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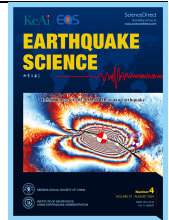
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Groundwater responses on the east European platform to earthquakes in Myanmar and the central trans-Asian seismic belt

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Key points:

- Groundwater responses to body and surface waves from the *M*7.9 Myanmar earthquake on March 28, 2025, were recorded.
- Response intensity depends on the permeability of the reservoir and aquifer type.
- The highest coherence functions between seismic and hydrogeological data occur at frequencies of 0.022 and 0.04 Hz for both natural and natural–anthropogenic conditions.
- Results from the Myanmar earthquake were compared with those from earthquakes in the central Trans-Asian Seismic Belt.

ABSTRACT

Seismic activity can dramatically impact regional groundwater systems. Mechanisms of groundwater reaction to the passage of seismic waves are poor understood. We explored the responses of natural and natural–anthropogenic aquifers on the East European Platform to earthquakes that occurred in the central Trans-Asian Seismic Belt and Myanmar. Hydrogeological monitoring was performed at two test sites beginning in 2009 (Mikhnevo) and 2019 (Gubkin). The Mikhnevo site is located along the northeastern edge of the Prioksko–Terrasny Nature Reserve. The Gubkin test site is located on the eastern outskirts of the town of Gubkin in the Belgorod District, where iron ore deposits exhibiting the Kursk Magnetic Anomaly (KMA) are being developed. The maximum variation in water level following the *M*7.9 Myanmar earthquake on March 28, 2025, was 37 mm in the weakly confined aquifer under natural conditions at the Mikhnevo site with an epicentral distance of 6100 km. Under the technogenically disturbed conditions of the Gubkin site, the same value did not exceed 4 mm in the confined aquifer at a distance of 5950 km. Our data obtained in 2014–2025 confirmed the previously established fact that groundwater response intensity depends on aquifer permeability and type. High amplitude responses were observed in the carboniferous reservoir, which displayed relatively high transmissivity. The dependence of dynamic oscillations in water level on particle velocity was approximated for this weakly confined aquifer using a linear function. Synchronous hydrogeological responses to the onset of



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shear S- and SS-waves before variations in water level produced by the passage of surface waves were observed in the reservoir–well system when seismic energy density exceeded $3 \times 10^{-5} \text{ J/m}^3$. In the confined aquifers, which displayed lower filtration parameters, similar coseismic oscillations were observed only during the passage of surface waves at the same seismic energy. Further analysis of hydrogeological responses to seismic activity recorded allowed us to trace the responses of groundwater on the East European Platform to Trans-Asian earthquakes. We consider the anisotropy of crack-porous aquifer to be the main factor that governs variations in pore pressure of the reservoir–well system under seismic impact.

Keywords: east european platform; reservoir–well system; coseismic groundwater response; natural and technogenic regimes

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1. Introduction

The central Trans-Asian Seismic Belt traces the junctions of the Indian and Eurasian plates, and is one of the most geodynamically active regions in China. Subduction of the Indian Plate under the Eurasian Plate at a rate of 40–50 mm/yr causes high seismicity (Turner et al., 2014). The interplate boundary in northern India is represented by the Himalayan Mountains, which is limited to the west by a fold–thrust belt, and to the east by the Indo-Burmese arc associated with the Sagaing fault. Since instrumental observation began in this region, the largest earthquake at the junction of the Indian and Eurasian plates was the *M*8.6 Assam earthquake on August 15, 1950, in the eastern Himalayas. In the 21st century, the most significant events ($M > 7$) have been confined to fold–thrust systems framing the Indian plate and seismically active transform faults. During the catastrophic *M*7.9 Nepal earthquake on April 25, 2015, which was confined to the frontal thrust of the Indian Plate under the Eurasian Plate, hydrogeological responses were recorded worldwide. On the Chinese mainland, coseismic oscillations and abrupt changes in groundwater level were recorded in 159 out of 314 wells (Ma TC and Huang FQ, 2017). The amplitudes of these responses varied from 4 mm to 1.2 m at epicentral distances of 637–4544 km. In Georgia, the amplitude of coseismic variations was 13 mm at an epicentral distance of 4007 km in one of the Nakalakevi observation wells, which was drilled in fractured andesite–basalts to a depth of 600 m and penetrates into a confined subartesian aquifer (Chelidze et al., 2019). In Kamchatka, Russia, at an epicentral distance of 6810 km, 5-mm oscillations in water level were recorded for 4 h in a confined aquifer (Kopylova and Boldina, 2020).

