Creating an earthquake scenario in China: A case study in Weinan City, Shaanxi province

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Abstract

In efforts to address government-identified gaps between top-down policies and local-level preparedness approaches, a team from China, the UK and the US undertook a transdisciplinary, participatory project to develop an earthquake scenario for two administrative districts of Weinan, Shaanxi province, located east of Xi'an. We designed the scenario study and communication materials, a first of their kind in China, to help local agencies describe and communicate earthquake risk to local decision-makers and the public. Weinan was destroyed by the 1556 M8¼ Huaxian earthquake, China's deadliest so far, and damaged by the 1568 M~7 Shaanxi Gaoling earthquake (also known as the M6¾ Northeast Xi'an earthquake). We chose a repeat of this 1568 event, because earthquakes of the size of the 1556 Huaxian event are extremely rare in the Weihe basin (and similar tectonic environments worldwide). We modelled the ground motion of the 1568 event, prepared a loss estimate, conducted field charrettes comprising field work and local consultations, and carried out disaster issue-focused social surveys to understand Weinan's main earthquake risk problems. We used a storytelling approach to create two science-based narratives, in Chinese and English, of the scenario earthquake's aftermath. One is a short graphic novel with earthquake mitigation and preparedness tips for the

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general public; the other is a narrative story with technical content and recommendations for relevant local agencies. The narratives can help people visualize the estimated losses and impacts, and provide mitigation and preparedness recommendations that, if implemented, will help reduce earthquake damage and consequences.

Key words: Transdisciplinary; participatory; narrative; storytelling; landslides; loss estimation

1. Earthquake scenarios: international experience and implications for China

Scenarios have emerged over the last few decades as a useful method to bring together physical, environmental and social scientists, engineers, policymakers, government agencies, private sector companies and citizens to plan for possible future events. They provide a forum to assemble existing scientific and other forms of knowledge about what might happen and to decide collaboratively what could be done to mitigate the impact of harmful events, or maximize the benefit of positive events. They have been used for a very wide range of events, including defense planning (for example by RAND Corporation) to develop a large scale early warning system for incoming ballistic missiles [1], governance reform (for example the Mont Fleur scenarios to deliberate the future of South Africa after the end of apartheid in 1991-92 [2]), and most relevant to our purposes, for planning to mitigate the impact of natural disasters (for example the United States Geological Survey (USGS) California ShakeOut earthquake scenario [3]).

Since the 1960s, scenarios have been used to understand and communicate the potential consequences of earthquakes, and as a basis for mitigation, preparedness, response and recovery planning. In California alone, scenarios have been used to inform disaster preparedness planning for local, regional, state and federal authorities; to develop guidelines and municipal ordinances for residential seismic strengthening; to provide guidance for policy and legislation development in scenario-affected regions; to serve as the basis for large-scale preparedness exercises; and to inform development of response, recovery and resilience plans. As used in this paper, an earthquake scenario refers to a study of the consequences from a specific, hypothetical earthquake, conducted for the above purposes. The same approach can be used for other natural hazard events. A scenario includes the technical “core” consisting of a loss estimate and documentation of how the estimate was made, along with a description of impacts, often in narrative form that presents the hypothetical disaster unfolding. Some scenarios also include recommendations to reduce losses and action plans to implement them, or specialized products for public communications and response simulation exercises. The scope, level of technical detail, and presentation style can vary widely between scenarios, but all share the common intent of presenting risk information in a way that allows the audience to conceptualize potential damage and its consequences. Guidance on scenario preparation, based on experience described below, is available from several sources (e.g., [4,5,6]).

A detailed, 15-year-long study of the effects of a repeat of the 1923 M7.9 Kanto earthquake on contemporary Tokyo, released in 1978 (described in [7]), was probably the first comprehensive earthquake scenario. In the early- and mid-1970s, the US National Oceanic and Atmospheric Administration (NOAA) and USGS released a series of loss estimates for potential US West Coast earthquakes [8,9,10,11], which were the beginnings of earthquake scenario use for preparedness in the US. Beginning in 1980, the California Division of Mines and Geology (CDMG, now the California Geological Survey) began to prepare infrastructure-focused earthquake scenarios for planning purposes (e.g., [12,13]). FEMA-176 [14] includes a list of early studies in the US, and lays out a significant portion of the conceptual framework that later scenario studies would follow. During this period and in the decades that followed, much practical progress was made in earthquake loss estimation (e.g., [15,16]), including the debut of freely available HAZUS loss estimation software, which supported more robust scenario studies.

In the 1990s, GeoHazards International (GHI) pioneered the use of earthquake scenarios for risk reduction in emerging and developing countries, adapting methods from California and Japan. In early examples of transdisciplinary, participatory approaches to scenario creation, GHI worked with local professionals to create scenarios in Quito, Ecuador [17] and Kathmandu, Nepal [18], as well as in additional cities under the RADIUS project [19]. Transdisciplinary approaches involve practitioners and researchers from multiple disciplines working together with stakeholders to solve difficult problems (see [20] for further information). GHI's Kathmandu scenario appears to have been the first to use the storytelling approach of following a fictional character in its narrative. GHI's more recent scenarios include Aizawl, India [21] and three districts in Nepal [22,23,24].

Meanwhile, use of scenarios for planning continued in the US, with major scenarios by the Earthquake Engineering Research Institute (e.g., [25,26,27]), and a series of large-scale scenarios by USGS, including the Southern California ShakeOut scenario [28]. The ShakeOut is probably the most widely known and used earthquake scenario to date, with extensive public outreach and communications described in [3]. The most recent is the Haywired scenario [29,30], focused on earthquake impacts to technology and lifelines in the San Francisco Bay Area. Researchers in Japan (see [7]; numerous studies by the Central Disaster Prevention Council for internal use; [31]), New Zealand (recent examples include [32,33]), Colombia (e.g., [34]), Nepal (e.g. [35,36]), India, Turkey, Kazakhstan, and others also prepared scenarios for similar purposes.

Because of the long-lasting, painful experience of the 1976 M7.8 Tangshan earthquake, China began to conduct work on earthquake disaster loss assessment (earthquake loss estimation/ELE) in 1980 [37]. For example, in 1980, the Institute of Engineering Mechanics, China Earthquake Administration (CEA) launched a two-year long project on earthquake building damage assessment in Anyang city, Henan Province [38]; in 1981, the Institute of Geology, CEA and the Institute of Engineering Earthquake Research, Chinese Academy of Building Sciences, launched a three-year long program on earthquake loss estimation (ELE) in Yantai City (Shan Dong province) and Xuzhou City (Jiangsu province) [39].

In the 1990s, with the start of the UN International Decade for Natural Disaster Reduction (IDNDR) campaign, the CEA set up the work on ELE as one of its key research topics. In 1989, CEA established the "Research Group/Task Force on Future Earthquake Loss Estimation", and carried out research on "China Earthquake Loss Estimation in the Forthcoming 50 Years" [40,41]. In order to further promote and guide ELE work, the CEA issued the "*Work Outline for Earthquake Loss Estimation (Draft)*" in early 1990, which advanced China's ELE to enter a new stage [37]. In 1993, research on "Prediction of Chinese Earthquake Losses with Scale of Ten Years" was carried out as a national research planning priority [42]. During the "9th Five-Year" planning period (1996-2000), ELE and earthquake disaster mitigation demonstration research and applications were carried out in multiple regional cities including Zigong, Sichuan Province, and Quanzhou, Fujian Province [43]. Reflecting years of progress, the standard *GB/T 19428-2003: Code for earthquake disaster evaluation and its information management system* was released in 2003 [44] and revised recently in 2014 (*GB/T 19428-2014*, [45]). The basic logic of China's ELE methodology originated primarily in the US Applied Technology Council methods (e.g., [15]). As early as in 1991, Chinese researchers translated *ATC-13 Earthquake Damage Evaluation Data for California* into Chinese [46]. Since then, the ATC-series documents have been widely referred to in the nation. Substantial efforts over the past three decades in China have resulted in earthquake loss estimates for around 40 large and medium-sized cities nationwide.

