSHA are, indeed, the *very same* individuals from business that are (at the same time) also *using* these methods in their daily practices! What is *surprising* … is *that* Universities have now *joined-in* with business in these efforts?

(II) NDSHA seeks RSHA … as is best *described* here by the historically eminent USGS Geologist "Rock Star" G.K. Gilbert, who offered these observations now more than a century ago (or the equivalent of *two* 50 yr. lifetimes … in PSHA's alternate universe):

"It is the duty of investigators − seismologists, geologists, and scientific engineers − to develop the theory of local danger spots, to discover the foci of recurrent shocks, to develop the theory of earthquake-proof construction. It is the duty of engineers and architects so to adjust construction to the character of the ground that safety shall be secured. It should be the policy of communities in the earthquake district to recognize the danger and make provisions against it." (G.K. Gilbert, 1909)*.

RSHA also incorporates this lesson from the twentieth century poet T.S. Eliot:

"Where is the *wisdom* we have lost in *knowledge*? Where is the *knowledge* we have lost in *information*?" And now … "Where is the *information* we have lost in *PSHA*?"

What, we wondered, makes the *similarities* between PSHA and NDSHA so *different;* while still at the same time so many of its practitioners continue to claim that *"there is nothing better"?* And we found in Celeste Adams' (2002) thoroughly enjoyable reflections on "The Vision of Buckminster Fuller" some both *amusing* and also very *realistic* answers! Buckminster Fuller (1895–1983) "was one of the world's first *futurists* and *global thinkers*," and "he set forth ideas that would *overthrow* all the old paradigms:"

(a) *Buckminster Fuller*, like NDSHA, focused on *large scale patterns*, rather than *details*, like PSHA.
(b) PSHA is "educated to death," such that it is "only able to communicate that *in which* it is educated."
(c) But Fuller's most applicable insight came from what he described as the "scandal of pi." That is, he said, "Generations of 'circle-squarers' *attested* to the persistent intuition that it [π] ought to have a rational value, but nobody ever found one! Eventually it was proven that *none* was findable. The decimal sequence for pi is 3.141592653589793 … and will go on *forever* … … … … … … … … I reached the decision right at that moment that ***nature didn't use pi*** … And I decided then, in 1917, that what I'd like to do was find *nature's geometry*."

NDSHA, we believe, is more soundly rooted in *nature's geometry* … and therefore, as proven … …. *provides* RSHA!

PSHA has been *going on forever* (*pi* sha, if you will), adding *integer* - after other *integer* - after other *integer,* but still without any "rational value" … or any end in sight that one can see (even if now with *supercomputing*)! And what *statistical gamesmanship* may seem logical for "one single engineering site" – *gambling with nature* to achieve (as the numbers seem to promise) a "maximum utility" … completely falls apart when required to be *scaled-up* to include *every* single building − with *all* of its supporting infrastructure, heritage buildings and community resilience *also* at stake! In *that* circumstance (e.g., "The Seismic Future of Cities"; Bilham, 2009) … *"taking a chance on a guess"* … well, it just doesn't seem rational anymore!

As previously noted above in *The Lesson*, a further implicit and important *confirmation* (through granting of legal authorization as a seismic building code procedure) of the *validity* of adopting NDSHA as the most realistic and effective available preventive tool is given in Norme Tecniche per le Costruzioni 2018 (NTC, 2018), which deepens and expands the concept contained in chapter 3.2.3.6 of NTC 2008 as follows:

"L'uso di storie temporali del moto del terreno generate mediante simulazione del meccanismo di sorgente e di propagazione è ammesso a condizione che siano adeguatamente giustificate le ipotesi relative alle caratteristiche sismo genetiche della sorgente e del mezzo di propagazione e che, negli intervalli di periodo sopraindicati, l'ordinata spettrale media non presenti uno scarto in difetto superiore al 20% rispetto alla corrispondente componente dello spettro elastico."

"The use of accelerograms generated simulating source mechanism and wave propagation is allowed, provided the hypotheses about the seismogenic characteristics of the *source* and the *properties* along the pathway are *duly justified* and that, in the considered period intervals, the average spectral ordinate is not less than 20% of the corresponding component of the elastic spectrum."