The China Earthquake Network Center reported that a right-lateral strike-slip fault along the steeply dipping and north-striking Sagaing Fault caused the *M*7.9 Myanmar earthquake on March 28, 2025. According to USGS National Earthquake Information Center satellite observations revealed that the slip zone was approximately $460 \times$

15 km, and the earthquake source was near the point where the Indian Plate subducts from the east under the Burma (Myanmar) Plate; this is represented geomorphologically by the Indo-Burmese arc (Sanujam et al., 2009). Tectonically, the arc is transitional. The orientation of the main structures (reverse faults and thrusts) changed from a submeridional strike in the south to a NE–SW direction in the north. The position of the subduction zone between 22°N and 26°N was confirmed by the distribution of teleseismic events with depth. Above 26°N, the marginal part of the Indo-Burmese region corresponds to the junction of the Himalayan and Burmese arcs, which are characterized by collisional tectonics (earthquake focal depths do not exceed 80 km).

Records of the hydrogeological effects associated with earthquakes in the Indo-Burmese region are limited. During the *M*6.8 Myanmar earthquake on March 24, 2011, oscillation intensity in the LGH fractured borehole of a confined limestone aquifer in China reached 66 mm over the 61–200-m interval and at an epicentral distance of 778 km, with a seismic energy density of $4.2 \times 10^{-3} \text{ J/m}^3$ (Lai GL et al., 2016). In South Korea, 3279 km from the epicenter, variations did not exceed 15 mm in a borehole drilled to a depth of 300 m in the damage zone of the Yangsan Fault, with a seismic energy density of $2 \times 10^{-3} \text{ J/m}^3$ (Yun SM et al., 2019). During another earthquake on November 11, 2012, in Myanmar, the amplitude of oscillations recorded in the DZ well of an artesian aquifer composed of sandstone was 58 mm over the interval of 79–112 m at an epicentral distance of 510 km and with a seismic energy density of $5.4 \times 10^{-3} \text{ J/m}^3$ (Zhang SC et al., 2023).

Under a quasi-stationary filtration regime, variations in groundwater level are considered indicators of the dynamic, quasi-reversible, and static deformation modes of fluid-saturated reservoirs, and are described by various mechanisms. Distally, hydrogeological effects are caused by the poroelastic response of a fluid-saturated reservoir to the passage of seismic waves. In the intermediate zone, they are caused by the infilling or emptying of cracks by

colloidal particles (Brodsky et al., 2003). Proximally, abrupt changes in the groundwater levels of wells may indicate an increase or decrease in the permeability of a fluid-saturated reservoir due to the disruption of the pore space structure. Records of coseismic effects caused by the Indian Plate are of particular interest on the East European Platform, located within the Eurasian Plate. A primary goal of this experimental study performed at the Sadovsky Institute of Geospheres Dynamics, Russian Academy of Sciences (IDG RAS) was to understand the responses of regional reservoir–well systems under natural and anthropogenic conditions to earthquakes in Myanmar and the central Trans-Asian Seismic Belt.

2. Geological Setting

Precise hydrogeological monitoring has been conducted by the Sadovsky Institute of Geospheres Dynamics, Russian Academy of Sciences (IDG RAS) at two test sites on the East European Platform in Russia: Mikhnevo since 2009 and Gubkin since 2019. The Mikhnevo site is located at the northeastern edge of the Prioksko–Terrasny Nature Reserve, ~80 km south of

Moscow, outside the zone of active technogenesis. This site is within a natural geosystem, the Moscow Artesian Basin, which is dominated by a subhorizontal layer of interbedded carbonate–terrigenous sediments. The Gubkin site lies within the crystalline Voronezh Massif on the western outskirts of the town of Gubkin, in the Belgorod District — an industrial region. This site is located in the mining allotment zone of the Korobkovskoe and Lebedinskoe iron ore deposits exhibiting the Kursk Magnetic Anomaly (KMA), which are recovered via explosive technologies. Therefore, this site is a natural–anthropogenic system; it is also within the zone of technogenesis.