Although significant progress in earthquake loss estimation in China has been achieved, there is still considerable space for further work, considering the full spectrum of internationally available earthquake scenario work. The major such areas for ELE in China are as follows:

- Although the work scope described in GB/T 19428-2014 is quite inclusive, most past analyses (especially the early ones) have often disproportionately centered on buildings, lifelines, and casualties and direct economic losses caused by damage to them. The analysis on other aspects such as earthquake-induced geo-hazards and secondary disasters has often been very limited, due to various factors such as resource limitations, end-user requirements, and limited availability of certain necessary expertise to assist the work team.
- Almost all existing ELE studies (i.e., the ELE work conducted for large and medium-sized cities) were mainly focused on urban areas, with rural areas barely or seldom addressed.
- Loss estimates have frequently focused on physical vulnerabilities of buildings and lifelines, with limited discussion of functionality and the consequences of damage on systems and people, thus reducing practical applicability. Communication between researchers and local relevant agencies has often been insufficient, resulting in researchers often having limited understanding of actual risks to functionality (i.e., if a water pipeline breaks, how many people would be impacted), and end-user agencies often lacking understanding of how researchers' work may be relevant to their responsibilities and ongoing work.
- Existing ELE work mainly aimed to help government and its relevant agencies to improve their top-down disaster reduction practices, with little bottom-up consideration on how to directly serve the broad civil society, especially the general public and grass-roots groups. For example, apart from physical damage of buildings and infrastructure, other situations the general public and communities may face (e.g., family and community level impacts and response) have barely been addressed. Associated human and social science-focused elements have almost never been examined substantively.
- There has been little examination of contextual information to understand: how the local population understands and practises earthquake preparedness; how ELE work can be understood and used; and how the work results and products should be made more useful.
- Past loss estimation work (particularly the earlier estimates) frequently ended with production of a report focused on detailed technical explanations of buildings and lifelines, with some general, high level recommendations. End-users often found these reports dry and difficult to understand, and unmanageable to use, creating a barrier to actually using the results to reduce risk. Recently, the products of some ELE work in China also included "an information management system" which was often sophisticated in information technology and professional in earthquake hazard and disaster analysis but seems more suitable for researchers to maintain and use than for end-users.

Given the above, and with the opportunity provided by the UK Natural Environment (NERC) and Economic and Social (ESRC) Research Councils and the Natural Science Foundation of China (NSFC) through their jointly supported project *"Pan-participatory Assessment and Governance of Earthquake Risks in the Ordos Area (PAGER-O)"*, we decided to prepare a pilot earthquake scenario for Weinan area, Shaanxi province, China, using the GHI approaches described above. The PAGER-O project is one part of the UK-China collaboration programme "*Increasing Resilience to Natural Hazards in Earthquake-Prone regions in China (IRNHiC)*", whose aim is to introduce international experience relevant to China's earthquake loss estimation work and beyond, advance earthquake scenario practice where possible, and address simultaneously the government-identified gap between top-down and bottom-up disaster risk reduction approaches in China [47,48], to the extent possible.

2. Weinan context

The study area in Weinan City consists of two municipal/administrative districts (Fig. 1), Linwei District and Huazhou District, which have a total population of over 1.30 million and a GDP of 46.55 billion RMB in 2017. Geographically, the study area is east of Xi'an in Shaanxi Province, along the Weihe River in the Weihe basin that lies south of the loess plateau and north of the Qinling Mountains. This great difference in the geomorphological point of view among high mountains, relatively flat Weihe basin, and uneven loess tableland in the area results in a variety of land use and land coverage. The climate is suitable for agriculture, although occasionally crops in this area suffer from summer drought and autumn floods. Weinan is a predominantly agricultural area, but there are also several large-scale chemical factories and thermal power plants, especially in the study area, which might experience secondary disasters when an earthquake occurs. On the route between Beijing and Xi'an, Weinan City is well served by multiple transportation modes including highways, regular and high-speed rail lines, and expressways.

Tectonically, Weinan City lies in the eastern part of the Weihe basin, south of the Ordos block of the North China platform, with the active tectonics of the Weihe sub-seismic belt well developed [49]. The Weihe basin contains a number of active faults (see Fig. 1 in Feng et al. [50], this issue), and was affected by at least 20 major earthquakes since 600 CE for which historical records exist (see Fig. 1 in Ma et al. [51], this issue, reprinted from [52]). Destructive earthquakes affecting Weinan City occurred primarily in two periods, 793-879 and 1501-1568. Between 1501 and1568, three major earthquakes occurred, including China's deadliest earthquake to date, the 1556 M 8¼ Huaxian earthquake. This period of strong seismic activity also included the 1501 M7 Chaoyi and1568 M~7 Shaanxi Gaoling earthquakes (see Ma et al. [51], this issue, for details of the latter), and three smaller earthquakes with magnitudes of M~5½ [53]. Secondary geologic hazards in the study area mainly include landslides in rock and loess, surface fault rupture, ground fissures and subsidence, liquefaction and lateral spreading.

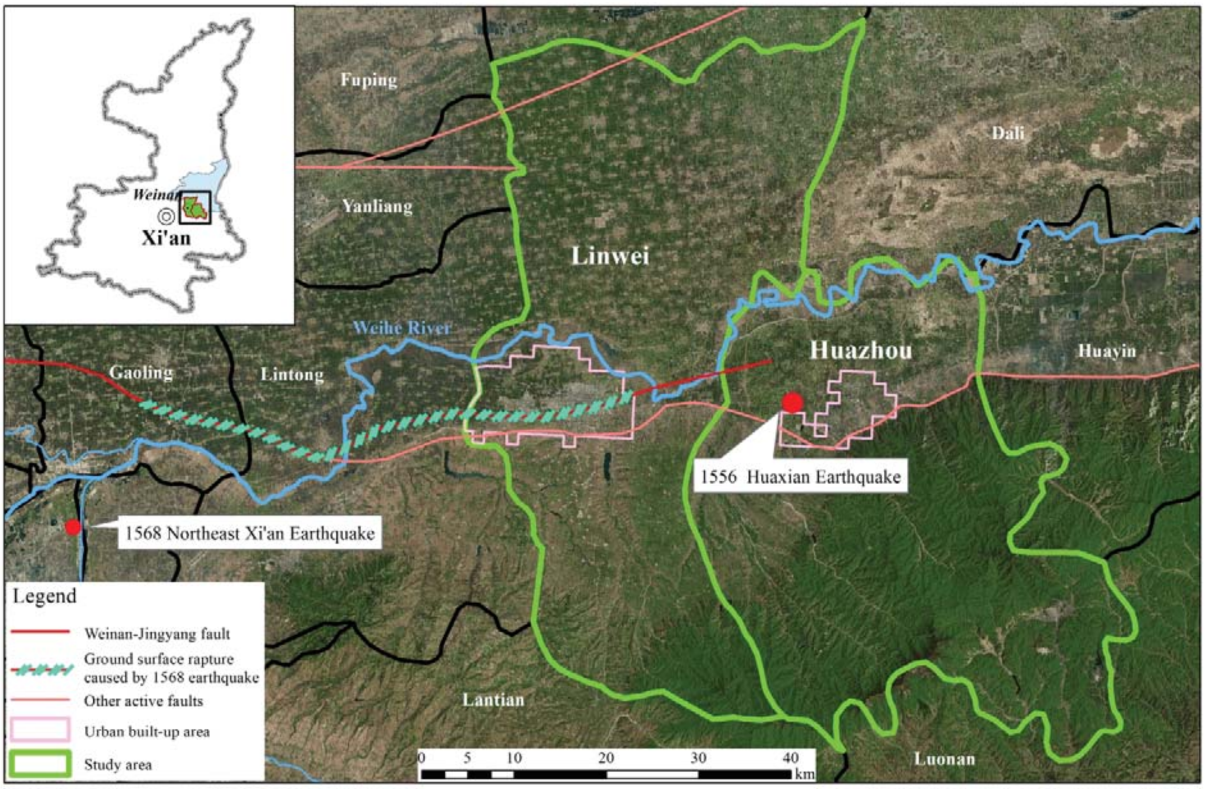


Fig. 1. Map of Linwei and Huazhou districts, Weinan city. Image source: Bing

3. Developing the Weinan scenario: Process

This section provides a brief overview of the main processes the team used to develop the scenario. These processes are based primarily on GHI's practice experience [4,6] and scenario development practices by others (e.g., [3,5]).

3.1. Project initiation and planning

The project's approach was developed collaboratively in planning workshops in Oxford (January) and Beijing (April) in 2016. We identified key objectives for the scenario development process, which included:

- Testing the use of scenario-building as a transdisciplinary process tool for both earthquake risk analysis and local engagement on earthquake risk governance in China; and creating a model scenario process that local researchers or relevant agencies could replicate in other earthquake-threatened areas;
- Basing the scenario on technically credible science and disaster loss estimates to give confidence in the results; and
- Most importantly, motivating both relevant local agencies and the public to take actions to more effectively mitigate earthquake risk and increase resilience.

