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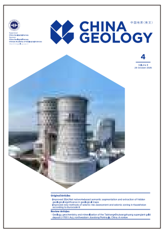

Improved new methods of seismic risk assessment and seismic zoning in Kazakhstan according to Eurocode 8

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ABSTRACT

This article aims to enhance seismic hazard assessment methods for Kazakhstan’s seismotectonic conditions. It combines probabilistic seismic hazard analysis (PSHA), ground motion simulation, site-specific geological and geotechnical data analysis, and seismic scenario analysis to develop Probabilistic General Seismic Zoning (GSZ) maps for Kazakhstan and Probabilistic Seismic Microzoning maps for Almaty. These maps align with Eurocode 8 principles, incorporating seismic intensity and engineering parameters like peak ground acceleration (PGA). The new procedure, applied in national projects, has resulted in GSZ maps for the country, seismic microzoning maps for Almaty, and detailed seismic zoning maps for East Kazakhstan. These maps, part of a regulatory document, guide earthquake-resistant design and construction. They offer a comprehensive assessment of seismic hazards, integrating traditional Medvedev–Sponheuer–Karnik (MSK-64) intensity scale points with quantitative parameters like peak ground acceleration. This innovative approach promises to advance methods for quantifying seismic hazards in specific regions.

1. Introduction

Central Asia faces persistent threats from destructive earthquakes and related phenomena due to its high seismic activity. Recent regional seismic zoning (SZ) maps show areas experiencing intense tremors, reaching 9–10 on the Medvedev–Sponheuer–Karnik scale (MSK-64) (Code of Rules of the Republic of Kazakhstan, 2017) (Fig. 1). These activities stem from the collision of the Hindustani and Eurasian plates, influencing the region for around 50–70 Ma according to modern geodynamics, particularly plate tectonics. This collision has significantly affected Central Asia, with the active movement of the Turanian and Tarim plates towards each other. Approximately 11% (300000 km^2) of Kazakhstan’s land is within a high seismic zone, housing over 5×10^6 people, 40% of its industry, and 400 settlements, notably Almaty with 1.7×10^6 residents. Almaty faced impactful North Tian Shan earthquakes in the late 19th-early 20th centuries, like the 1887 Verny *Ms*7.2 and 1911 Kemin *Ms*8.2 earthquakes. A similar event near Almaty could cause catastrophic damage due to both magnitude and underestimated seismic risks (Silacheva NV et al., 2018).

For the first time, Kazakhstan analysed seismic hazard probabilistically, focusing on ground motion parameters. This encompassed national and detailed Almaty studies. Traditionally, Kazakhstan’s seismic research focused on the southeast, yet recent investigations revealed natural and human-induced activity in the central, western, and eastern regions. Accurate assessment in these areas is crucial. Despite Almaty’s seismic microzoning decades ago, the city’s expansion prompted a contemporary seismic hazard analysis, forming the basis for city-scale zoning and guiding similar studies across Kazakhstan.

Some scientists have already addressed a similar topic. Silacheva NV et al. (2020) conducted a study where a probabilistic approach was used for seismic microzonation,

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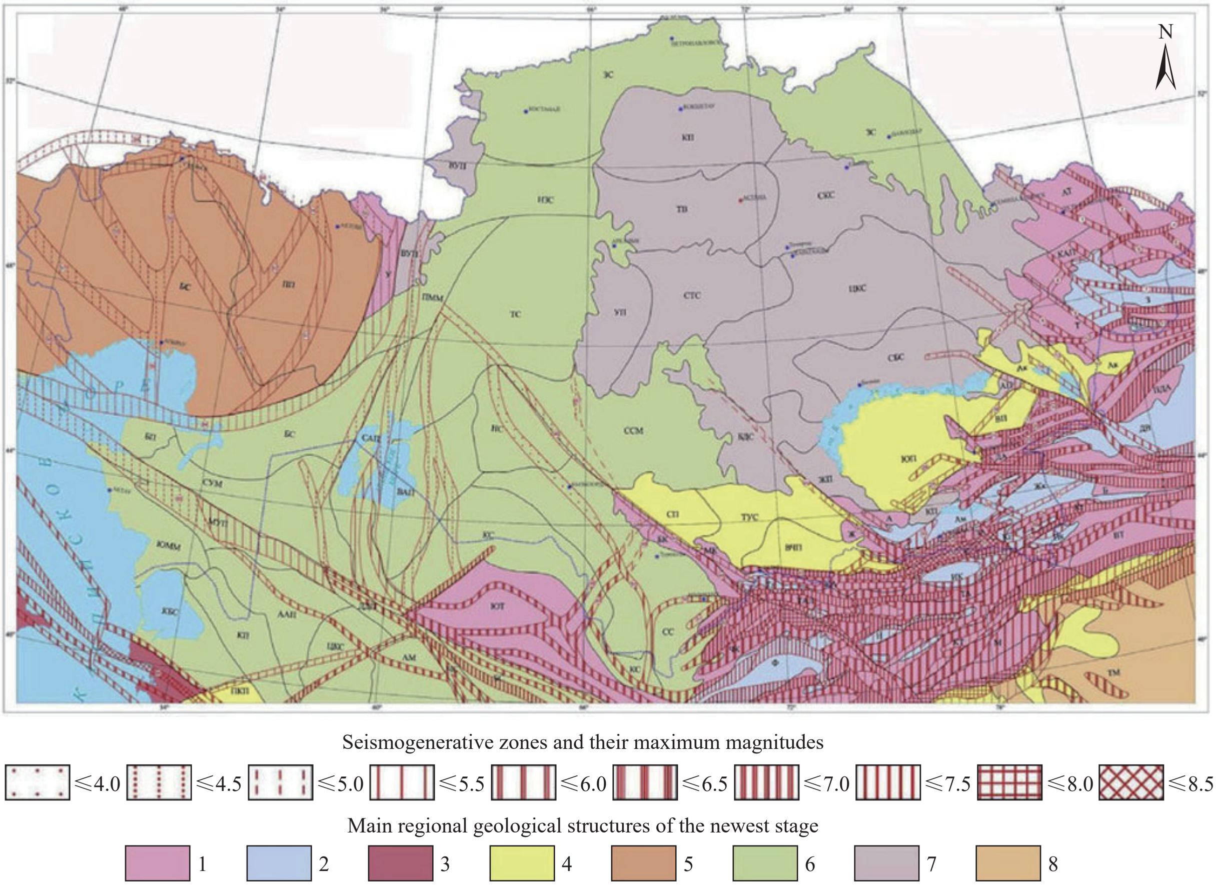

Fig. 1. Map of seismogenerative zones of the Kazakhstan's Earth crust (after Silacheva NV et al., 2018). 1–epiplatform orogens; 2–interand intra-montane depressions; 3–epigeosynclinal orogens; 4–orogen and platform conjunction zones; 5–ancient platform with Paleozoice Cenozoic slab complex (the Caspian basin); 6–young Turan epihercine platform with MesozoiceCenozoic slab complex; 7–Kazakh Shield (consolidated basement) of the young platform; 8–Tarim Massif.

and a continuum approach was used to account for the influence of local ground conditions. The adopted methodology allowed avoiding the use of soil categories and abrupt changes in ground conditions and seismic effects. In the study of Zhanabayeva A et al. (2023) comparative analyses of seismic design standards applied in Kazakhstan. It is emphasized that Eurocode-8 yields outcomes that are more cautious and a heightened safety level when contrasted with the national rulebook. Amey RMJ et al. (2021) in their study investigated the seismic hazard and potential hazard to Almaty using earthquake scenarios. It was pointed out that across all scenarios, the greatest proportion of damage and loss occurred in regions directly located above the subsurface fault.

The research by Alshembari R et al. (2020) investigates whether frozen ground at the surface enhances ground instability after the 1911 Kemin earthquake, potentially causing liquefaction of near-surface layers due to impeded dissipation of excess pore pressure. The results obtained suggest that seasonal factors should be considered in local environmental assessments. Rashid MS et al. (2023) in their work explored the issue of the seismic risk assessment for buildings constructed in Soviet times (before the 1990s). Reinforced concrete and precast buildings were determined to be subject to probable severe damage requiring in-depth analysis due to the assumed non-linear response and uncertainty in seismic performance. It is important to note that considering the conducted studies, the topic of development of new methodological foundations for seismic hazard assessment and seismic zoning in Kazakhstan in connection with Eurocode-8 has not been fully disclosed.