Groundwater observations at the Mikhnevo site have been conducted in wells 1M since 2013 and 2M since 2009, and at the Gubkin site, in wells 1G and 2G since 2019 and in well 3G since 2021. The distances between wells are: 30 m for 1M–2M (Mikhnevo), 2 m for 1G–2G, and 1.6 km for 2G–3G (Gubkin). The stratigraphic composition of wells 1M and 2M, from top to bottom, includes 10-m-thick Quaternary sediments, Middle Carboniferous Kashirsky (46 m) and Vereisky (20 m) carbonate–terrigenous horizons, and the Lower Carboniferous Aleksinsko–Protvinsky complex exposed at a depth of 115 m (Figure 1).

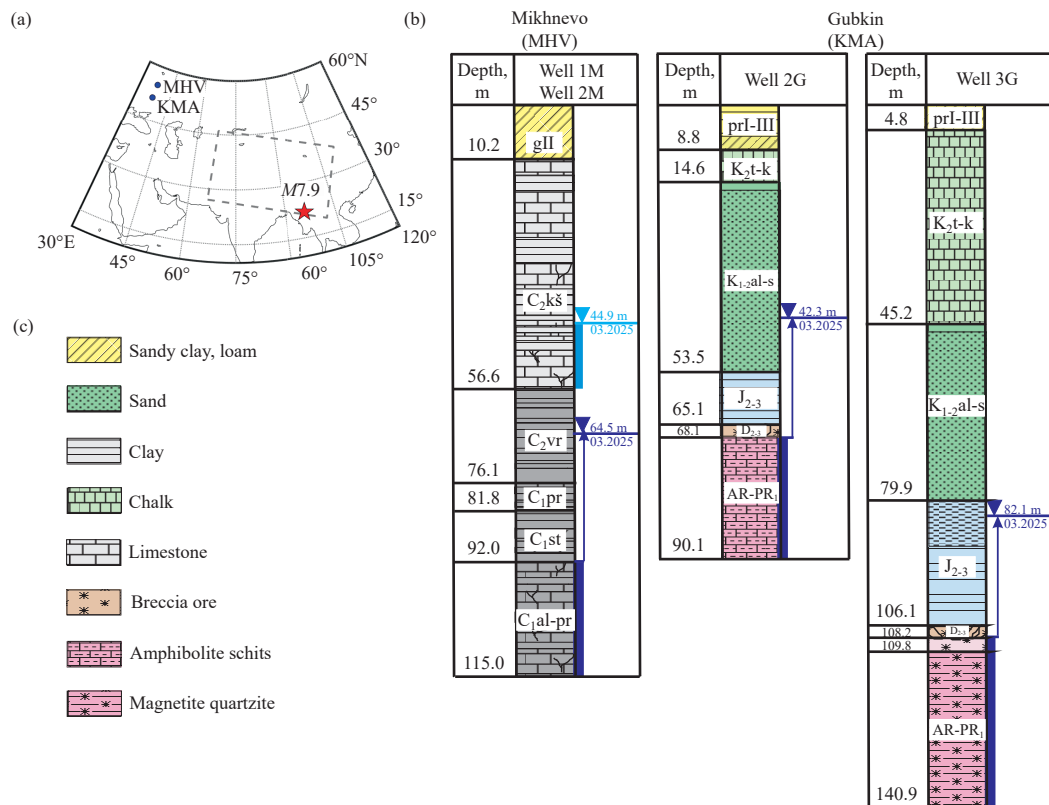


Figure 1. Location of IDG RAS test sites (blue circles) and epicenter of *M*7.9 Myanmar earthquake on March 28, 2025 (red star) (a), geological cross-sections (b), and lithological description (c). The dotted line in panel (a) shows the area examined in Figure 8.

Two confined aquifers dominate the Gubkin site. The first is confined to Lower–Upper Cretaceous sandy deposits up to 40 m in thickness. From 2019–2025, the hydrogeological responses of the upper aquifer to earthquakes in the central Trans-Asian Seismic Belt were not established. Therefore, the results from the upper aquifer in well 1G were excluded from this study. The second aquifer occupies a zone of exogenous weathering of the crystalline bedrock and is monitored in wells 2G to 90 m and 3G to 140 m. The hydraulic gap between the levels is due to the presence of aquiclude—Jurassic clay up

to 30 m thick (Figure 1). The highest baseline transmissivity in the study area is 15 m²/day in well 1M (Mikhnevo), which is characteristic of the unevenly fractured limestones of the Kashirsky aquifer. The lowest transmissivity is 0.4 m²/day in well 3G (Gubkin), seen in the flooded layer of Archean–Proterozoic ferruginous quartzites (Tables 1 and 2). The transmissivities of the weakly fractured limestones of the Aleksinsko–Protvinsky aquifer (well 2M, Mikhnevo) and metamorphosed shales of the Archean–Proterozoic (well 2G) showed similar values of 4 m²/day.