3.2. Scenario city selection

Through online communications since the initial planning workshop in Oxford, the team selected the scenario city candidates based on the following main criteria, discussed extensively during the April 2016 Beijing launch workshop: a) modest population size, to keep the scope manageable; b) strongly shaken by one of four major historical earthquakes: 1920 Haiyuan, 1739 Yinchuan, 1709 Zhongwei and 1556 Huaxian; c) previous work on historical earthquakes, active tectonics, disaster loss estimates, earthquake hazard micro-zonation, and disaster preparedness, along with potential for meaningful additional physical and social science research; d) receptive local government and community; e) local research and practitioner partners available; f) representative buildings and infrastructure; g) landslide hazard; and h) China Earthquake Administration (CEA) or Ministry of Civil Affairs (MoCA) disaster risk reduction demonstration sites present. We selected these criteria to identify a setting that would allow us to demonstrate how to address a full range of risk problems including infrastructure, buildings and social issues, and possible linkages between top-down and bottom-up earthquake disaster risk reduction (DRR) approaches in China. Labor division was also discussed in this launch workshop, during which Institute of Geology, China Earthquake Administration (IGCEA) and The Hong Kong Polytechnic University, China (Poly-U Hong Kong) teams decided to focus on social science-relevant issues and bottom-up earthquake DRR elements in particular. Between April and November 2016, the China team visited all candidate cities to meet officials and assess each against the key criteria, including the level of interest in collaboration, and selected Weinan as the scenario city.

3.3. Initial site visits, field research and planning meetings

In December 2016, the international team made a technical site visit to Xi’an and Weinan, including meetings with the Shaanxi Earthquake Administration (Shaanxi EA) and local NGOs in Xi’an, field reconnaissance in the two districts of Weinan, and meetings with relevant Weinan authorities and agencies. We held detailed discussions about possible scenario earthquakes and refining the scenario process for the China context.

The Chinese team began field research, including a detailed survey of buildings by a team of over 30 local engineering students, and around 20 Shaanxi EA staff; interviews and analysis of mobile phone data to gather information on building occupancy; visits to water, power and telecoms companies; and collection of information about existing earthquake preparedness and response capacity of government agencies. Research work on preparing shaking intensity maps began. The Chinese team visited the UK in May 2017 to meet with, share experiences with, and learn from other groups working on earthquake disaster risk reduction.

3.4. Charrette 1

In June 2017, the team held a *charrette*, an intense, focused collaborative effort to solve a problem, a process originating in architecture, in Weinan and Xi’an. This charrette focused on understanding the main earthquake risk problems in Linwei and Huazhou districts. Using field charrette processes GHI developed in prior scenario work in India, team members from multiple disciplines spent time together in the field to jointly observe tectonic features and geologic evidence of historical earthquakes (including earthquake induced landslides), lifelines, rural and urban buildings, schools, hospitals and DRR demonstration communities. The team met frequently to review emerging data and ideas, held large-scale participatory stakeholder consultation meetings with officials in Xi’an and Weinan, and selected the scenario earthquake.

3.5. Scenario preparation and review

Following Charrette 1, the Chinese team prepared loss estimates for buildings in rural and urban areas of the scenario districts, and further explored vulnerabilities of lifeline infrastructure (see the subsequent technical approach and methods section for discussion). The Chinese team visited California in October 2017 to meet with organizations involved in earthquake safety and scenarios, and to work with GHI to review the loss estimate results and identify missing information. In November 2017, key international and Chinese team members met in Beijing to present the emerging scenario findings to officials from Shaanxi and Weinan EAs, and agree on the next steps including the most useful products and mechanisms for local engagement and action planning. At this meeting, we agreed on a storytelling approach, and began to prepare the narrative story. Following this meeting, the IGCEA team began to prepare for a large-scale questionnaire surveys to understand local people’s awareness of earthquake risks and, personal and household earthquake resilience, and relevant disaster preparedness across the Weinan prefecture. In addition, the Poly-U Hong Kong team performed face to face interviews in three villages within the study area, specially probing the relationship between poverty and natural-hazard related disasters (Yu et al. [54], this issue). The purposes of these surveys and interviews included addressing, in particular, bottom-up earthquake DRR issues and to inform the development of the narrative story.

3.6. Charrette 2

The second transdisciplinary field charrette in May 2018 was timed to coincide with national events to mark the 10th anniversary of the 2008 Wenchuan earthquake, and focused on discussing, presenting and ground-truthing estimated impacts of the scenario earthquake with local agencies and experts. We presented emerging findings (e.g., building loss estimation results) to government officials in Weinan, and consulted with earthquake administration officials and experts in Xi’an to finalize the most effective form and content of the narrative and start the action-planning phase. We held collaborative writing sessions to improve the narrative and incorporate local feedback.

3.7. Scenario finalization and closing workshop

We incorporated all of the local feedback from Charrette 2, prepared the final building loss estimates, and completed estimates of landslide probability and likely impact on lifelines. We then worked with an illustrator and a book designer to create the scenario narratives for audiences consisting of the general public and local officials, with their input, in both Chinese and English. We presented these draft documents at a January 2019 workshop in Beijing, with participating Chinese experts and officials from CEA, UNICEF China, Beijing Normal University, Ministry of Emergency Management, the Chinese Academy of Sciences, and both Shaanxi EA and Weinan EA acting as peer-reviewers, to obtain feedback on the scenario narratives and the replicability of the transdisciplinary project approach. The workshop produced 30 immediate recommendations to improve communication products, which were incorporated in the final versions of the scenario narratives, as well as exploring ideas for wider replication of the approach. The team also reviewed the overall achievements of the project against the original objectives as set out in the PAGER-O project's original proposal and "Project Initiation and Planning" section in an internal team meeting. The final project results and products were presented at the IRNHiC program-end workshop in Beijing in March 2019, during which two officials from the Huazhou earthquake office of Weinan also attended, reflecting the continuing participation of the relevant local officials during the entirety of this scenario development effort. The project results and products were well received.

4. Preparing the Weinan scenario: Technical approach and methods

This section provides an overview of the methods used to generate scenario results, which other papers in this issue describe in detail. The scenario development team realized that sharing local data is very complex, resulting in all direct work with local data being accomplished by the China team members alone, as the international participants could not access local data. International participants worked with summary results that the China team provided and data available outside China, such as publicly available satellite imagery. Any references to the team's direct use of local data refer to China team members only.

4.1. Selecting the scenario earthquake and estimating shaking

The team confined its consideration of possible scenario earthquakes to repeats of historical earthquakes, for two principal reasons. First, communication of the risks and mitigation strategies is more direct if they are based on a real, rather than hypothetical, earthquake. Second, had we chosen to place the scenario earthquake on one of the active faults in the region that have not hosted a historical earthquake, there would have been the unavoidable risk that some would regard our choice as resembling a forecast of future seismicity. We considered three historical events: the 1501 M7 Chaoyi, 1556 M 8 ¼ Huaxian, and 1568 M~7 Shaanxi Gaoling earthquakes. Of these, we selected the last, because it generated strong but not completely devastating shaking in Linwei and Huazhou (Ma et al. [51] and Chen et al. [55], this issue). Given the number of active faults in the Weihe Basin, the team's earth scientists considered this level of shaking to have a plausible likelihood of occurring, within the next 100 years, somewhere within the region of responsibility for the authorities with whom we were engaged.

In contrast, a ~M8 earthquake, like the 1556 Huaxian event, is expected to occur on the Huashan fault once in more than 5,000 years. Studies of how humans perceive risk (see [56]) and past scenario user needs assessments [14] indicate that it is difficult to motivate action to prepare for threats of such rarity. The 1568 earthquake was preferred to the 1501 Chaoyi earthquake because the causative fault is now well characterized (Feng et al. [50], this issue) and the historical record of ground shaking can be reliably related to the fault (Ma *et al.*, this issue). Furthermore, the epicenter of the 1501 earthquake was too far east to produce damaging shaking in urban Linwei District or the loess tableland, both of significant interest for scenario studies in this area.

Estimates of ground shaking for the 1556 and 1568 earthquakes were prepared using the methods of Chen et al. ([55], this issue), to confirm that the M~7 1568 Shaanxi Gaoling earthquake was the appropriate choice. Local ground motion prediction equations (GMPEs) are not available for the Weihe basin and, although commonly used GMPEs contain some information from earthquakes within mainland China, such data are sparse and it was considered essential to compare computed shaking intensity distributions with historic isoseismals for the M8 ¼ 1556 Huaxian earthquake, which is the best documented of Weinan's historical earthquakes. It was found (Chen et al. [55], this issue) that a satisfactory fit to the historical isoseismals could be obtained by using intensities having a uniformly lower probability of exceedance than predicted by the median values of the parameters to the GMPE ASK13 (see Chen et al. [55], this issue, Figures 4 and 5). The same GMPE and modelling assumptions used for the 1556 earthquake were then used to compute shaking intensity distributions for the scenario repeat of the M~7 1568 earthquake, for which considerably less historic documentation is available. Based on studies by Feng et al. ([50], this issue), this earthquake was modelled as occurring on a 56-km segment of the Weinan-Jinyang Fault, a 105km nearly east-west striking, north-dipping normal fault.