Central Asia, which includes Kazakhstan, is consistently exposed to significant risks from devastating earthquakes because of its elevated seismic activity (Rusho MA et al., 2024). The main emphasis of seismic research in Kazakhstan has been on the southeaster region, and the seismic microzoning of Almaty was carried out many years ago. Nevertheless, recent inquiries have uncovered both naturally occurring and human-caused seismic events in the central, western, and eastern regions. This emphasises the importance of conducting precise evaluations of seismic hazards in these specific areas. Prior seismic investigations frequently utilised deterministic methodologies, which may not comprehensively encompass the intricacy and unpredictability linked to seismic risks. Furthermore, these studies have primarily concentrated on seismic intensity, disregarding the quantitative ground motion parameters that are essential for earthquake-resistant design and risk evaluation.

This article introduces an enhanced methodological framework for evaluating seismic hazards that is specifically designed for the seismotectonic conditions of Kazakhstan. The study utilises a blend of probabilistic seismic hazard analysis (PSHA), ground motion simulation, analysis of site-specific geological and geotechnical data, and seismic scenario analysis. The Probabilistic General Seismic Zoning (GSZ) maps of the Kazakhstan territory and the Probabilistic Seismic Microzoning maps of Almaty city have been created using these methods. These maps adhere to the seismic design principles of Eurocode 8 and provide information on seismic intensity and engineering parameters, including peak ground acceleration (PGA).

In this regard, the purpose of this paper is to introduce enhanced methodological frameworks for seismic hazard assessment, specifically tailored to align with the unique seism tectonic characteristics of Kazakhstan. This article introduces novel seismic hazard assessment methods tailored to Kazakhstan's seism tectonic conditions.

2. Theoretical overview

Seismic hazard is the likelihood of an earthquake of a certain magnitude occurring in a given area over a period. It can be expressed as the probability that an earthquake of a certain magnitude will occur in a given area within a certain period. To address the needs of sustainable economic development and national security, all countries, including Kazakhstan, undertake the task of developing seismic zoning maps of various levels of detail. These maps are essential for understanding the seismic risks faced by different regions.

Depending on the objectives, the scope of the study, and the nature of the subject, SZ can take three main forms: GSZ, DSZ, and SMZ. Additionally, in specific cases, special seismic zoning (SSZ) may be conducted for particular structures or objects (Ansari A et al., 2023). GSZ is primarily used for large-scale evaluation and strategic planning of seismic hazards at a national or regional level. This tool is utilised to create regulatory documents for constructing buildings that can withstand earthquakes. It also guides economic planning and implementing measures to prevent seismic damage. GSZ maps are generated using extensive geological, tectonic, geophysical, and seismological investigations to evaluate seismic capacity. These maps are usually displayed at a scale of 1∶2500000. DSZ is primarily used for precise evaluation and strategic planning of seismic hazards at the regional or national level, specifically for economic facilities. DSZ maps are utilised as substitutes for regulatory DSZ maps and are generated according to methodological guidelines. They are commonly displayed at scales ranging from 1∶1000000 to 1∶500000.

SMZ is primarily used for assessing and planning seismic hazards in urban areas, large towns with a population exceeding 30000, and planned industrial or hydraulic facilities. SMZ maps are generated by analysing engineering-geological conditions and conducting research on soil properties. These maps are utilised to determine seismic intensity. They are commonly displayed at scales of 1∶50000 or higher. SSZ is primarily focused on evaluating seismic risks in specific regions where studies on GSZ or Site-Specific Seismic Zoning (SMZ) have been conducted. It is specifically designed for critical facilities like nuclear power plants and hydraulic engineering structures. SSZ maps are designed to fulfil precise safety criteria for these establishments and are commonly displayed at scales of 1∶10000 or higher. GSZ is primarily utilised for conducting comprehensive seismic hazard evaluation and strategic planning on a large scale. DSZ, on the other hand, is employed for conducting evaluations that are more intricate and planning at the administrative or national economic facility level. SMZ is specifically designed for assessing and planning seismic hazards in urban areas and large towns, while SSZ is focused on evaluating critical facilities in limited areas. Worldwide, the assessment of seismic hazards typically follows a standardised model, progressing from a broad overview to more detailed analyses (Fig. 2). This systematic approach helps in better understanding and mitigating seismic risks at different levels.

2.1. Purpose and scale of seismic zoning maps

Seismic hazard assessment is the initial step in predicting a seismic situation, involving the identification of regional seism generating zones, their potential, and the spatial-temporal patterns of earthquakes. The Map of general seismic zoning (GSZ) is a mandatory regulatory document for earthquake-resistant construction in Kazakhstan, created according to the "Construction in Seismic Zones" (Code of Rules of the Republic of Kazakhstan, 2017) and CN RK 2.03-28-2004 (2004). It includes comprehensive geological, tectonic, geophysical, and seismological research to assess seismic potential, leading to probabilistic spatial reference system (SRS) maps (1∶2500000) used for economic planning and anti-seismic measures (Lario J et al., 2016).

The DSZ maps use scales ranging from 1∶1000000 to 1∶500000 to show predicted seismic impacts on administrative regions and significant national economic facilities. These investigations replace regulatory DSZ maps and follow methodological guidelines (Soehaimi A et al., 2023). On the other hand, SMZ maps evaluate the seismic risk in urban areas, big towns with a population greater than

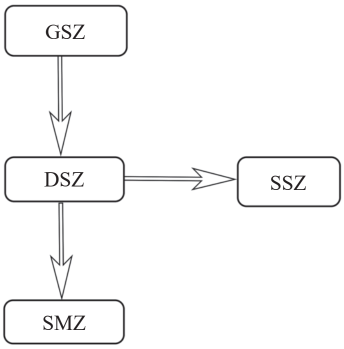

Fig. 2. A general model of consistent assessment of seismic hazard of territories by seismic zoning of different ranks (after Sotiriadis D et al., 2023).

30000, and planned industrial or hydraulic facilities (CN RK 2.03-28-2004, 2004). These maps are intended for locations where the seismic hazard index is 6 or higher (MSK-64(K)). Based on engineering-geological circumstances and research of soil properties, SMZ maps calculate seismic intensity. According to methodological guidelines, they are produced at scales of 1∶50000 or greater (Wang W et al., 2023). Special maps of seismic zoning are for particularly critical facilities like nuclear power plants and hydraulic engineering structures. They assess seismic hazards in limited areas where GSZ or SMD studies were carried out, meeting specific safety requirements for these facilities.

2.2. Methodological foundations for the development of probabilistic maps of general and detailed seismic zoning

Probabilistic maps for seismic zoning and seismic hazard assessment are used to determine the likely intensity of seismic impacts over a specific period. These maps are developed using a method that combines domestic and Western engineering approaches, as well as data on the Earth's crust, lithosphere, geodynamics, regional seismicity, and engineering seismology. A phased assessment of seismic hazard is essential, involving three interconnected predictive models: Earthquake focus zones, seismic activity models, and the resulting seismic effects (Rasulov KhZ et al., 2023). The fourth stage analyses the probability of exceeding the seismic effect during specified periods, measured in the points of the MSK-64(K) seismic intensity scale and other quantitative parameters of ground shaking.

The seismic zoning maps of Kazakhstan are prepared for two probability levels, 10% and 2%, considering occurrences and seismic effects that exceed 50-year intervals, aligning with the average time between earthquakes of estimated intensity, around 475 years and 2475 years. The methodological approach defines the following main tasks for seismic hazard assessment (Silacheva NV et al., 2018).

Seismotectonic and geological-geophysical investigations are performed to analyse active faults and their characteristics, resulting in the creation of a seismotectonic model of the area. This model aids in the identification of earthquake focal zones and areas with scattered seismic activity. It also helps determine the seismic potential, depth, and mechanism of anticipated earthquake focal points (Kamali Z et al., 2023). In the field of seismology, a thorough earthquake catalogue is compiled, local observations of seismic activity are carried out, and the characteristics of the seismic regime are assessed (Komilova N et al., 2023). This process entails creating a model of the seismic regime that accurately represents the pattern of earthquake occurrence.

Seismic impacts are forecasted by utilising macro seismic scale points and quantitative parameters, such as peak ground accelerations (Shtohryn L et al., 2023). Seismic zoning maps of varying levels of intricacy are created by analysing the patterns of attenuation at the seismic focus to forecast the effects of earthquakes. Geographic Information System (GIS) technologies are used to generate seismic zoning maps by integrating hazard assessment findings. The results show the probabilities of a seismic intensity exceeding 10% and 2% within 50 years, corresponding to the average time intervals between earthquakes of estimated intensity, which are 475 years and 2475 years respectively.

A uniform earthquake catalogue is generated to maintain data consistency. The representativeness of earthquakes is assessed by considering recurrence intervals, the range of earthquake magnitudes that are representative of different energy levels, and the cumulative frequency of earthquakes with magnitudes greater than *Ms*2.0. The earthquake recurrence law is used to determine the parameters of the seismic regime in different regions. The quantitative assessment of seismic activity involves analysing various factors such as the spatial distribution of earthquakes, the density of earthquake epicentres, and the type of seismotectonic deformation, the slope angle of the repeatability graph, the specific power of seismic energy sources, and the thickness or depth of the seismically active layer.