Table 1. Hydrogeological parameters of study aquifers.

Test Site	Well No.	Aquifer Index (water-bearing rock)	Water Intake Interval (m)	Flooded Interval (m)	Water Intake Interval (m) via Resistivity	Emerging Level (m) / Steady State (m)	Pressure head (m)
Mikhnevo	1M	C ₂ kš (unevenly fractured limestone)	48.5–60.5	44.0–56.2	48.5–52.0	$\frac{46.0}{44.0}$	-
	2M	C ₁ al-pr (weakly fractured limestone)	91–115	92–115	92–94 99–100	$\frac{92}{68}$	24
Gubkin	2G	AR-PR ₁ (metamorphosed shale)	77.1–90.1	68.1–90.1	(77.0–80.0; 84.0–86.0)	$\frac{68.1}{41.4}$	26.7
	3G	AR-PR ₁ (ferruginous quartzite)	110.4–140.9	108.2–140.9	110–116; 134–139 (in 2021 only)	$\frac{108.2}{83.8}$	24.4

Table 2. Pumping data for study aquifers.

Test Site	Well No.	Aquifer Index	Pumping Data			
			Discharge (L/sec) / Lowering (m)	Specific Discharge (L/sec)	Transmissivity, T (m ² /day)	Hydraulic Conductivity, k _f (m/day)
Mikhnevo	1M	C ₂ kš	$\frac{0.5}{3.3}$	0.15	15.0	1.2
	2M	C ₁ al-pr	$\frac{0.5}{11.5}$	0.04	4.0	0.12
Gubkin	2G	AR-PR ₁	$\frac{0.44}{14.8}$	0.03	3.8	0.17
	3G	AR-PR ₁	$\frac{0.04}{23.2}$	0.002	0.4	0.02

Over a long-term observation period, seasonal variations in the level of the weakly confined aquifer in the well 1M at the Mikhnevo site (under natural conditions) vary from 0.9 m in 2020 to 2.3 m in 2021. The amplitudes of the spring rise in the level of the confined aquifer in the well 2M vary from 1.3 m in 2018 to 2.2 m in 2024 (Figure 2a). The annual cyclicity of groundwater level changes is episodically complicated by additional recharge during autumn and winter. From 2020 to 2024, a general trend of an increase in the piezometric surface of the weakly confined and confined aquifers by 2 and 2.5 m,

respectively, was observed at the Mikhnevo site. The groundwater regime has been disturbed at the Gubkin test site by human activities (Figure 2b). Seasonal variations in the level of the Archean–Proterozoic aquifer in well 2G are weakly expressed, and the amplitude of water level increases during the spring floods of 2020–2022 did not exceed 0.8 m. Meanwhile the deeper confined aquifer in well 3G recorded a shift in the onset of extreme water level fluctuations to the autumn–winter period. Specifically, an increase in the piezometric surface of the Archean–Proterozoic aquifer by 1–1.5 m was

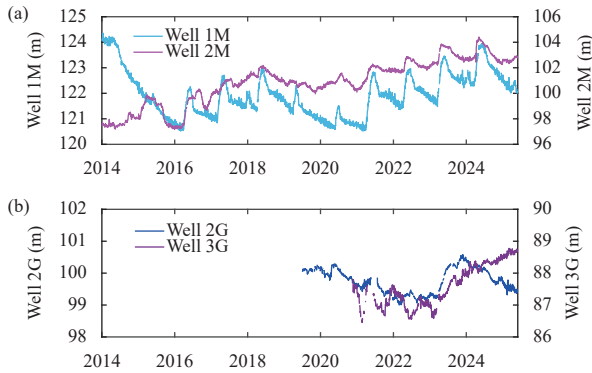


Figure 2. Water levels relative to sea level for (a) natural (Mikhnevo) and (b) natural-technogenic (Gubkin) geosystems.

observed in 2023. The increasing pressure trend was maintained in well 3G, downstream and in the direction of underground flow. From 2024–2025, a decrease in the level of the Archean–Proterozoic aquifer was established in well 2G, which was likely associated with an increase in the amount and depth of mining activities of the Korobkovskoe iron ore deposit.