4.2. Determining effects of potential fault rupture, liquefaction, and lateral spreading

According to recent studies (Feng et al. [50], this issue), causative Weinan-Jinyang fault ruptured the surface in the 1568 Shaanxi Gaoling event, so the scenario assumes that surface rupture occurs. Based on published scaling relationships [57], the amount of offset in the scenario event is estimated to be between 0.6 m and 1 m, which is consistent with geologic observations of offset on the order of 1 m (Feng et al. [50], this issue). The assumed scenario surface trace was overlaid on satellite imagery to determine whether the scenario surface rupture would intersect infrastructure.

Past earthquakes, including the 1556 M 8¼ Huaxian and 1501 Chaoyi earthquakes [52,58] have triggered liquefaction in the Weihe basin. Based on liquefaction potential maps (Shaanxi Earthquake Administration, unpublished report, 2011) reviewed by IGCEA team, saturated alluvial soils near the Weihe River and local tributaries such as the Youhe River are expected to be particularly susceptible to liquefaction. (Liquefaction refers to the phenomenon that occurs when saturated sandy soils lose their strength due to earthquake shaking, often associated with the flow and ejection of subsurface water and soil onto the ground surface.) Near the Weihe River, liquefaction-induced lateral spreading may occur as subsurface layers of soil liquefy, resulting in ground settlement, and large blocks of soil above them slide toward the free faces created by the river's steep banks. The team qualitatively estimated the impacts of liquefaction on infrastructure by comparing the areas of liquefaction potential against infrastructure locations.

4.3. Estimating the extent of coseismic landslides

Several major northern China earthquakes since 1900, including the 1920 Haiyuan and 2008 Wenchuan earthquakes, have triggered numerous and deadly landslides. Historical records indicate that the 1556 Huaxian earthquake [52,58] and the 1568 Shaanxi Gaoling earthquake (Ma et al. [51], this issue) also triggered landslides in the Weinan area, but there is less detailed information on the extent of landsliding or its consequences. Because landslide hazard appeared significant, the PAGER-O team collaborated with researchers from a related project on Community Based Disaster Risk Reduction in China (CBDRRiC), part of the same IRINHiC China-UK collaboration program as PAGER-O. CBDRRiC researchers developed estimates of the likelihood of significant landslides (>100 m^2 in area) during the scenario event (Milledge and Densmore, unpublished report, 2018). Technical details of the methodology are reported here, because, unlike other components, they do not appear elsewhere in this issue.

To create estimates, Milledge and Densmore (unpublished report, 2018) differentiated between areas underlain by loess and by bedrock because these rock or stratum types show important differences in coseismic landsliding. Hill slopes within the Weinan region considered by PAGER-O can be divided into two broad material types that have very different material strengths: loess, which is weakly-consolidated fine-grained sediment deposited by wind, and all other rock types, collectively termed ‘bedrock’. While this is a very simplified division, it is noticeable at the landscape scale. Loess underlies the broad tableland immediately to the south of urban Linwei district (colloquially, Weinan city) and the short but steep hillslopes that form the margins of the tableland and the valleys that dissect it. Bedrock underlies the higher mountainous areas to the south and southeast of Weinan city.

Landslide hazard was estimated with statistical models trained on exemplar coseismic landslide inventories: the 1920 Haiyuan earthquake for loess areas, and the 2008 Wenchuan earthquake for bedrock areas. Landslides triggered by the Haiyuan earthquake were derived from the inventory of [59], while those triggered by the Wenchuan earthquake were derived from the comprehensive inventory of [60].

For each inventory, logistic regression was applied to develop a functional relationship between peak ground acceleration (PGA), skyline angle of the topography, and landslide hazard (the probability that a grid cell is covered by either scar or runout). Skyline angle was calculated for each 90x90 m pixel (using [61]) from SRTM digital elevation data with a 90 m spatial resolution. PGA estimates for the Wenchuan earthquake are from the USGS ShakeMap version 3.5.1586 [62]. Haiyuan earthquake shaking intensity estimates are from the Seismological Institute of Lanzhou, CEA and the Seismological Team of Ningxia Hui Autonomous Region (quoted in [59]), converted to Modified Mercalli Intensity (using Appendix I of GB/T 17742-1999) and then to PGA (using [63]).

Logistic regression equations were applied to forward-predict landslide probability for the two separate domains in the Weinan study area mapped as loess and bedrock, using the parameters from their respective exemplar earthquakes. The same method as for the training inventories [61] was used to derive skyline angle from SRTM elevation data. PGA estimates for the PAGER-O scenario earthquake were linearly interpolated to the same 90 m grid. Finally, the two coseismic landslide probability predictions for loess and bedrock areas were combined to generate a single landslide hazard map. Use of different logistic regression equations for the two different domains is a novel feature of this work.

Ten scenario realizations of landslide occurrence were generated from the landslide probability map to provide an indication of potential landslide impacts that could be more readily understood. Loess and bedrock domains were treated separately, picking landslides from the appropriate empirical size distributions of the Haiyuan [59] and Wenchuan [60] inventories, then randomly assigning their locations guided by the landslide probability from the hazard map and constrained by a feasibility rule such that landslides were only placed where there was sufficient relief for them to occur. The total landslide area for each realization was defined by the expected landslide area from the landslide probability map.

4.4. Modeling building damage, casualties, and direct economic losses

Two research teams prepared loss estimates related to building damage in the urban and rural areas of Linwei and Huazhou districts, respectively. Due to significant differences in the building stock and number of buildings to cover, the teams used different approaches. Li et al. [64] and Liu et al. [65] (this issue) from Institute of Geology, China Earthquake Administration (IGCEA) and China Earthquake Networks Center (CENC) presented new methods involving the combination of remote sensing, building-relevant local knowledge, and broad online data resources [66,67] used for rural areas, while Wang and Gao [68] and Wang and Wang [69] (this issue) from China Earthquake Disaster Prevention Center (CEDPC), described new methods used for urban parts, though the central logic of loss estimation calculations adhered to existing, tested approaches that are described in the relevant national standard *GB/T 19428-2014: Code for earthquake loss estimation and its information management system* [45].

Both teams collected large georeferenced building inventory datasets, and followed the general procedures in government standard GB/T 19428-2014.These procedures specify that estimates of damage be made for each intensity VI through X on the Chinese Seismic Intensity Scale (GB/T17742-2008, included as an appendix in Ma et al. [51], this issue). Using the scenario shaking intensity maps from Chen et al. [55] (this issue), the research teams assigned the correct intensity to the georeferenced building inventory with the help of the spatial-join tool of ArcGIS V10 software to arrive at the overall loss estimate. Damage matrices and vulnerability functions that form the basis for building damage estimates were developed using damage data from Chinese historical earthquakes. For urban areas, this included a large database of damaged masonry buildings [70] and published damage data from the 2008 Wenchuan earthquake and several subsequent earthquakes in China with M>6. For rural buildings, vulnerability functions were created on the basis of historical destructive earthquake records and corresponding earthquake loss evaluation compilations (1993-2016), employing the fitting method of beta probability density functions (BPDF), in order to estimate losses for intensities above VIII for which data are scarce, as Li et al. [64] (this issue) describe. Casualties and economic losses were estimated using published relationships [70] based on data from less recent Chinese earthquakes. We assumed the scenario earthquake occurs at 2:02 pm on a Saturday in April.

4.5. Understanding potential threats to utility infrastructure and transportation systems

Like any sizeable city, Weinan relies on its water, electric power, communications, gas and fuel, and transportation infrastructure to function. Weinan is located in a key corridor between Xi'an and Beijing (more broadly, between eastern and western China), and important transportation routes such as the G30 expressway, National Road 310, and regular and high-speed rail lines pass through Linwei and Huazhou districts. Weinan's location in the Weihe basin means that components of these infrastructure systems are located in areas susceptible to ground failure, cross active faults, or are close enough to them to experience strong shaking. Infrastructure locations are also constrained to some degree by the presence of the Weihe River floodplain; the G30 expressway and regular rail lines run just north of the northern margin of the Weinan loess tableland, and of the Huashan mountain front, avoiding the floodplain. Only the high-speed rail line and local roads and rail lines are located out in the basin.

We focused on identifying concerns about the intersection of utility and transportation infrastructure with known geologic hazard areas, such as locations where infrastructure crosses active faults and areas of heightened landslide susceptibility or high liquefaction potential. Publicly available satellite imagery and limited field observations were the main tools to understand the severity of geologic hazard impacts on them.