The Fig. 3 depicts the procedure for verifying seismotectonic models through geological and geophysical means. This diagram illustrates the progression of stages involved in developing structural schemes for various layers of the Earth's crust and subsequently identifying currently active faults. The process entails examining the composition of the integrated foundation, researching the protective layer of the platform, and exploring the most recent geological movements.

Seismotectonic models for earthquake-focus zones, also called seismic-generating zones, are constructed by developing both regional and local models. The regional model includes a wider geographical area, which includes earthquake epicentres and potential structures that can cause seismic activity within the mapped region up to a magnitudes of *Ms*5.0 on the MSK-64 scale (K). The cartographic scale of the regional model is determined by the size of the territory, usually falling within the range of 1∶5000000 to 1∶2500000. On the other hand, the local seismotectonic model specifically examines the mapped area, including both existing and potential zones that can generate seismic activity. It is conducted at the scale of the primary seismic zoning map. In addition, engineering-seismological data is generalised and used to develop macro seismic field equations and ground-shaking prediction models (damping models) for various regions. This is achieved by integrating macroseismic materials from regions with diverse tectonic and engineering-geological conditions, along with data from instrumental observations (Artikov TU et al., 2020).

The Fig. 4 illustrates the procedure for evaluating the effects of an earthquake. The process comprises three primary stages: An initial evaluation of the impact, the delineation of the consequences of powerful earthquakes in the designated region, and an examination of the patterns of intensity attenuation, considering multiple factors such as magnitude, distance, wave azimuth, and geological characteristics of the surroundings.

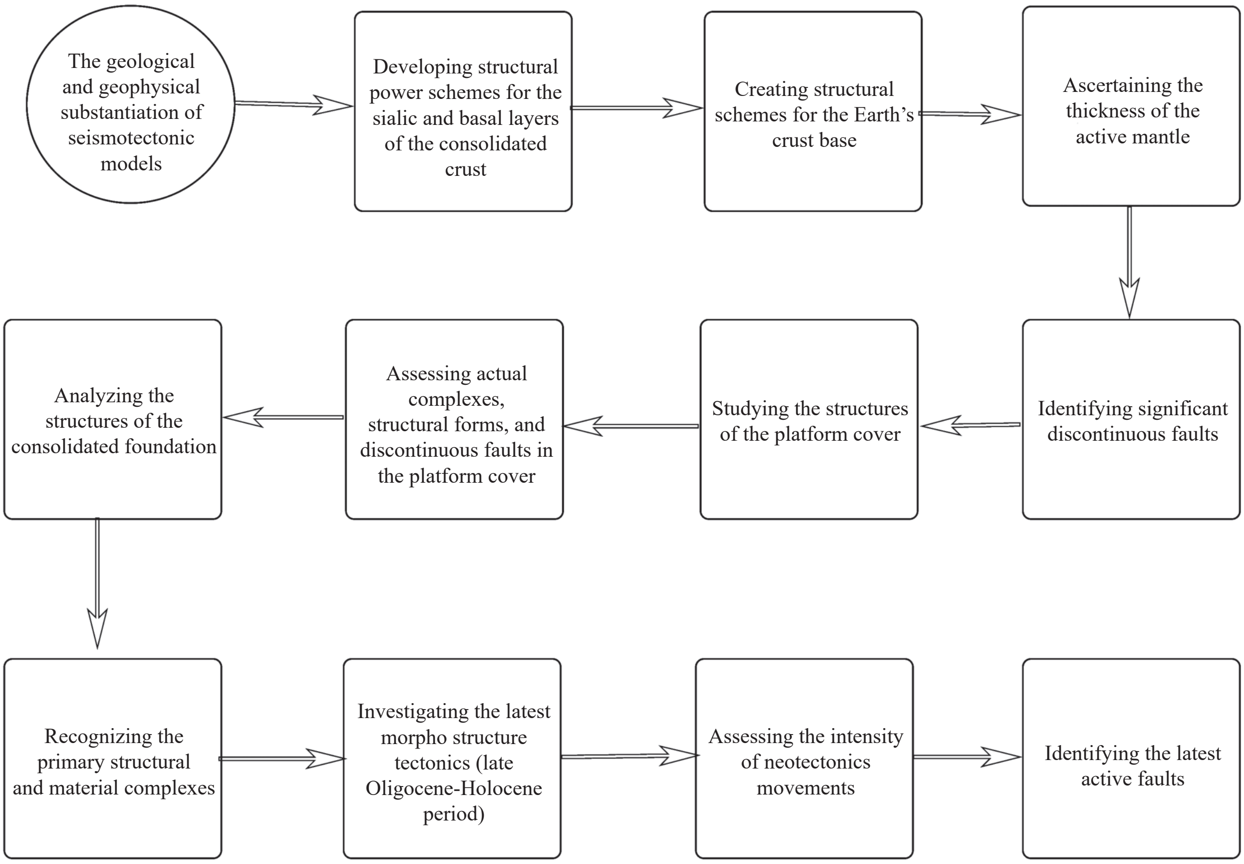

Fig. 3. Geological and geophysical substantiation of seismotectonic models for earthquake focus zones (revised from Ammirati JB et al., 2022).

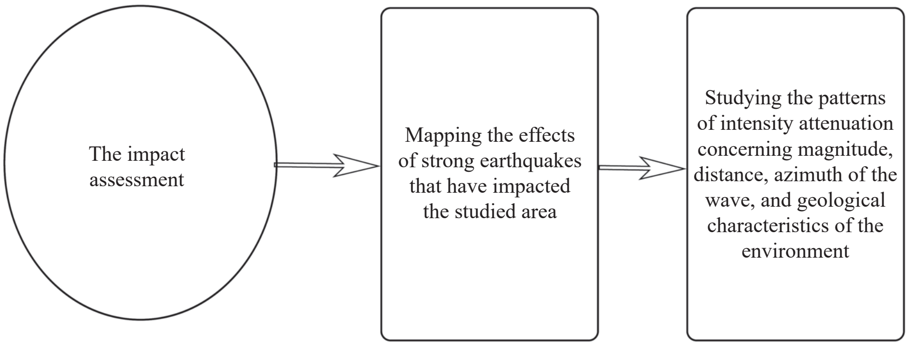

Fig. 4. Procedure for evaluating the effects of an earthquake (after Artikov TU et al., 2020).

Fig. 5 illustrates the process of seismic mode parameterization. The subject encompasses the examination of areas where seismic activity originates, the creation of a comprehensive plot that shows the frequency of earthquakes over time, the calculation of the average number of earthquakes that occur each year, the estimation of the time interval between significant historical earthquakes, and the determination of the physical characteristics of active faults and the depth at which earthquakes occur.

2.3. Methodological foundations for the development of seismic micro districting maps (SMD)

Seismic micro-redistricting is conducted to assess the local impact of various conditions (e.g., soil composition, terrain features, dangerous geological phenomena) on initial seismicity, indicating changes in intensity at specific points and/or instrumental seismic vibration parameters. The seismic vibration parameters correspond to the distribution of soil seismic properties in the mapped area, obtained from comprehensive engineering-geological and seismic geophysical investigations. Seismic micro districting maps are essential for urban and settlement planning, as well as for designing structures of special, important, and general significance (Isık E et al., 2021).