Further details can be seen in Rugarli et al, (2019).

EARTHQUAKE PREDICTION

"Some things are so unexpected that no one is prepared for them."

Although damaging earthquakes cannot yet be *predicted* with ultimate precision, intermediate-term (i.e. several months scale) and middle-range (i.e. few hundred kilometers scale) predictions of main shocks above a *pre-assigned threshold* (based on seismicity "alarms" generated by interpretive algorithms like CN and M8) (ICTP Report 2010, 2011) may be properly used for the *implementation* of low-key preventive safety actions, as recommended by UNESCO in 1997 (Kantorovich and Keilis-Borok, 1991; Keilis-Borok and Soloviev, 2003; Peresan et al, 2005; Panza, 2010; Davis et al, 2012; and Peresan et al, 2012). The proper integration of both *seismological* and *geodetic* information together has now been shown to reliably contribute to a *reduction* of the geographic extent of CN and M8 alarms (e.g. the 2016–2017 Seismic Crisis in Central Italy and the 2012 Emilia earthquake sequence) − and defines a *new paradigm* for *time-dependent* hazard scenarios.

In this supporting framework, GPS data are used to *reconstruct* the station *velocities* and *strain* patterns along pre-selected transects, which are properly oriented according to information about the known tectonic settings. Overall experience has shown promisingly that *analyses* of the available geodetic data (highlighting both *ground velocity variations* and related *strain accumulations* within the areas alarmed by CN and M8) can permit significant reductions of their sizes and extents (Panza et al, 2017; Peresan et al, 2018)!

A first attempt at *earthquake prediction* was made a few years ago in the framework of Project SISMA (SISMA-ASI, 2009, 2010)*, funded by Italian Space Agency (ASI), to jointly use: (i) seismological tools (like CN algorithm and scenario earthquakes); and (ii) geodetic methods and techniques (like GPS and SAR monitoring) − to effectively identify and constrain *priority areas* where prevention and seismic risk mitigation measures should be concentrated. A further development of this very productive *integration* of seismological and geodetic information has been applied to the case of the Seismic Crisis that began in Central Italy on 24 August 2016 with the M 6.1 Amatrice earthquake. Differing from the much more common approach, here GPS data are *not* used to estimate the standard two-dimensional ground velocity and strain fields in the area, but rather to *reconstruct* the *velocity* and *strain* patterns along specifically chosen *transects*, which are properly oriented according to a priori information about the known main regional *tectonic settings*. SAR data related to the Amatrice earthquake *coseismic displacements* are used as independent checks of the GPS station results. Overall, in the case of the Amatrice event, an analysis of the available geodetic data indicates that it is now possible to *highlight* both the *velocity variation* and also the related *strain accumulation* in an area of about only 5000 km^2, within the area alarmed here by CN since 01 November 2012. The considered counter examples, across CN alarmed and non-alarmed areas, do not show any spatial accelerations along localized trends, comparable to the one that is *well-defined* along the Amatrice transect. Similar conclusions, duly considering the *stress pattern* of the study area, have also been drawn for the 2012 Emilia earthquake (Peresan et al, 2018).

CONCLUSIONS

> ***"You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete."***
>
> — Buckminster Fuller

NDSHA has, for over now *two decades*, provided both Effective and Reliable Seismic Hazard Assessment tools (RSHA) for understanding, communicating and mitigating earthquake risk (Panza et al, 2001). The procedure for the NDSHA-derived Seismic Hazard Maps at the regional scale is described in some detail at http://www.xeris.it/Hazard/index.html.

NDSHA Seismic Hazard Assessment has been *well validated* by all events occurring in regions where NDSHA maps were available at the time of the subsequent earthquakes; including these observations from four recently destructive earthquakes: M 5.9 Emilia, Italy 2012; M 6.3 L'Aquila, Italy 2009; M 5.5–6.6 Central Italy 2016–2017 Seismic Crisis; and M 7.8 Nepal 2015. This *good performance* suggests that the wider adoption of NDSHA (especially in tectonically active areas – *but* with perhaps relatively *prolonged* seismic quiescence, i.e. where only few major events have occurred in historical time) can better prepare civil societies for the *entire* suite of potential earthquakes that can … and will occur!