3. Methods

At the Mikhnevo site, two aquifers were tapped: the weakly confined Kashirsky (well 1M) at 44.0–56.2 m, and the confined Aleksinsko–Protvinsky (well 2M) at 92–115 m. At the Gubkin site, wells 2G and 3G were drilled into Archean–Proterozoic deposits represented by metamorphosed shale at 77.1–90.1 m and by ferruginous quartzite at 110.4–140.9 m (Figure 1, Tables 1 and 2). The resonant frequencies of the wells were determined as follows (Cooper et al., 1965):

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{H_e}}, \quad (1)$$

where $H_e = H + 3d/8$, g is gravity (m/s^2), H is the height of the water column in the well (m), and d is the interval of the opening of the wellbore (m). The resonant frequency of well 1M was 0.17 Hz; the frequencies of wells 2M, 2G, and 3G were similar (0.08 Hz).

Wells 1M and 2M were equipped with level sensors LMP308i (BD Sensors, Germany), and wells 2G and 3G were equipped with PR-36XW level sensors (Keller, Switzerland). The accuracy of recorded water level variations at a sampling rate of 1 Hz at the Mikhnevo site and 200 Hz at the Gubkin site was $\pm 0.1\%$ FS. Pressure sensors PAA-33X (Keller, Switzerland) were used to monitor changes in atmospheric pressure (Gorbunova et al., 2021).

Seismic recordings at the Mikhnevo site were performed using an SM-3-E seismometer (Special Construction

Department of the Otto Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Russia; natural frequency: 0.01 Hz) installed at a depth of 20 m and using a sampling rate of 100 Hz. At the Gubkin site, recordings were performed using an SPV-3K seismometer (Geotech, Russia) mounted on the surface and using a sampling rate of 200 Hz. The SPV-3K recording range was extended to 120 s by using a digital inverse filter. The reconstructed seismograms obtained at the Gubkin site after filtering were used to qualitatively assess waveforms in comparison to records of groundwater fluctuations. The sampling frequency for processing seismic, hydrogeological, and barometric records was reduced to 1 Hz.

The main parameters of seismic events (original time, arrival time of the longitudinal wave at Obninsk station (OBN), located at a distance of ~ 100 km from the Mikhnevo site, and the coordinates and depth of the earthquake sources) were taken from the catalog of the Geophysical Survey of the Russian Academy of Sciences (FRC GS RAS, www.ceme.gsras.ru). Magnitude (M_W) was obtained from the Global CMT Catalog (<http://www.globalcmt.org/CMTsearch.html>). In some cases (2021–2025), when analyzing hydrogeological responses to remote earthquakes, the data recorded at OBN by the international seismic network, IRIS, equipped with a broadband STS-2 seismometer (Streckeisen, Switzerland), were used. These data were comparable to those obtained at the Mikhnevo site for teleseismic events.

Fourteen earthquakes that occurred in the central Trans-Asian Seismic Belt in 2014–2025 were selected from the compiled database, for which distinct hydrogeological responses were observed at Mikhnevo and Gubkin sites during the passage of seismic waves. The original series were cleared of high-frequency noise and limited to a range of periods of 2–100 sec (0.01–0.5 Hz). Maximum amplitudes of particle velocity and fluctuations in weakly confined and confined aquifers were determined in groups of surface waves identified in the seismograms. These maxima were measured between successive maxima and minima in a sliding window of 72 s with 50% overlap. To exclude the influence of local site conditions, the spectral ratio of the earthquake record (2 h after wave arrival) to the background values (2 h before wave arrival) was calculated. When analyzing the seismic impact on aquifers of different ages under natural and anthropogenic conditions, an assessment of the coherence function was made between the particle velocity (vertical component) and groundwater fluctuations recorded at each site (i.e., the seismic and hydrogeological parameters recorded at different sites).