During the development of seismic micro-redistricting maps for the territory of Almaty based on a new methodology, the two main stages were revised. First, the initial seismicity

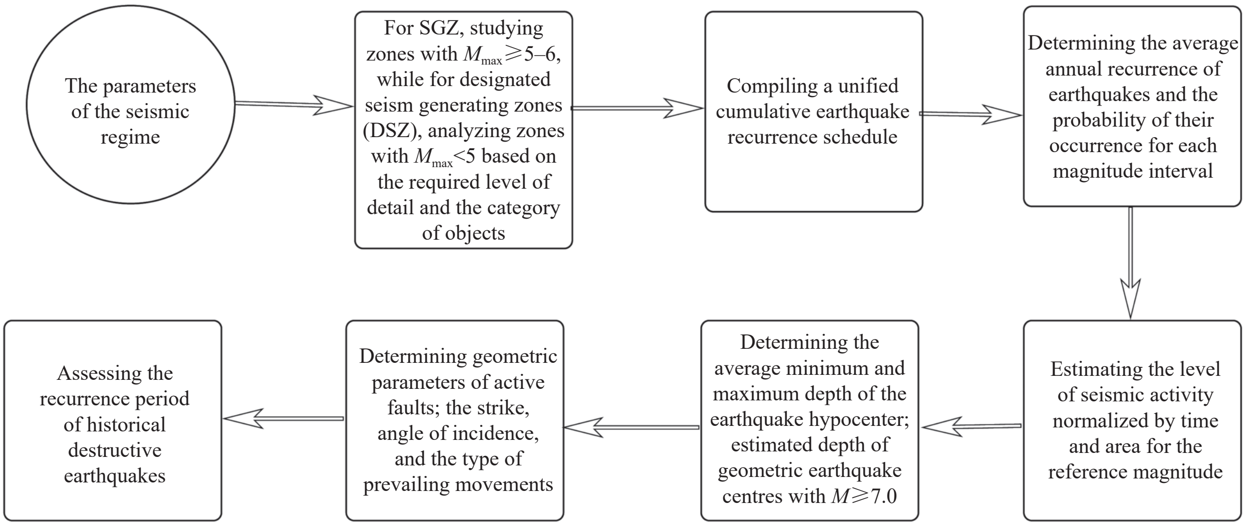

Fig. 5. Process of setting the parameters of the seismic regime (after Silacheva NV et al., 2018).

is now assessed using a probabilistic approach rather than a deterministic one as before. The seismic hazard is expressed in both the points of the MSK-64(K) scale and quantitative characteristics like peak ground accelerations. Second, when evaluating changes in ground vibration intensity, both points and accelerations are considered, and the soil mass characteristics at observation points are determined to a minimum depth of 30 m. The assessment of accelerations relies on the continuous spatial distribution of seismic impacts and ground layers' properties.

3. Materials and methods

To create a seismotectonic model, a comprehensive analysis of the geological and tectonic characteristics of the study area is necessary to establish a solid geological and geophysical foundation for the model. This study utilised an analytical method to improve the implementation of seismic risk assessment and seismic zoning by Eurocode-8 for Kazakhstan. The study consisted of multiple stages, which included conducting a literature review and developing a framework, assessing the seismic hazard in the area, creating a ground motion prediction equation (GMPE), examining the side effects and soil classification, incorporating the principles and recommendations of Eurocode-8 into the seismic hazard assessment and zoning process, producing seismic microzonation maps, and validating and peer reviewing the findings.

The study commenced by examining the composition of the consolidated basement, specifically identifying the primary structural-material complexes and notable structural discontinuities that originated from the late Oligocene-Holocene era. In addition, the analysis of the platform cover's structure involved a detailed investigation of material compositions, recent geological movements, the intensity of ongoing tectonic activity, and the precise locations of active faults.

Before constructing the seismotectonic model, an extensive examination of seismicity and seismic regime was undertaken to acquire a thorough comprehension of the causes and conditions of earthquakes. This entailed examining patterns in the evolution of source areas to create physical models of the seismic activity and make preparations for powerful earthquakes. The purpose of the seismic hazard assessment was to determine the potential intensity and frequency of earthquakes in the area, while the GMPE was used to estimate the movement of the ground that could occur during an earthquake. The study also examined the adverse consequences of earthquakes, such as liquefaction and landslides, and categorised the soil compositions in the region to assess their vulnerability to these risks. By incorporating Eurocode-8 principles and recommendations into the seismic hazard assessment and zoning process, the outcomes were aligned with global standards.

The hydrogeological conditions of the mapped territory play a crucial role in the development of these processes and the occurrence of seismic-conditioned dangerous geological phenomena. Particularly noteworthy are plastic "lubricants", such as thermal waters of deep circulation, found in fault zones, as they reduce the initial stresses required for block displacement along faults, thus influencing the resulting maximum shock ($M_{\max}$). DSD data from the researchers Hamdy O et al. (2022) confirmed this effect. The seismic effect on DSZ maps can be influenced by soil and hydrogeological conditions. Areas with loose soils and aquifers may experience a weakening or strengthening of the seismic effect, leading to corresponding changes in the initial score. In regions with deep groundwater levels in loamy sediments (within 10 m from the surface), hydraulic shocks may occur during earthquakes, resulting in a positive increment of +1 point. Conversely, areas mainly composed of pebbles with deep groundwater levels (over 10 m) outside the seism generating zones may have their initial score reduced by 1 point. In rocky areas undisturbed by ruptures, the initial score can also be reduced.

Seismic microzonation maps were ultimately created to offer a comprehensive comprehension of the seismic hazard in various regions of the study area. The accuracy and reliability of the maps were confirmed through a process of peer review. The primary objective of the study was to attain a thorough comprehension of the seismic hazard in the region and to formulate suggestions for seismic zoning and measures to mitigate risk. The seismological data for Kazakhstan and adjacent regions consists of catalogues of strong and weak earthquakes refer to the range of magnitudes, compiled from macroseismic and instrumental data. Global catalogues from various institutes are also utilized. These unified catalogues aid in understanding seismicity distribution and identifying highly active zones. This approach helps determine maximum earthquake magnitude by establishing seismicity criteria encompassing quantitative and qualitative geological attributes. It reveals new seismogenic zones in Kazakhstan, such as the Ulba and Dzhungar-Ashisuu earthquake-producing zones, enhancing seismic characterization in the Tarbagatai-Altai region. Initially, probabilistic seismic hazard assessment (PSHA) in Kazakhstan utilized the Cornell methodology and Global Earthquake Model Foundation (GEM) program. PSHA involves quantifying the likelihood of ground vibration exceeding specific thresholds at observation points over a fixed 50-year period, considering diverse self-generating earthquake sources.

The new approach integrates ground motion simulation, site-specific geological and geotechnical information, probabilistic seismic hazard analysis (PSHA), and seismic scenario analysis. This leads to a greater level of specificity and precision in zoning, enhanced accuracy in estimating ground motion parameters, quantitative and probabilistic evaluations of seismic hazards, and improved emergency planning and response strategies. The advantages of the new approach become apparent when comparing the seismic zoning maps obtained through the new method with the conventional maps in the Almaty region. The updated maps offer enhanced precision, intricate details, and extensive data for seismic zoning, risk evaluation, and emergency preparedness in seismically active areas of Kazakhstan. This facilitates a deeper comprehension of the seismic capacity and susceptibility of the region, resulting in more efficient measures to mitigate and prepare for risks.

The Virtual Seismic Observatory (VSO) incorporates seismic source models, earthquake frequency distribution, ground shaking calculations, and estimates of exceedance over time. Parameters are derived from MSK-64(K) scale scores and moment magnitude (*M*). Seismic source models rely on seismotectonic data, rupture information, and epicentre depths. Predictive models for seismic effects are pivotal in hazard assessment. Kazakhstan considers three tectonic regimes: crustal earthquakes in active areas, crustal earthquakes in stable regions, and subduction zone events. Hazard calculations encompass various input parameters and distributions using software and logic trees. The Institute of Seismology, Ministry of Emergency Situations, conducted seismic zoning for Kazakhstan (2013–2015) following Eurocode-8 (EN 1998-1: 2004). This methodology guides earthquake-resistant structure design within the country.

4. Results

The Himalayas, the largest mountain structures in the region, continue to exhibit significant movement, maintaining high seismic activity in Central Asia, including Kazakhstan, with movement speeds of 4–5 cm per year, accumulating energy. About one-third of the Republic of Kazakhstan’s territories are prone to earthquakes. Over the past 100–120 years, the region has experienced more than a dozen destructive earthquakes (Table 1). Notably, earthquakes with magnitudes of 8.4 were classified as global seismic catastrophes, resulting in human casualties, substantial material damage, and environmental changes (European Union, 2004). With the ongoing development of earthquake-prone areas, urban growth, settlements, oil and gas extraction, and other mining activities, the seismic danger increases each year, exacerbating the destructive consequences of seismic processes. In accordance with Eurocode-8, Kazakhstan’s upgraded seismic hazard assessment includes design concepts that guarantee earthquake-resistant building takes into account local seismic circumstances and possible risks.

The situation described has a regional scope (CN RK 2.03-28-2004, 2004). As depicted in Table 1, the map displaying the seismic hazard of Central Asia based on peak ground accelerations (m/s²) shows that the Southern and Southeastern regions of Kazakhstan, along with neighbouring territories of other Central Asian countries, are particularly susceptible to high seismic hazard (Fig. 6). This highlights the fact that Kazakhstan’s seismic risk is influenced by the occurrence of powerful earthquakes in neighbouring regions.

In recent years, significant progress has been made in conducting relevant fundamental and applied research in various fields such as seismology, neotectonics, geophysics, geodynamics, hydrogeology, and geochemistry in Kazakhstan. These research efforts are aimed at ensuring the seismic safety of the population and the protection of critical infrastructure within the country.

Table 1. $Ms \geqslant 6$ earthquakes that have occurred in Kazakhstan and adjacent territories over the past 120 years.