Better to retire and then *bury* PSHA, which is more *concept* and *"trust in numbers"* than it is a tested pathway to seismic safety, R.I.***PSHA*** … than to "take a chance on a guess" and then, in the future, to experience *more* earthquake disasters and catastrophes, because *erroneous* hazard maps depicted only "low hazard", but the active tectonic regions *again* acted otherwise!

PSHA, *unlike* NDSHA, has: (a) *never* been validated by "objective testing"; but has (b) actually been proven *unreliable* (Panza et al, 2014 and references therein) as a forecasting method on the "rates" (but claimed *probabilities*) of earthquake occurrence (e.g. "Seismic Roulette" in Kossobokov, 2017; and also Rugarli et al, 2019); and (c) has *nevertheless* mandated that earthquake-resistant design standards and societal earthquake preparedness and planning should be based on "engineering seismic risk analysis" models – models which incorporate assumptions, really *fabulations* (or "magical realisms") now known to conflict with what we have learned scientifically regarding earthquake geology and earthquake physics over this same (almost 50-yr) time frame … of PSHA's: (i) initial hype; (ii) acceptance; and (iii) eventual 30-40 yr. rise to dominance.

PSHA, because it has too often delivered not only *erroneous* but also *too deadly* results (Wyss et al, 2012; Panza et al, 2014; Bela, 2014; and Kossobokov, 2017), has remained a "conundrum", despite it having been extensively debated and also challenged over these last three decades; a sample of contributions is contained in the PAGEOPH Topical Volume 168 (2011) and references therein. In the evidence against PSHA: too many damaging and deadly earthquakes (like the 1988 M 6.8 Spitak, Armenia earthquake; the 2011 M 9 Tohoku, Japan Megathrust; and the 2012 M 6 Emilia, Italy events) have all occurred in regions rated to be "low-risk" by PSHA Seismic Hazard Maps (e.g. Peresan and Panza, 2012; Mulargia et al., 2017).

> ***"The conundrum, though, is that, once serious questions are raised, it's hard — and perhaps even wrong — not to debate them."***

It should be widely taken to heart, we advise, that the continued practice of PSHA for: (a) determining earthquake-resistant design standards for civil protection; and for (b) mitigation of both heritage and existing building vulnerabilities, as well as mitigation of community economic well-being and resilience − is still in its *perpetual* state-of-crisis!

Alternative methods, which are already available and ready-to-use, like NDSHA, could and should be applied *worldwide!* The results will then be threefold: (1) to extensively test these alternative methods; (2) to prove that they globally actually perform more reliably and safely than PSHA; and (3) to make the "real earthquake" more *understandable* and more *tangible* to design professionals in their undertakings of earthquake-resistant design considerations to protect civil populations, heritage buildings, and a more resilient infrastructure … **R.I.P*SHA!***

A novel scheme has now been developed in order to delineate, as precisely as possible, the *more earthquake-prone regions* where *preparedness* actions and *seismic risk mitigation planning* should be concentrated − and one method is promisingly guided by our abilities to now fully exploit the information content of all the available data, together with seismological and geodetic analyses that were unavailable in 1968, the year both PSHA and plate tectonics were born! Plate tectonics, better still … *polarized plate tectonics*, provides indeed the main *driving mechanisms* at the base of seismicity − with the moon and sun as continuous sources of energy for *plate motions* (Doglioni and Panza, 2015).

From the *seismological* point of view, both: (a) long-lasting practice; and (b) results obtained for the Italian territory over two decades of rigorous prospective testing of fully formalized algorithms (e.g. CN), as well as worldwide (M8) (Keilis-Borok and Kossobokov, 1987, 1990; ICTP Report 2010, 2011; Kossobokov and Soloviev, 2015; Kossobokov, 2017) − characteristically prove the *feasibility of* earthquake *forecasting*, based upon the analysis of seismicity patterns at the intermediate-term (i.e. several months) middle-range (i.e. few hundred kilometers) scale (ICTP Report 2010 (2011), pp. 52–53; Peresan et al, 2012; Molchan et al, 2017; 2018). Although these algorithms, as a rule, are not specifically aiming their forecasting efforts at issuing "red alert" (as might be appropriate for a volcanic eruption – per Peterson, 1988), they may allow *preparedness* and *risk mitigation* actions to be both better focused and more localized.