Because water systems are critical for overall resilience of an area and past earthquakes demonstrate that system damage frequently causes water service interruptions [71,72,73]. The team's water system engineer, landslide geologist, and structural geologists conducted joint fieldwork with local EA and water agency staff at the key water infrastructure sites, such as the main drinking water reservoirs and treatment plants. This transdisciplinary process allowed the team to rapidly understand the multiple disciplinary dimensions of the water system's earthquake risk problems. Based on these consultations with local water professionals/staff and fieldwork, we developed a qualitative understanding of the four subsystems (using the classification of [72]) that comprise the water supply system in Linwei and Huazhou districts: raw water supply systems, treatment systems, transmission systems and distribution systems, and of their potential seismic and seismic-induced geo-hazard vulnerabilities.

As frequently occurs in other countries due to security concerns, it was difficult for utility system operators to share information on their systems with anyone outside the organization. This is particularly true for operators of electric power and gas systems; the team was able to obtain only minimal information on these systems. However, utility and transportation system operators can use this scenario as a starting point to prepare their own detailed loss estimates for their systems, using the scenario shaking and identified areas of higher susceptibility to ground failure of various types. We also investigated infrastructure interdependencies qualitatively, with a focus on identifying areas in which damage and loss of function in one system would substantially adversely impact another.

4.6. Understanding social impacts and bottom-up earthquake DRR-focused issues

Apart from modelling typical impacts on the local population and economy, such as casualties, injuries, 'homeless population' who need temporary shelter, and direct economic loss, (see Li et al. [64], this issue), and trying to understand in the sense of a pilot study what other situations the general public and local community (village) would face, apart from physical damage of buildings (see Liu et al. [65], this issue), we particularly emphasized on how aware local people at the grass-roots are of earthquake issues, to what extent they have practised earthquake preparedness and mitigation, and how resilient they are currently. We believe this context is a contributing factor that helps determine whether our scenario work can be understood and used more broadly, and if so, how we should make our results and products more useful. We also believe understanding this context is crucial for improving relevant bottom-up earthquake DRR approaches.

To obtain this big picture, the IGCEA team, collaborating with educators from Beijing Normal University, firstly proposed an education-oriented framework of public awareness of earthquake disasters and two actor level-sensitive models of personal and household earthquake resilience. For the awareness framework, we established it after carefully examining the implications of UNISDR's general term of public awareness [74], systematically summarizing our 10 year-long similar prior work (e.g., [75]), and incorporating the enlightenment through careful study of what Environmental Education Objectives mean [76,77] in particular. We value UNESCO-UNEP's Environmental Education Objectives because they are all very "actual application-oriented," thus we think the proper intake of such understanding of UNESCO-UNEP is also helpful for dealing with practical earthquake disaster education issues, and beneficial for society by raising people's earthquake disaster awareness through better education practices. Generally, UNESCO-UNEP's Environmental Education Objectives are as follows: to help individuals and social groups to acquire "awareness, knowledge, attitudes, skills" of/for (resolving) environmental problems and to facilitate them to "participate" in actual actions. For the two resilience models, we mainly based them on our similar prior work (e.g., [75]) and UNISDR's definition of resilience [74,78], and also incorporated relevant pieces from disciplines outside geo-sciences and engineering, including understanding of people's psychological resilience and family resilience from psychology and family studies [79,80,81,82]. With these frameworks and models, we then developed a large set of earthquake disaster awareness and resilience measurement questionnaires (over 20 in total). These tools closely align with broad China contexts (e.g., the nation's powerful and effective top-down disaster management, which might cause the general public to shift too much responsibility to the government and lower their own motivation to prepare) and various local realities (hazard and disaster, building and housing practices, disaster management, education and disaster education, etc.) and to deliberately target different public groups: primary and high school students in different grades, their parents and teachers, and broad general public. In 2018, both pilot and formal surveys that covered almost the entire Weinan prefectural area (not just Linwei and Huazhou districts) were completed, with over 15,000 copies of various questionnaire data collected.

With a multi-hazard point of view, the Poly-U team then used structured face-to-face interviews to look at hazard and disaster understanding, and actual disaster reduction practices of the rural population in the study area. They conducted interviews in three carefully selected sample villages (communities) in Linwei district, which have distinct topographical and geomorphologic differences: Weihe basin, loess tableland, and Qinling mountains, where commonly experienced natural hazards are also different. Apart from addressing people's risk perception, disaster preparedness, adaptation intentions, interpersonal communications, and associated interaction mechanism(s) between them, this team particularly emphasized the relationship between poverty and disasters. The three case study villages are all the government-named "poverty villages" (e.g., Yu et al. [54], this issue; and [83]). Incorporating poverty issues becomes very relevant when dealing with disaster risk reduction, because poverty and natural disasters are frequently "twin brothers" in many rural areas in mainland China. Poverty alleviation and disaster reduction should be synergistic; people living in poverty are frequently more vulnerable to disasters (e.g., [84,85]; and Yu et al. [54], this issue). And most importantly, integrating earthquake disaster reduction mobilization into poverty alleviation activities might be more effective for the general public in such areas, because people may view strong earthquakes as being too far removed from their daily life.

Based on these social science-focused studies and thinking, the necessity of conveying the role that social vulnerability, for example "poverty", plays in exacerbating disaster risk shaped greatly the risk communication strategy for the scenario results. This included prominently featuring a more vulnerable population common in the poor rural area of Weinan, and most poor rural areas of mainland China—so-called "left-behind children"—as main characters in the fictional narrative describing what happens during and after the scenario earthquake.

As scenario work progressed, it became clearer that "community-based disaster risk reduction (CBDDR), school-based DRR, family-based DRR, and broad disaster reduction knowledge dissemination and education" should be the most feasible and sustainable linkages between top-down and bottom-up earthquake DRR approaches, because these items are all closely related to government or its relevant agencies' daily responsibilities and functions. For example, promoting "disaster reduction knowledge dissemination and education" has long been a key daily function of the CEA system. We invested great effort to produce interesting scenario narratives useful for these DRR education functions.

5. Scenario results and findings regarding Weinan earthquake risk

A repeat of the 1568 M~7 Northeast Xi’an / Shaanxi Gaoling earthquake in present-day Linwei and Huazhou districts would have devastating consequences: thousands of building collapses, over 2100 deaths, more than 10,000 serious injuries, substantial damage to infrastructure and disruption of utility services, and over 41 billion Yuan RMB in direct economic losses from building damage alone which almost equals the present-day annual GDP of the two districts (46.55 billion Yuan RMB in 2017). Repairing the damage to infrastructure and restoring services would add substantial costs. Unreinforced masonry buildings, most prevalent in rural areas but also present in urban parts of the study districts, would suffer the most damage. Fig. 2 shows the extent of building damage, using a damage rate allowing comparisons of damage severity.

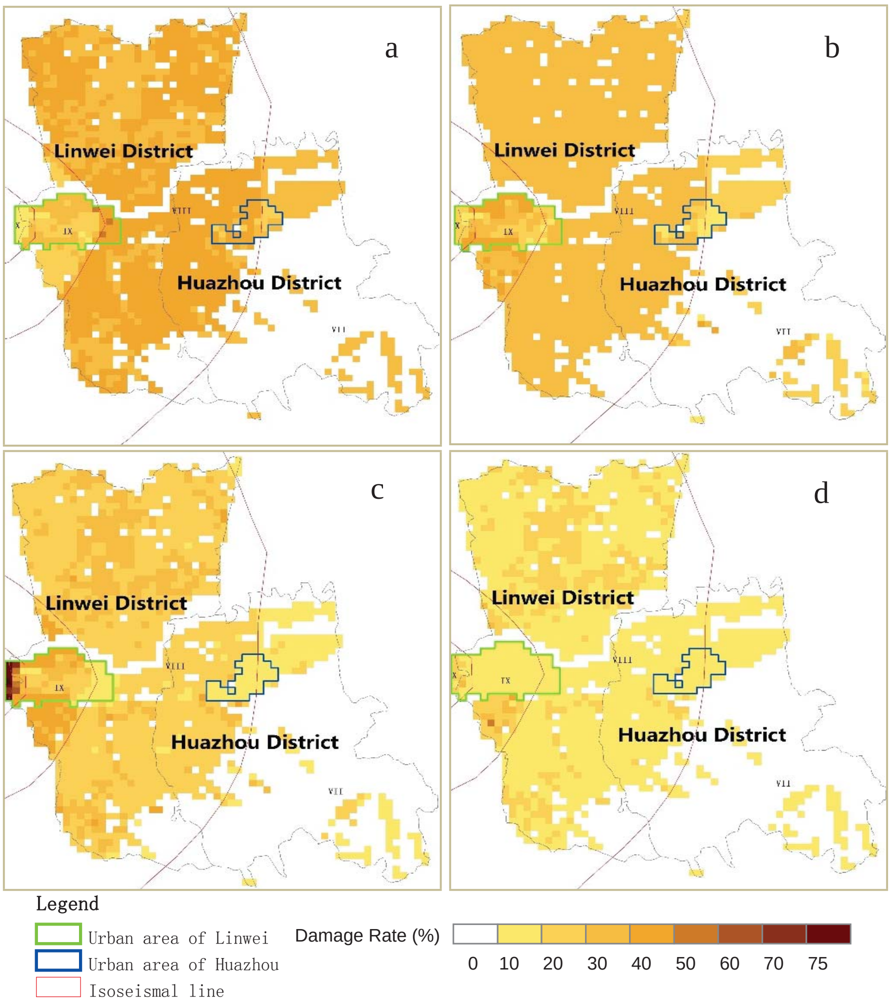


Fig. 2. Estimated damage rate of buildings with different damage degrees: a) slight damage; b) moderate damage; c) severe damage; and d) collapse. The regions marked in green and blue respectively show the locations of the urban area of Linwei and Huazhou.