No.	Name of the earthquake	Implementation time	Magnitude
1	Keminskoe	1911	8.4
2	Chatkalskoe	1946	7.5
3	Kemino-Chuyskoye	1938	6.3
4	Sarykamyshskoe	1970	6.4
5	Kokshalskoe	1971	6.1
6	Zhalanash-Tyupskoye	1978	6.4
7	Baysorunskoe	1990	6.4
8	Susamyrskoe	1992	7.3
9	Tekeliyskoe	1993	6.1
10	Sumbinskoe	2003	6.1
11	Chuiskoye	2003	7.3
12	Lugovskoe	2003	6
13	Saryjazskoe	2013	6

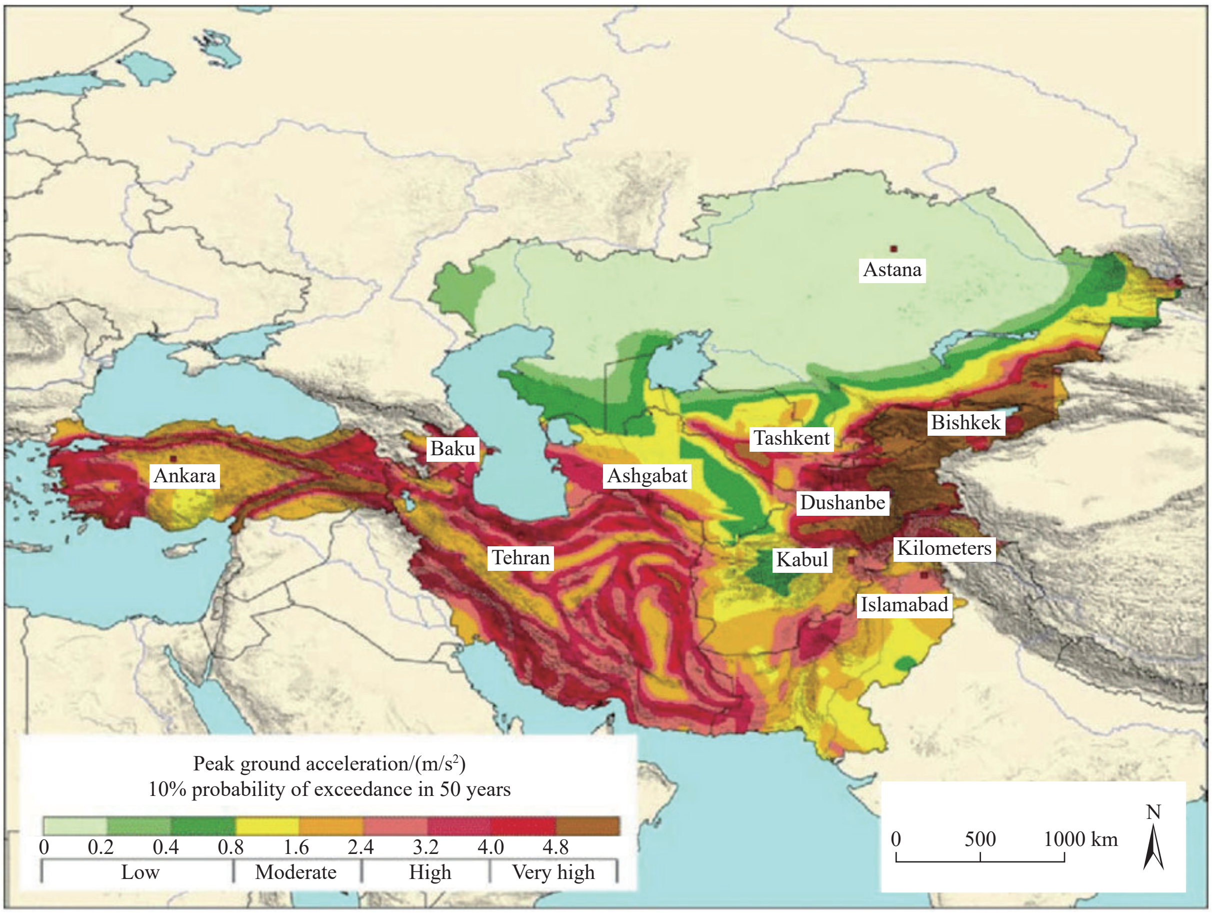

Fig. 6. Seismic hazard assessment in the Central Asia region (modified from Tyagunov S. et al., 2012).

Seismic disasters can result in significant damage due to not only the destructive force of an earthquake but also when the seismic hazard is underestimated during feasibility studies and the selection of construction sites for various facilities, ranging from critical infrastructure like nuclear power plants and hydraulic structures to residential areas and agricultural buildings (Bannikov DO et al., 2019). To reduce human casualties and minimise damages, it is essential to conduct the most accurate assessment of seismic hazards, create realistic seismic zoning maps, and adhere to appropriate seismic construction standards. Continuous efforts in seismically active regions to improve the level of seismic protection and raise awareness among the population and management bodies about earthquake threats and self-protection are paramount (Butenweg C et al., 2021). Seismic zoning is a way of mapping the potential seismic hazard of an area. It helps us to understand the likely intensity of an earthquake and its impact on a community. Seismic impacts are expressed using points on the macro seismic scale, which is a measure of the severity of an earthquake (Kendzera O and Semenova Y, 2020; Kobets A et al., 2023). Eurocode-8 requires that soil-structure interaction (SSI) be considered when designing structures for seismic performance (European Union, 2004). This involves taking into account how various types of soils and ground conditions influence structural seismic response. In Kazakhstan, SMZ maps give crucial data on local ground conditions, allowing engineers to follow Eurocode-8 criteria to guarantee that structures have proper foundations and structural reinforcements.

PSHA was conducted using mean values of geometric mean PGA for both rock and soil similar to rock, spanning the area between 40°E–56°N and 46°E–88°E at a grid spacing of 0.25, determining map spatial resolution. Each grid node accounted for seismic source (zone) influence within a 250 km radius, respecting their seismotectonic regime. Figs. 7–8 illustrate Kazakhstan’s maps for return periods of 475 years (10% probability over 50 years) and 2500 years (2% probability over 50 years).

According to Eurocode-8, PGA values greater than 0.1 g necessitate additional building design measures, such as reinforced structural elements, to improve seismic protection (European Union, 2004). Buildings in high-risk regions, such as Almaty, where PGA values surpass 0.4 g, must fulfil Eurocode-8's strict seismic safety regulations. The GSZ map for a 10% probability indicates that nearly half of the country experiences PGA values surpassing 0.02 g. In the southern, southeast, and eastern regions, these values range from 0.05 g to 0.15 g and higher. Notably, areas situated southeast of Almaty, corresponding to highly seismic zones like Kemin and North-Kungey, exhibit anticipated maximum values of 0.5 g to 0.6 g. In Almaty, the PGA estimate at this return period averages 0.4 g (ranging from 0.29 g at the northern border to 0.48 g at the southern). Other cities follow suit, with Taraz – 0.18 g, Taldykorgan – 0.21 g, Shymkent – 0.12 g, and