An improved, but not an ultimate precision, can be achieved by *reducing* as much as possible the *space-time volume* of the alarms; by jointly considering both *seismological* and *geodetic* information together, as it has been *now shown* by the retrospective analyses (including stability tests) carried out on GPS data preceding the 2012 Emilia earthquake and the Central Italy Seismic Crisis (beginning 24 August 2016 with the M 6.1 Amatrice earthquake). *Another* very promising improvement comes from the careful monitoring and assessment of "Pre-Earthquake Signals" monitored from both earth and space (Ouzounov, 2018; Ouzounov et al, 2018 a,b; Pulinets and Ouzounov, 2018).

Geodetic tools have been developed which allow for a systematic analysis of GPS *velocity* variations (together with their accuracies) along a number of *transects*− properly located tectonically along-strike and across-strike, according to the tectonic and seismological information. The aim is to identify *reliable anomalies* in the *strain rate distribution* within an *alarm space*; as, in fact, no time-dependence has been detected in the more than 10 years preceding the occurrence of these studied events. Some counter examples, considering both along-strike and across-strike transects, traversing both CN alarmed and non-alarmed areas, do not show any spatial acceleration localized trends, comparable to the ones well-defined along both the Amatrice (across-strike) and Emilia (Apennines crest) transects (Peresan et al, 2018). Therefore the *extent* of the alarmed areas, *identified* based on seismicity patterns at the middle-range scale (i.e. linear dimensions of a few hundred kilometers), can perhaps be significantly reduced for *planning* more focused and localized preparedness actions and mitigation measures.

SOME NOMENCLATURE

CN	California-Nevada algorithm for intermediate-term middle-range earthquake prediction.
DGA	Design Ground Acceleration.
EMS	European Macroseismic Scale.
EPA	Effective Peak Acceleration.
GMPE	Ground Motion Prediction Equation.
GNSS	Global Navigation Satellite System - standard term for orbiting satellite navigation systems that provide autonomous geo-spatial positioning.
GPS	Global Positioning System, part of GNSS - Global Navigation Satellite System.
GR	Gutenberg-Richter relation; a log-linear frequency-magnitude law only at global scale.
M	Unspecified scale magnitude.
m_b	Body waves magnitude.
M_s	Surface waves magnitude.
Mw	Moment magnitude.
M8	Algorithm for intermediate-term middle-range earthquake prediction.
MCE	Maximum Credible Earthquake.
M_{max}	Maximum Observed or Estimated Magnitude.
M_{design}	Magnitude indicated by NDSHA ($M_{design} = M_{max} + \gamma_{EM}\sigma_M$).
M_{eq}	Magnitude larger than M_{design}.
NDSHA	Neo-Deterministic Seismic Hazard Assessment.
PGA	Peak Ground Acceleration.
PGD	Peak Ground Displacement.
PGV	Peak Ground Velocity.
PRA	Probabilistic Risk Assessment.
PSHA	Probabilistic Seismic Hazard Analysis/Assessment.
R.I·P.	Requiescat In Pace (May he/she rest in peace).
RSHA	Reliable Seismic Hazard Assessment.
SAR	Synthetic Aperture Radar.
SHA	Seismic Hazard Assessment.
SISMA	Seismic Information System for Monitoring and Alert.
USNRC	U.S. Nuclear Regulatory Commission.
γ_{EM}	Further tunable increment to M_{max}.
σ_M	Accepted global standard deviation of M.

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* Indicating an important reference, but one that is only listed in the *Supplementary material* (BIBLIOGRAPHIC JOURNEY to a NEW PARADIGM), which contains the “complete list” of all citations mentioned in the paper.

Declaration of Competing Interest

Potential competing interests do not exist pertaining to this manuscript.

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“A painter should begin every canvas with a wash of black, because all things in nature are dark except where exposed by the light.”

- Leonardo da Vinci

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- Giuliano Panza

Ne quid falsi dicere audeat, ne quid veri non audeat

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enggeo.2019.105403.

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