Rural areas in western Linwei district are among the areas that would experience the heaviest damage, due to very strong shaking. Most rural buildings in these areas were not constructed to any building code and without any earthquake-resistant measures. In rural Linwei, nearly 9,840 houses with an area of 1.3 million square metres of these masonry buildings alone would collapse, and a further 22,350 houses with an area of 3.0 million square metres would be too badly damaged to use. In urban Linwei, small commercial and older residential masonry buildings would also suffer proportionally heavier damage. Many of these buildings were built before modern earthquake-resistant codes. In newer buildings, damage to finishes and partition walls would need repair. Huazhou district is further from the portion of the fault that ruptures, so the shaking is not as strong and there would be less damage.

Unfortunately, infrastructure near the northern tableland margin is exposed both to long-runout loess landslides and to strong shaking and fault rupture from the Weinan-Jinyang fault that runs near the tableland margin in this area. Landslides along the margins of the loess tableland (estimated to be 30-40 landslides with area >8000 m^2) and along its valleys (estimated to 70-110 landslides with area >8000 m^2) would damage infrastructure, including roads, rail lines and the Youhe Reservoir, urban Linwei's secondary drinking water reservoir, and disrupt access to the tableland, as Fig. 3 shows. In the Weihe River flood plain, liquefaction would damage roads, water lines, irrigation canals, and buildings. Along the Weihe River itself, thin layers of soil are expected to liquefy, causing large areas of soil above them to slide slowly toward the river, a process known as lateral spreading. Floodwalls and embankments would be damaged in several locations, causing significant damage to flood protection systems for Linwei district. Vertical offsets of up to 1 m created by surface rupture of the Weinan-Jinyang fault would damage roads, rail lines, pipes, and flood protection structures crossing the fault.

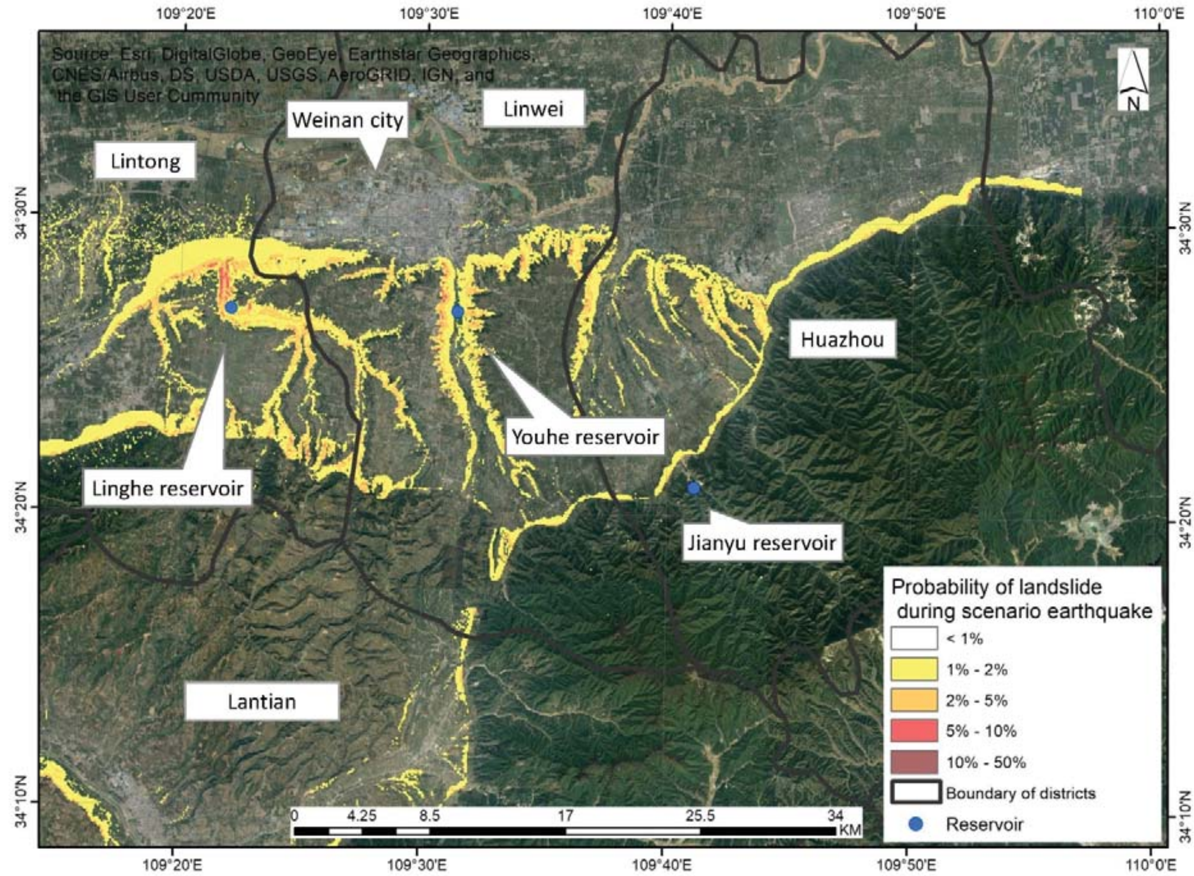


Fig. 3. Probability of landslides with area greater than 100 m^2 during the scenario earthquake. Note the concentration of potential landsliding along the northern edge of the tableland, located just south of Weinan city, and in the incised valleys within the tableland.

Damage to the water system would leave some local residents without water service for hours to months, depending on their location. Some facilities are expected to lose pumping capacity due to power outages caused by damage to the electrical system. Loess landslides along the tableland valley margin may damage the Youhe Reservoir and could affect the dam itself. The primary drinking water reservoir for Linwei district, the Jian Yu reservoir, is located far enough away that it should escape any significant damage. Soil failures would damage the canals and buried pipelines that bring water from the Yellow River to the new North water treatment plant, interrupting its supply. In the treatment plants, buildings crack and equipment slides and overturns. Unanchored chlorine tanks would roll from their cradles, break their lines, and release dangerous gas; these can easily be restrained. In rural areas, brick water towers located above borewells would suffer heavy damage, and some would collapse. Even towers that have been taken out of service pose a hazard to people nearby.

These results illustrate several major earthquake risk problems Weinan faces:

- Seismically vulnerable unreinforced masonry residential buildings, both in urban and rural areas;
- Older hospitals;
- Water system vulnerabilities;

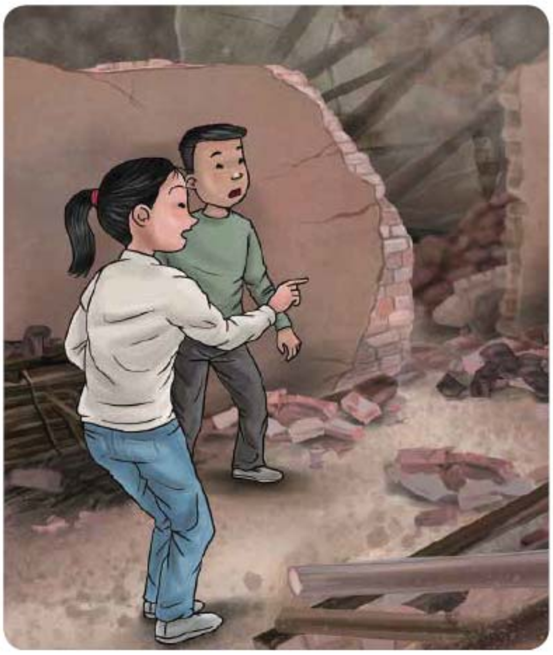
- Areas susceptible to earthquake-induced landslides along the tableland margin and valleys, and along the mountain front in Huazhou district;
- Areas with soils susceptible to liquefaction and liquefaction-induced lateral spreading;
- Infrastructure (roads, railways, gas pipelines, etc.) that crosses major local active faults or is exposed to landslides, liquefaction or lateral spreading; and
- Vulnerabilities created by family separation and the prevalence of rural households consisting of “left-behind” children, grandparents, and in some cases, women.