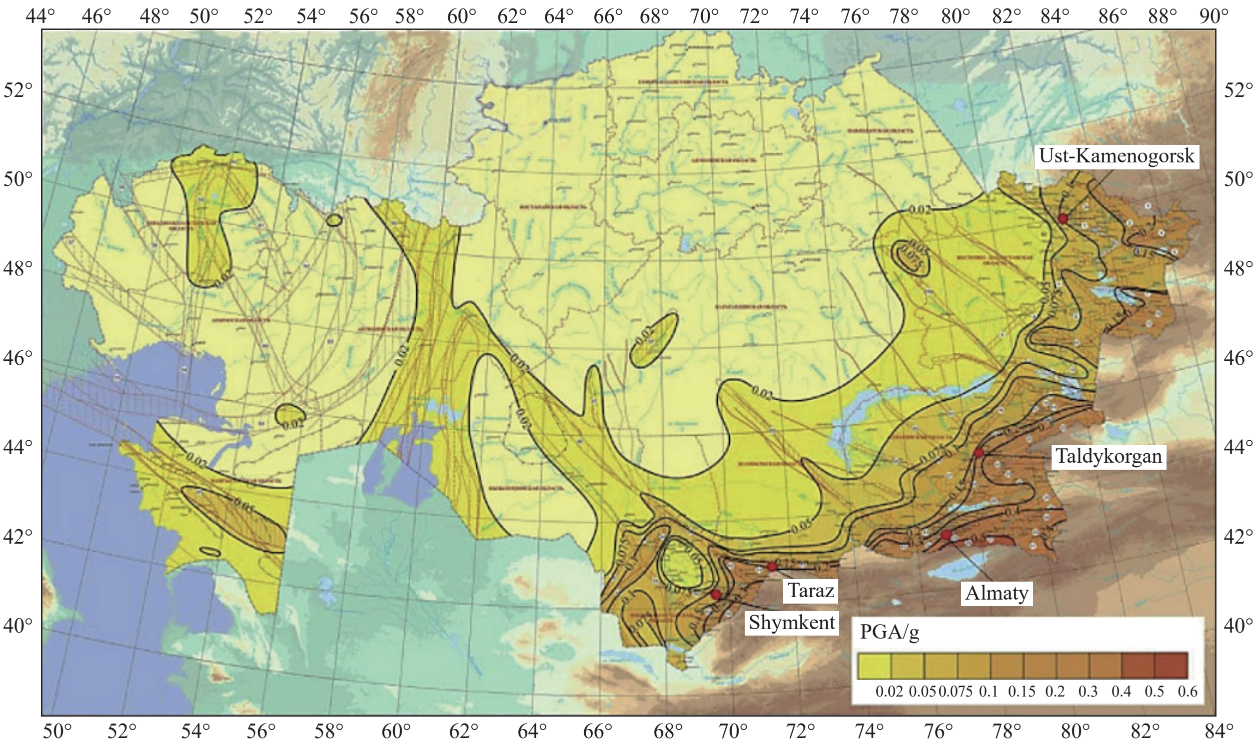

Fig. 7. Seismic zoning map of the territory of Kazakhstan in PGA for probability of exceeding 10% during 50 years (after Silacheva NV et al., 2018).

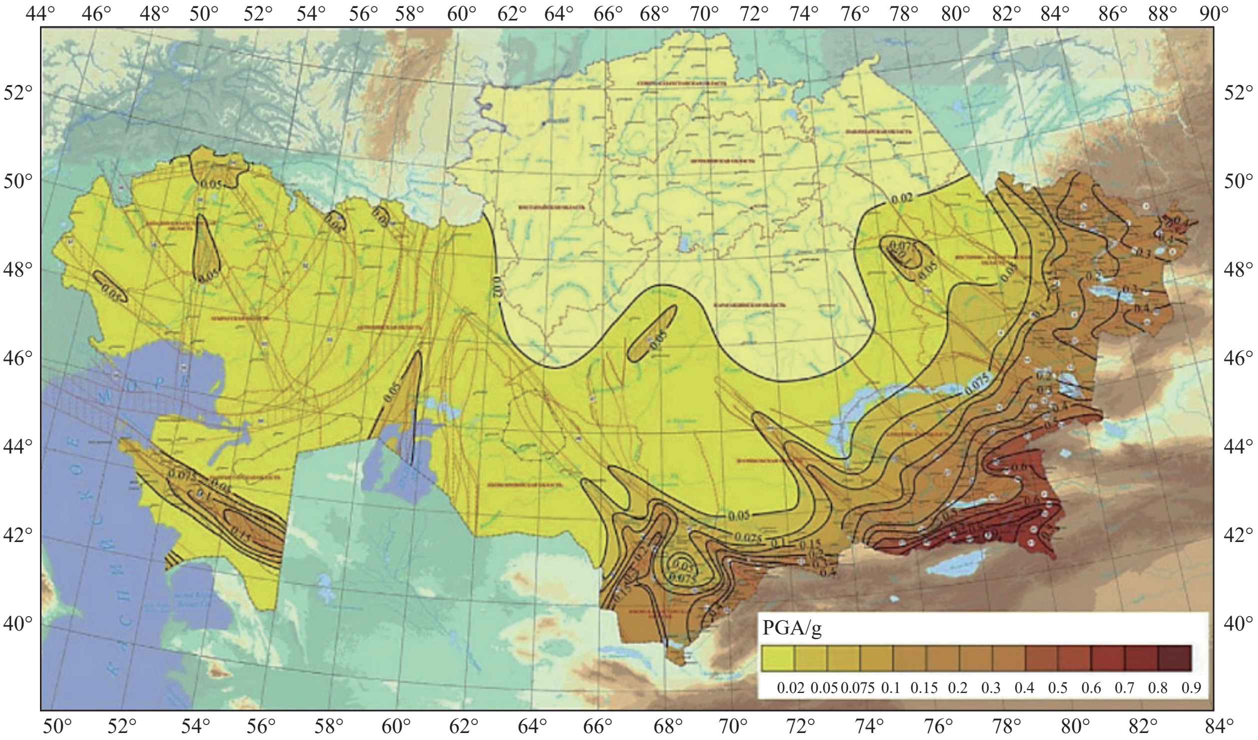

Fig. 8. Seismic zoning map of the territory of Kazakhstan in PGA for probability of exceeding 2% during 50 years (after Silacheva NV et al., 2018).

Ust-Kamenogorsk at 0.11 g.

Areas with values exceeding 0.05 g are situated in the eastern part of the Kazakh Shield due to the recently identified Zhezkazgan-Ulytau seismogenic zone (with seismic potential $Mw_{\max}$ 6.0) and in the Mangyshlak-Ustyurt uplift area due to the CentralUstyurt-Mangyshlak zone (with $Mw_{\max}$ 5.4–5.8). Eurocode-8 emphasises the need for localised seismic hazard reduction, especially in places with complicated ground conditions and fault lines (European Union, 2004). The seismic zoning maps created for Kazakhstan utilise Eurocode-8's localised hazard assessment concepts, ensuring that ground characteristics such as soil type and fault proximity are considered throughout the design phase to reduce possible seismic hazards. The GSZ map for a 2% probability in 50 years presents a broader spatial distribution and higher hazard levels, with maximum values aligning with southern Almaty. Additional areas of heightened values exceeding 0.05 g appear in Central Kazakhstan due to the Zhezkazgan-Ulytau seismogenic zone near the North Aral uplift (zones with $Mw_{\max}$ 5.5) and the Central Caspian depression in the zones with $Mw_{\max}$ 5.0. Overall, these predictions align well with prior deterministic estimates, with some increased seismicity in regions where recent seismic data expansion occurred due to new stations and revealed seismogenic zones in the past decade. The updated methodological framework for both GSZ and DSZ includes seismic micro-districting (SMD) to determine the initial seismic impacts for two probability levels: 10% and 2% probability of possible intensity exceedance over 50 years. These initial seismic impacts are measured in macro seismic scores or quantitative characteristics like peak accelerations and spectral accelerations of seismic vibrations (Ņikuļins V, 2017). The utilisation of Eurocode-8's design response framework guarantees that seismic activities at these probability levels are incorporated into the design of earthquake-resistant structures (European Union, 2004). Eurocode-8 specifies reaction spectra for several types of buildings depending on their relevance, such as hospitals, schools, and residential buildings, to ensure that structures are built to resist predicted seismic pressures based on the local hazard level.

Engineering and geological studies play a crucial role in the comprehensive SMD and DSZ works, and these studies are conducted by specialised organisations. The primary methods used for studying the engineering and geological properties of the soil massif include drilling wells to a minimum depth of 30 m and analysing the physical and physico-mechanical properties of soils through laboratory and field methods. To ensure sufficient data coverage, the number of observation points for engineering-geological and geophysical studies should be at least two per 1 km^2 area, as justified in the work program. This ensures a thorough understanding of the soil conditions and seismic properties within the mapped region.

Instrumental geophysical studies are conducted to gather data on the seismic properties of soils by comparing engineering-geological and seismic profiles. This comprehensive approach involves a combination of instrumental geophysical techniques, including seismic and seismological methods, along with the registration of earthquakes and microcosms. The investigation of the territory’s engineering-geological and hydrogeological conditions aims to identify and map various types of rocky and loose soils (including loose or unconsolidated materials) while developing an engineering-geological legend. The study of seismic characteristics of soils involves the following: Recording accelerations and velocities of strong or significant earthquakes; recording industrial explosions in the study of weakly seismic areas; utilising values of weighted average densities, weighted average velocities of transverse waves, and weighted average seismic stiffness to characterise the seismic properties of soils that impact the parameters of seismic impacts at observation points.

The calculation of seismic impact parameters considers the initial seismic impact and the influence of local ground conditions, hydrogeological aspects, geomorphology, tectonics, and other factors affecting the intensity and spectral characteristics of seismic impacts. This comprehensive analysis helps to better understand the seismic behaviour of the studied area and its response to various seismic events. The seismic micro-redistricting maps consist of the main and additional packages. The main package includes:

(i) A map of seismic micro-districting in calculated accelerations, considering the maximum of two options: Peak acceleration with a 475-year repeatability period or 2/3 of peak acceleration with a 2475-year repeatability period, directly used for construction calculations.

(ii) A map of seismic micro-districting in the points of the MSK-64(K) macro-seismic scale for a 475-year repeatability period (with a 10% probability of exceeding in 50 years).