These risk problems are expected to create substantial consequences in a number of different potential damaging earthquakes, not only the scenario event. Weinan leaders and residents can begin to address these problems by taking practical measures such as: educating and empowering rural owner-builders on construction of earthquake-resistant buildings; replacing older, vulnerable hospitals with new earthquake-resistant ones and instituting functional continuity programs that seismically protect equipment and backup utility systems and implement preparedness measures; improving infrastructure systems and making them more robust and redundant over time; avoiding new development in geologic hazard zones such as along active faults and areas of high landslide and liquefaction hazard; and planning for the types of damage and consequences that this scenario describes. Infrastructure system operators can assess the risk earthquakes pose to their systems, and prepare their own internal loss estimates and scenarios, as an extension of this scenario.

6. Risk communication approaches to disseminate and use the scenario

We chose to present the scenario’s main findings and recommendations to local officials and the public using storytelling approaches, in order to make the technical information accessible and more approachable for people who are not earthquake and disaster professionals, and to motivate action. Storytelling approaches provide a powerful method of influencing behaviour and decision-making (e.g., [86,87,88,89]). To do this, we prepared two versions of a fictional narrative that describe a local rural family’s experiences in the earthquake and its aftermath [90,91]. According to communications with local officials, they were most interested in the personal story format, compared with other possible formats such as a technical narrative arranged by topic, a newspaper story, and an impersonal narrative arranged by time of occurrence. For technical and research audiences, including those outside China, we prepared the papers in this issue and elsewhere.

We first prepared a narrative story for local agencies, with boxes, graphics, and maps presenting the loss estimation results, key technical details, risk problems, recommendations, and associated earthquake DRR policy information woven into the storyline. The narrative helps people in these agencies visualize the losses described in the loss estimate, as well as important impacts–such as lifeline interdependencies–that are difficult to quantitatively model using currently available approaches, so as to improve to associated top-down DRR practice. Fig. 4 provides an example illustration and a paragraph of the story, describing the reaction of parents who finally reach their rural family home from the cities where they work (Shanghai and Xi’an) only to find it severely damaged, and their children, left behind with their grandmother while they worked, missing.



After four long hours, the truck rolled to a stop in the lane outside their house, and Haiyan jumped out. With Jianguo behind her, she ran through the gate into the courtyard.

"Xiaoshuai! Xiaomei! Ma! We're here!" she shouted. Everything was completely still. She dashed around to the back of the house, and saw the gaping hole in the back corner. It appeared there had been a rescue of some sort – bricks were piled in odd spots and boards of different lengths and sizes were lying about. That meant someone had been underneath all those bricks. Haiyan couldn't breathe for a moment. Jianguo held her by both shoulders.

"They are going to be okay. They are going to be okay, Haiyan. Maybe they're at the Wang or Zhang house," Jianguo said slowly. "Let's go."

Fig. 4. Example illustration by Siu Kuen Lai, and story paragraph from the narrative version for government officials.

For the general public, we adapted the story into a short graphic novel, removed overly technical information, and added practical preparedness tips for local families. We carefully constructed the plot of the story to highlight key earthquake risk problems facing Weinan, such as: seismically vulnerable rural housing inhabited by populations comprised mainly of older people and "left behind" children; older seismically vulnerable urban buildings; landslides in the loess tableland; damage to the health system; and disruptions to transportation, communications, and utility service. We designed our characters to experience realistic emotions and to model a progression in attitude from being indifferent to earthquake risk, to actively adopting important earthquake safety measures such as building an earthquake-resistant house. It is our intent that readers become educated and then motivated to act to make themselves and their families safer from earthquakes. We created these two different versions of narratives simultaneously, with the hope to facilitate bridging the gap between top-down and bottom-up earthquake DRR approaches, (for details, see the introduction to our narratives in Chinese [91] and English [90]).

7. Discussion of project effectiveness

The project results show that scenarios, especially when constructed using transdisciplinary or pan-participatory methodology are a practicable approach to address the gap between top-down and bottom-up disaster risk reduction policies and practice in China. For some time, China has recognised the need for greater engagement with local communities, civil society organizations, and local interests in DRR (e.g., [92,93]). The results of this project, however, also show that scenarios' effectiveness in addressing this gap will depend on how well their transdisciplinary process is implemented. In this respect, the PAGER-O scenario achieved to a great extent the objectives it set out at the start. It has proven effective in generating technically credible science, and disaster loss estimates to underpin the scenario results, and in producing opportunities for close interaction among various researchers and local stakeholders as detailed in this paper and in the remaining papers of this issue.

In the project closing workshop in January 2019 and in the *IRNHiC* program's final conference in March 2019, the transdisciplinary process received much praise from the audience and from Chinese stakeholders, as having achieved more than what is usually expected from conventional academic research. For example, an Integrated Research on Disaster Risk (IRDR) China representative identified PAGER-O as one of the few examples in China's disaster research field of integration between the 'hard' and 'soft' (or physical and social) sciences to produce earthquake risk analysis and local engagement on earthquake risk governance. The scenario narratives received particular recognition from all stakeholders participating in the January and March meetings, as innovative tools to communicate earthquake risk and to educate both officials and the general public. Moreover, the team also learned important lessons during collaboration, which have implications for the China context and for methods used internationally (i.e., the transdisciplinary approach).

7.1. Implementation of transdisciplinary in building the earthquake scenario

Transdisciplinary processes of knowledge generation involve co-analysis of problems and co-production of solutions involving actors with diverse scientific and societal views of the problem who engage in mutual learning in an iterative fashion [94]. In China's disaster reduction context this also involves the balance between and the engagement with actors in both top-down systems and bottom-up networks. While broad and iterative participation of international, national and provincial experts and the provincial government (i.e. Shaanxi EA) and some relevant Weinan agencies (e.g., Weinan EA) was achieved in the project, the involvement of certain groups of local end-users was either less than planned (e.g., local NGOs, key public service providers), or a bit behind relative to the ideal process of a scenario effort (e.g., our large scale local public and community-focused surveys and interviews were administrated a bit late, as explained previously). Our interactions with local stakeholders have focused more on gathering information to develop the scenario and to understand various local contexts and current status and less on co-analysis and co-production with double-loop learning. This is a combined effect of multiple causes: local officials and people's diverse attitudes and varied levels of enthusiasm towards the scenario work, time and resource limitation, and interest in addressing infrequently-occurring earthquakes when faced with daily challenges. Future transdisciplinary scenario building efforts should try to balance them properly. With China's positive record of policy experimentation (e.g., [95]), it would be interesting to experiment with approaches that include more co-analysis and co-production, with associated double-loop learning, in future scenario development efforts.

7.2. Impacts from the nation's powerful top-down administration system

The earthquake disaster reduction approach in China is essentially top-down, which is highly effective in mobilizing large-scale disaster reduction activities. Many other large scale initiatives, including application-oriented disaster research utilize a top-down approach. In our experience, clearly understanding local receptivity and then obtaining active support from local government and its relevant agencies is the first priority for smoothly and successfully implementing a large scale scenario-building project in China. This receptivity sometimes or in some cases appears even independent of whether research team has advanced expertise or financial resources. Our team experienced very different levels of receptivity, depending on the agency. We received tremendous support for the building surveys and the local public and community-focused surveys and interviews, to the extent that a considerable part of the data collection was free of cost to the project. This allowed the team to conduct very detailed large scale examinations on the associated issues. In contrast, due to relevant agencies' concerns on the security of key lifelines as discussed in the infrastructure section, there was basically no way for the team (even mainland China members) to obtain quantitative data on them.

7.3. Impacts of the varied "general disaster literacy" and receptivity of local agencies and people

A scenario building effort always involves many local agencies and people, because a damaging earthquake can impact almost every part of a society. Our scenario effort was welcomed by the local government in general. However, earthquake safety is not among the top several daily responsibilities or functions of most agencies. Moreover, because damaging earthquakes are rare in any one location, they fall further down the list of priorities. This inevitably results in these agencies having a lower level of general disaster literacy and placing less value on mitigation and preparedness activities than agencies with more direct responsibility for earthquake safety (e.g., agencies focused on earthquakes, land resources, civil affairs, and the like). For the general public, the situation is the same. Keeping this in mind, the research team must seek a proper balance of what is feasible versus the ideal, and identify entry points to engage local agencies in ways that align well with their responsibilities.