(iii) A map of seismic micro-districting in the points of the MSK-64(K) macro-seismic scale for a 2475-year repeatability period (with a 2% probability of exceeding in 50 years).

(iv) A map displaying types of ground conditions based on seismic properties.

(v) A map of engineering-geological zoning of the territory.

Symbols and explanatory tables, and reports accompany the seismic micro-redistricting maps on completed works and map sets (GSZ, DSZ) undergo review and approval by the authorised body of the Republic of Kazakhstan. The Committee for Construction and Housing and Communal Services of the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan utilises the provided materials and maps to establish technical regulations, national standards, and curates a compilation of regulatory legal acts and documents associated with architecture, urban planning, and construction operations (UNECE, 2018). Kazakhstan's earthquake-resistant building construction requirements follow Eurocode-8 and are based on the hazard level established by the GSZ and DSZ maps. These maps are used to guide the design response spectrum, which determines the reinforcements and materials required to fulfil Eurocode-8 safety standards (European Union, 2004).

The Institute of Seismology of the Ministry of Emergency Situations of the Republic of Kazakhstan developed Sets of GSZ and DSZ Maps, forming the basis for State regulatory documents in architecture, urban planning, and construction, including the Eurocode 8 (European Union, 2004). These Maps were later transferred to KazNIISA JSC (Committee for Construction and Housing and Communal Services of MIIR RK), and the Institute of Seismology continues to provide necessary consultations as the developer of the scientific and methodological base for the Joint Venture of the Republic of

Kazakhstan. Innovative research efforts in Kazakhstan resulted in a probabilistic assessment of seismic hazards and the establishment of a comprehensive set of Maps for general seismic zoning. These maps depict the 10% and 2% likelihood levels of seismic occurrence and possible impact exceeding particular thresholds during 50-year intervals, equivalent to seismic events recurring every 475 years and 2475 years, respectively. For the specified recurrence intervals, points on the macro seismic intensity scale (MSK-64) and peak ground accelerations (given in fractions of “g”) represent the seismic effect.

The description below applies to the Maps for a 475-year recurrence period, giving data on macro seismic intensity scale (MSK-64) points and peak ground accelerations. Maps of the general seismic zoning for Kazakhstan represent the degree of seismic hazard through numerical values of points continuously varying over the area and display only integer values of seismic intensity for soils of the 2nd category. These maps primarily consist of isolines, delineating zones with maximum concussion intensity ranging from 6 to 9 points (with a 10-point zone on a map with a 2% probability level). The maps also illustrate the main regional geo structures of the latest developmental stage using colour-coding, as well as active faults with their types (overshoot, reset, and shift) in the legend. Zones of extended lineaments identified from satellite images are represented with hatching without sharp borders. A detailed evaluation of seismological, seismotectonic, geodynamic, and other geological and geophysical data identifies seismic producing zones, where earthquake foci are prone to form. The legend specifies that in zones with $M_{\max}\leqslant 7.5$, $M_{\max}\leqslant 8$, and $M_{\max}>8$, on the MSK-64 scale, the highest earthquake intensity can reach 10 points or more.

Through recent complex studies involving seismological, seismotectonic, and geophysical research, significant changes and reassessment of seismic hazards have occurred in certain regions. In the Tarbagatai-Altai region, the configuration of seismic generating zones such as Narym, Zharma, Chingiz-Alakol, and East Dzungarian has been revised, and new seismic generating zones – Ulba and Dzungaro-Ashysui – have been identified with their seismic potential clarified. Areas with intensities of 9, 8, and 7 points have enlarged, and the arrangement of 6-point zones has changed, according to the expected zones. In the Northern Tien Shan and Dzungarian Alatau, where recent seismological, seismotectonic, and geophysical studies were conducted, significant reassessment of seismic hazards occurred. As a result, new regions with 9-point intensity were discovered in the Dzungarian Alatau, Boro-Horo, Ketmen ridges, among others. The most hazardous 8–9-point zones are connected to the Kungei, Trans-Ili, South Dzungarian, Borotala seismic generating zones, situated in the southern and northeastern parts of the region.

The remaining land is inside a zone with seismic concussion intensities ranging from 5 to 7 points. Concussions can be caused by both distant and local seismogenic zones. As a result, the Southern Balkhash region’s regions with 8-, 7-, and 6-point concussions have grown. For the first time, 6-point zones were detected inside the weakly seismic areas of Central and Northeastern Kazakhstan using a structured examination of seismic geophysical properties. The most serious hazard in the Karatau-Talas region is posed by the Kyzyl-Kum, Kumkol, and Bastarau potential seism producing zones, which have the capacity to create surface tremors with a 6-point impact. The seismic hazard in the Caspian region underwent a significant re-evaluation. By conducting a detailed analysis of regional seismicity, the consolidated crust structure, platform cover, recent tectonic movements, and employing a formalised analysis of seismic geophysical characteristics, it was evident that the Caspian region’s structures exhibited considerable activity. For the first time, potential seism generating zones were identified in the Central Mangyshlak-Ustyurt and South Embensk-Mugodzhar areas, with seismic potential of M=5.5 and M=4.5, respectively. Additionally, regions with seismic intensities of 7 and 6 points covering Mangystau and part of Atyrau were recognized. Furthermore, the areas of 6-point concussions in the South Embensk and Central Mangyshlak-Ustyurt zones were also identified. In the Central part of Northwestern Kazakhstan, the configuration of 6-point zones has been altered due to the presence of local seism generating zones. The rest of the region falls within a zone with a concussion intensity of 5 points, resulting from both distant (in the southwest) and local seism generating zones.

The maps of Kazakhstan’s general seismic zoning show isolines with unequal steps of peak ground accelerations, designed for ease of usage by builders. These isolines correspond to the following average computed rms peak acceleration values in fractions of “g”: 0.02 g, 0.05 g, 0.075 g, 0.1 g, 0.2 g, 0.3 g, 0.4 g, 0.5 g, 0.6 g, 0.7 g, 0.8 g, and 0.9 g. The values, which reflect the limits of peak acceleration intervals, are displayed on the isolines and in the caption. In specific areas, particularly southeast of Almaty, the Maps indicate maximum values of 0.5–0.6 g, corresponding to highly seismically active zones such as the Kemin and North Kungey seismic generating zones. Additionally, an area with elevated values exceeding 0.05g is observed in the Aral Sea region due to the impact of zones with a seismic potential of $M_{\max}$ greater than 5, as well as in the Mangyshlak-Ustyurt uplift ($M_{\max}$ 5.4–5.8) and the south of the Caspian Sea from the impact of highly seismic subduction zones.

Regarding the main directions of further research in the development and improvement of new methods for assessing seismic hazard and seismic zoning (SZ), the experience from Kazakhstan and Kyrgyzstan suggests that the methodological foundations lie at the junctions of the relationship between the seismic potential and the occurrence of the most powerful ($M_{\max}$) earthquakes (Sawires R et al., 2020). The seismic potential of the Earth’s crust is an integrated concept, wherein various geological-tectonic, geophysical, and hydrogeological conditions characterising the seismic process in seism generating zones determine the maximum magnitude of earthquakes that have occurred and are anticipated (Yetirmishli G and Kazimova S, 2019). As seismicity is a geological phenomenon reflecting the tectonic consequences of modern mountain formation, these processes should be reflected in the upper part of the Earth's crust structure. The seismically active belt of Kazakhstan, encompassing the Tien Shan region, experiences high seismicity due to several significant factors: Contrasting vertical and lateral deformation of the earth's crust and structural-material complexes (SMC); changes in the thickness of the earth's crust in the seismically active areas, which may increase or decrease; influence of the latest tectonic movements, manifested in the modern relief of the earth's crust; density of the development of discontinuous geological disorders.

To comprehensively understand the relationships between geological conditions and seismicity parameters, a specialised database is being developed at the research centre. This database includes essential elements such as the neotectonics affiliation of the seismically active area within the main structural and material complex (SMC). It also comprises information on the consolidated foundation, fault density, and the thickness of the Earth's crust. Other factors recorded in the database encompass the presence of the lowering-uplift mode, marks of vertical movement, the maximum thickness of the alpine cover, as well as seismic parameters such as the magnitude of the maximum earthquake for a given area unit, the highest density of epicentres, and the maximum value of the seismic activity. This extensive database aids in studying the patterns of geological conditions and seismic behaviour, contributing to a better understanding of seismic hazards in the region. A formalised analysis of these data in the context of the $M_{\max}$ search for relationships of seismic potential (seismotectonic potential) shows the following dependencies that the largest number of earthquakes and at the same time $M_{\max}$ of them are connected (Petricca P et al., 2022): Palaeozoic arrays of intrusive granitoid (the larger the array, the stronger the earthquake); increasing the power of the earth's crust; increasing the density of breaks per unit volume of blocks; intensity of neotectonics movements; the height of the relief.

The selected seismotectonic criteria can be categorised as areal (volumetric) and linear in a narrow sense. Assigning relative weights to each criterion as percentages yields the seismotectonic potential of the territories, represented by numerical values totalling 100. While it is possible to expand the series of criteria, doing so might introduce noise to the seismotectonic field. Therefore, it is crucial to analytically choose the optimal set of main and subordinate criteria. These quantitative characteristics form the basis of the seismic potential map. Overlaying this map on a separate map showing earthquake epicentres with known magnitudes (ranging from minimum to maximum), it can be established a correlation between the seismotectonic potential and the observed magnitudes. The representativeness of the source materials in the graph allows us to identify a direct correlation between the seismic potential and the maximum earthquake energy ($M_{\max}$). This approach enables us to assess the impact of earthquakes originating from seism generating zones, which can be felt beyond their boundaries. The intensity of these tremors diminishes with increasing distance from the earthquake's point of origin, following a known pattern of attenuation.

In recent years, a clear and unequivocal connection has been established between possible earthquake foci and large intrusive bodies spanning approximately 300–500 km. Seismically active regions are often characterised by the presence of large geological structures composed of granitoids. The neotectonics activity of these structures is closely linked to their volume within the earth's crust. In areas where recent activation is observed, these structures are strong and extend to depths of 2.5 km or more. They are also fragmented and contain active faults, which are associated with known strong earthquakes having a magnitude of ⩾5.5. Such complexes are typically located within the primary zones of inflection of divergent structures subjected to sub-vertical compression of the earth's crust (van Hinsbergen DJJ et al., 2020).

Conducting research in this area can yield valuable insights into the seismic potential of specific regions. Initial estimates have already been made regarding this connection. For instance, there is a hypothesis suggesting a correlation between the intensity of an earthquake and the width of a granitoid mass. Initial observations indicate that earthquakes with a magnitude of ⩾4 tend to occur within granitoid masses with a minimum width (Lm) of approximately 10 km. When Lm ⩾20 km, events with $M⩽6$ may occur, and the most powerful earthquakes with $M⩾8$ are observed when the width exceeds 40 km. However, it is important to note that this relationship is not universally accepted as a theoretical basis and may be considered a statistical conjecture. This is because earthquakes of similar intensity can also occur in areas where no granite is exposed. Understanding and recognizing such patterns is of significant importance in assessing the seismic potential of seism generating zones in newly studied territories where detailed seismic research (DSR) is carried out.

5. Discussion

The current study modifies several principles of Eurocode-8, specifically focusing on adapting them for regional seismic conditions and soil characteristics. In particular, the seismic risk assessment model employed by Tyagunov S et al. (2012) highlights the need for region-specific parameters when dealing with Central Asia's unique geotechnical profile. This study incorporates those parameters into the guidelines, modifying general provisions related to seismic loads on structures, considering the unique seismic patterns observed in Central Asia. Specifically, Article 4.3.3.1 of Eurocode-8, which addresses the seismic action for design situations, has been amended to include region-specific seismic hazard parameters derived from local seismic data

(European Union, 2004).

The adaptation to loess soils, as investigated by Artykbaev D et al. (2024), necessitated adjustments in soil classification and response factors. The guidelines for soil categories were redefined to better capture the behavior of loess soils, which are prevalent in the area and significantly influence the seismic resistance of structures. This modification aligns with the findings of Yang PT et al. (2021) regarding regional groundwater dynamics, which can substantially affect seismic stability due to liquefaction risks and hydrochemical factors. Specifically, Clause 3.1.2 of Eurocode-8, which deals with soil classification, has been revised to include a new category for loess soils and adjusted response factors based on local soil data (European Union, 2004).

Additionally, high-precision gravity measurements, as discussed by Han J et al. (2022), were integrated to enhance seismic load calculations. This addition refines the accuracy of predicting potential seismic impacts, allowing for better-suited design parameters in high-risk zones. This approach differs from traditional Eurocode-8 applications, which often rely on more generalized data. Specifically, Article 5.2.2.2, which covers the determination of the seismic action, has been updated to incorporate high-precision gravity measurements for more accurate seismic load calculations (European Union, 2004).

Several elements of Eurocode-8 remain unaltered due to their universal applicability, regardless of regional differences. The core principles related to structural ductility, as well as general provisions for building safety, continue to align with Eurocode-8 standards. This is because, as Stober I and Bucher K (2021) indicate, the fundamental requirements for structural robustness in seismic design are well-established and applicable across various geological conditions, minimizing the need for region-specific alterations. Furthermore, guidelines concerning the geometric configuration of structures and material properties were retained. These guidelines ensure the general stability and integrity of buildings, providing a baseline that remains consistent across different regions, even as other parameters are adjusted for local conditions. The decision to maintain these elements is grounded in their proven effectiveness, as emphasized in the theoretical exploration of urban infrastructure resilience by Orgoványi P and Karches T(2024).

The modifications introduced in this study aim to enhance the accuracy and relevance of seismic assessments for the specific conditions found in Central Asia. Compared to previous applications of Eurocode-8, the integration of high-precision measurement techniques and region-specific soil data represents a significant advancement. This approach provides a more tailored and precise model for assessing seismic risk, a key advantage over the generalized frameworks that do not account for local nuances. However, this regional adaptation also brings challenges. For instance, the reliance on specialized data sources, such as hydrochemical characteristics outlined by Yang PT et al. (2021), and the use of complex metrological inputs described by Korchynska OC and Mykyychuk M (2023), can limit the study's scalability. The need for specialized equipment and data analysis can complicate the application of this modified Eurocode-8 framework in areas with less advanced monitoring infrastructure.

Despite these disadvantages, the study demonstrates that incorporating local seismic data into structural guidelines can significantly improve resilience. This is particularly relevant when comparing the seismic risk assessment approach of Tyagunov S et al. (2012) to more generic models, which may not sufficiently address region-specific risks. The customization of soil response factors and the use of updated gravity measurements illustrate a commitment to precision, though these modifications may require additional resources and expertise for implementation. The modified scheme offers a more accurate and reliable framework for Central Asia's unique seismic environment, though it may not be as easily transferable to other regions without similar adaptations.

6. Conclusions

(i) Based on a comprehensive analysis of geological-tectonic, geophysical, hydrogeological, and seismological data, both regional and local seismotectonic models have been developed. These models have effectively identified actual and potential earthquake foci zones (seism-generating zones), enhancing our understanding of seismic risks in the study area. A seismic potential model for specific structural-material complexes has been established, forming the basis for creating seismic zoning maps at various levels, in alignment with the Eurocode-8 international standard. This ensures that the seismic zoning aligns with recognized global safety standards.

(ii) Detailed seismic zoning maps have been developed using deterministic criteria for different probability levels (90%, 95%, and 99%), indicating the likelihood of not exceeding the calculated intensity on the MSK-64 scale over the next 50 years. Additionally, probabilistic maps show the distribution of seismic impacts in terms of peak ground accelerations for probability levels of exceeding calculated values over 10% and 2% within a 50-year timeframe, corresponding to repeatability periods of 475 years and 2475 years.

(iii) For the first time, this research incorporates hydrogeological, Cosmo-physical, geomagnetic, and geochemical data to assess seismic hazards. This innovative approach enhances the accuracy and reliability of seismic hazard assessments, making them more comprehensive and precise. A significant focus has been placed on analyzing the relationship between seismic potential and the occurrence of maximum earthquakes ($M_{\max}$) in specific areas, providing a clearer picture of the regions' most at risk. The study's advancements contribute significantly to earthquake preparedness and risk mitigation strategies by improving the methodologies for seismic hazard assessment and zoning.

These efforts support the creation of more resilient infrastructure and better-informed safety measures.

(iv) Future research recommendations include the continued exploration and integration of additional data sources from diverse fields, such as remote sensing, satellite observations, and advanced geophysical techniques. This multidisciplinary approach is expected to further refine seismic hazard models. Additional in-depth studies of seismic-conditioned dangerous geological processes and phenomena, including seismic dislocations, slides, and other surface effects, are essential for a more detailed understanding of earthquake impacts. Efforts should also be directed towards producing high-resolution seismic zoning maps that employ both deterministic and probabilistic approaches, providing more accurate and location-specific risk assessments. This will enable the development of targeted strategies for mitigating seismic risks.

CRediT authorship contribution statement

Daulet Sarsenbaev, Abdulaziz Abdullaev and Nursarsen Uzbekov conceived of the presented idea. Alla Sadykova and Yelizaveta Yessenzhigitova carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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