Our project provides several examples. We devoted major efforts to CBDRR, school-based DRR, and broad disaster education, because they are all within the daily responsibilities for relevant local agencies (e.g., earthquake, civil affairs, and education), thus should be the most feasible and sustainable linkages between top-down and bottom-up earthquake DRR approaches. We focused on creating narratives as our key scenario products, because innovative disaster education material is very limited not only in the study area, but also in the whole nation. We relied on the local education agency's help to complete our very large scale surveys, not only because they believed that our surveys are very useful for them to improve their own daily duties (and are thus very willing to help us implement them efficiently), but also because with their help we can more easily and widely access the ideas of the local public whose overall general disaster literacy and associated cooperation attitudes are even more diverse. We prepared questionnaires for both students and their parents, because China's education field has a long-established idea in safety education called "big hand in small hand" (i.e., parents learn from their children). When doing rural CBDRR-focused interviews, we combined the topics of disaster reduction with poverty alleviation, not only because the government called for this combination for many years, but also because this may make local villagers more willing to talk with us. We investigated earthquake-induced landslides, not only because it is important for our scenario analysis to consider them, but also because landslides are more common than earthquakes, thus may attract more attention from local agencies and people. Accepting the varied general disaster literacy of the target population and finding appropriate entry points is not only essential for scenario development and other transdisciplinary research in China, but also in other countries.

7.4. Time, schedule, and language

Our original plan in the PAGER-O' proposal was "GHI will lead the production of a detailed scenario for one town or township area first, and then the team (especially local researchers and local agencies) would replicate this scenario process in several other towns or townships with distinct physical and socio-economic settings. However, in order to increase the representativeness of our scenario development in both the national and international sense (for China, a model scenario building on both China's existing ELE work and international experience, while for the international research community, a scenario example defined by or from China contexts), we discussed through online communications since the initial planning workshop in Oxford (January, 2016) and then decided in the Beijing launch meeting (April, 2016) to change this original plan to focus on preparing a model scenario for a moderately-sized city (up to about 1 million people), which could include tens of towns and townships. This ambitious change means a great increment in workload and finally, a great increment in the time required.

Second, the transdisciplinary approach and multilateral international collaboration featured significantly in our scenario development, which, however, is also a source of time cost. For example, considerable time was spent on the "intangibles" of the project, such as working across different countries, languages and local dialects, cultures and styles of working, and above all on integrating the different types of knowledge and even worldviews that each stakeholder had – a core element that differentiates transdisciplinary from other approaches (single-discipline, multi-disciplinary, and even inter-disciplinary). As posited by [96], this involved: a) communicative integration that aimed at developing mutual understanding of common terms (e.g. different interpretations of 'policy' in Chinese and English language); b) social integration which allowed understanding of the different organisations' interests and roles within local stakeholders and even within the project team; and c) cognitive integration which linked different knowledge bases, theoretical concepts and methods (e.g. understanding basic knowledge, logic, and terminology from other disciplines other than own) to create a common understanding. The team developed practical strategies for implementing the international collaboration, including regular and effective electronic collaboration amongst the large team (e.g., on-line meetings), and communicating with Shaanxi and Weinan stakeholders despite the shortcomings for technical discussions of best-available (and expensive) simultaneous interpretation.

Future scenarios prepared in China can avoid some of these challenges. If scenarios are prepared without international participation, all the stakeholders would be familiar with the country context, cultures and working styles, and would be able to use a single language to reduce time and complexity in project execution and communication.

7.5. Early results

It is still early to judge whether the project will prove successful in motivating relevant agencies and the public to take actions to more effectively mitigate earthquake risk and increase resilience, or be replicated in other areas of China. But there are already signs that show positive impacts might take place in the future. For example, besides stakeholders' enthusiasm about the innovative communication approach (storytelling-led narratives), there are signs of results uptake from the Shaanxi EA, which has introduced some ideas from the PAGER-O approach into their next five-year earthquake DRR plan. Huazhou district of Weinan has been in close contact with the research team to explore options to integrate the scenario narratives into a possible local

"Earthquake Disaster Education Museum" that they would like to establish, as well as to explore further ideas for development. Furthermore, Shaanxi EA plans to carry out an earthquake risk assessment, based on the experience of PAGER-O, in Baoji city, Shaanxi province. Zhejiang provincial EA also requested information and material on the scenario approach from the IGCEA team, so as to inform their own similar work. Shaanxi Gender Development Solution (Shaanxi GDS), a local NGO that focuses on women's and children's welfare, also expressed interest in collaborating with the team.

8. Conclusions and recommendations for future work

The scenario development effort for Weinan included several notable features used for the first time in China, and some aspects that have not been included in international scenarios to this level of detail. These include:

- A trans-disciplinary approach integrating, and giving equal emphasis to physical sciences, engineering, human and social sciences, and the arts.
- A holistic scenario development effort, with a perspective that was as comprehensive as possible, addressing the full spectrum of earthquake risk problems and exploring associated risk reduction and resilience enhancement practices and policies. We began from tectonic and geophysical issues under the earth surface, then to buildings and lifelines, and then to population and economy, and finally to the thinking of local public, in other words, from the material world to people's mental world.
- An integrated thought process of serving both government agencies and general public and grass-roots, and facilitating the combination between top-down and bottom-up DRR policies (e.g., by using two versions of narratives, for the general public and for officials).
- Using storytelling, illustrations and both public and government versions of the narratives, to emphasize in particular how to make our scenarios easily understood both by the people in the relevant government agencies who are not hazard specialists, and by relevant local stakeholders in broad civil society. The graphic novel format used for the pubic scenario narrative document has not been implemented in international scenario practice to this level of detail. Our intent is to foster common understanding, attitudes, and emotions toward of earthquake disaster risk reduction, so as to motivate local agencies and general public to take action collectively to make Weinan more resilient and safer.
- Integrating understanding of scientists and researchers with those of local stakeholders. We believe it is local people themselves who know their communities and their environments best. We conducted participatory activities to the extent possible by holding various consultative meetings with local agencies and by conducting questionnaire surveys and interviews to understand the views of the local public.
- A multi-scale perspective; for example, when estimating building losses, individual buildings in the urban part of the study area were addressed, while in the rural area, we addressed buildings in bulk at village level. In resilience studies, we addressed personal resilience, family resilience, community preparedness and resilience, and upward, with the aim of exploring the interface/interaction between top-down and bottom-up DRR policies and practices.

- A combination of quantitative and qualitative analysis, which was essential given the limited time and resources, as well as difficulties in obtaining some key local data. Specifically, we were able to make extensive use of remote sensing, available online data and social surveys.

This effort has provided Weinan with substantial information regarding local earthquake risk and how it can be managed. If implemented, the recommendations made during the process will make Weinan residents safer from future earthquakes.

For wider application in China, we recommend that scenario development processes be immediately followed by mitigation action planning processes (which were not possible during the PAGER-O project due to time and resource constraints), as a first step toward putting the scenario findings and recommendations into practice. It is also advisable to study the effectiveness of newer risk communication approaches and tools, such as the scenario narrative publications and related products. Future scenario efforts will be more effective if local stakeholders are more deeply involved, and if efforts more closely align with and leverage existing policies and practices, such as demonstration DRR communities. The initial results from the PAGER-O project indicate that scenarios are a promising approach to identifying earthquake risks and communicating both the potential impacts and most importantly, what people can do about them. More work of this type has the potential to increase resilience, particularly in urban areas with complex earthquake risk challenges.

Acknowledgments

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Author contributions

PIs Guiwu Su, John Young and Philip England provided project leadership; Janise Rodgers and Guiwu Su led scenario development; Philip England, Guiwu Su, Timothy Sim, Craig Davis, Arrietta Chakos, Emily So, John Young, Barry Parsons, Alexander Densmore, David Milledge, Janise Rodgers and Yue Cao provided disciplinary expertise; Wenhua Qi, Xiaoli Li, Lei Sun, Junlei Yu and David Milledge analyzed data; Janise Rodgers wrote the scenario narrative with assistance from Guiwu Su, Timothy Sim, Wenhua Qi, Chunlan Guo, Junlei Yu, Arrietta Chakos and Philip England; Guiwu Su and the CEA team translated the narrative into Chinese; and Janise Rodgers, Guiwu Su, Wenhua Qi, David Milledge, Alexander Densmore, Craig Davis, Philip England, John Young, and Yue Cao wrote the paper. In terms of overall contributions, Janise Rodgers and Guiwu Su can be considered co-first authors.

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