To assess the synchronicity of the response of

reservoir–well systems during the passage of seismic waves from a distant earthquake in Myanmar, correlation analysis was performed between the seismic and hydrogeological data. The correlation coefficient and time shift were calculated for a sliding window of 90 s with an overlap of 50%. When comparing the hydrogeological effects of distant earthquakes, the seismic energy density (ϵ) was calculated using the empirical dependence (Wang CY, 2007):

$$M_w = 2.7 + 0.69 \lg \epsilon + 2.11 gr, \quad (2)$$

where r is the epicentral distance (km). Additional information on the OBN, including waveforms and body wave arrival time data for earthquakes in the central Trans-Asian Seismic Belt, were obtained from the United States Geological Survey (USGS, <https://earthquake.usgs.gov/earthquakes/eventpage/us7000pn9s/executive>).

4. Results and Discussion

Since 2009 (the beginning of groundwater observations at the Mikhnevo site), earthquakes with magnitudes of 5.2–6.9 have occurred within the Indo-Burmese arc, which

traces the interplate boundary of India from the east. Such earthquakes have predominantly been shallow, with the exception of three, the foci of which were located at depths of 80–135 km within the Indo-Burmese ridge west of the Sagaing Fault (Sanujam et al., 2009). No hydrogeological effects associated with the seismic impacts of these earthquakes were recorded at the Mikhnevo or Gubkin test sites. The seismic energy density did not exceed $(3\text{--}4) \times 10^{-6} \text{ J/m}^3$, which is the threshold for registering hydrogeological responses at the Mikhnevo site.

4.1. Coseismic responses of groundwater to the M7.9 Myanmar earthquake in 2025

Representative data were obtained from the two IDG RAS sites during the M7.9 Myanmar earthquake on March 28, 2025. Hydrogeological responses to the arrival of shear S- and SS-waves before coseismic vibrations associated with the passage of surface waves were recorded in water level fluctuations in the weakly confined Kashirsky aquifer (well 1M, Figure 3a) and in the confined Archean-Proterozoic aquifer (well 2G, Figure 3c). The maximum recorded amplitude from the weakly confined aquifer was 37 mm.

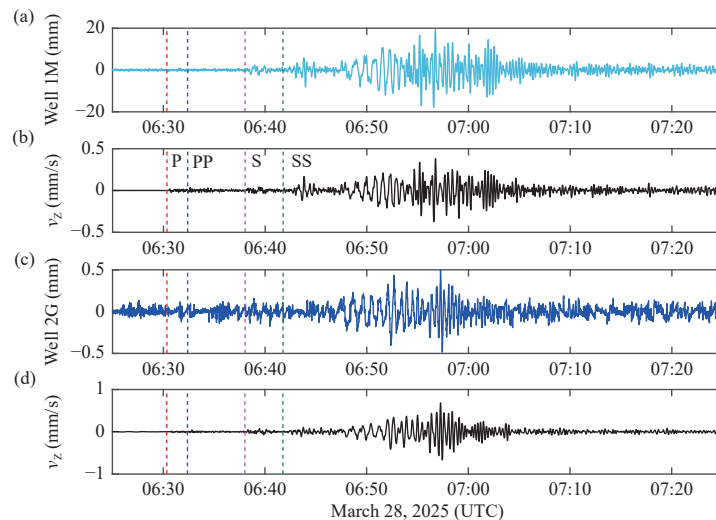


Figure 3. Waveforms of seismic (b, d) and hydrogeological (a, c) responses recorded at the Mikhnevo (a, b) and Gubkin (c, d) sites during the M7.9 Myanmar earthquake on March 28, 2025 (vertical lines mark the onsets of P, PP, S, and SS waves according to the USGS). Data were band-pass filtered at 0.01–0.5 Hz.

Responses to the Myanmar earthquake were only observed in the confined Aleksinsko–Protvinsky horizon in well 2M and the Archean–Proterozoic horizon in well 2G during the passage of surface waves. The main changes in seismic and hydrogeological parameters recorded in spectrograms were detected over a frequency range of 0.01–0.5 Hz (Figure 4). These frequencies lie below the resonant frequencies of the wells, which are each ~ 0.08 Hz

(see Methods). The duration of the reservoir response in both wells was ~ 1.5 h. This was most clearly distinguished under natural conditions (well 2M) during the dynamic deformation of the carbonate reservoir.

The main frequency ranges corresponding to the maximum values of the parameters under consideration were determined by comparing the spectral amplitudes of the particle velocity and groundwater fluctuations

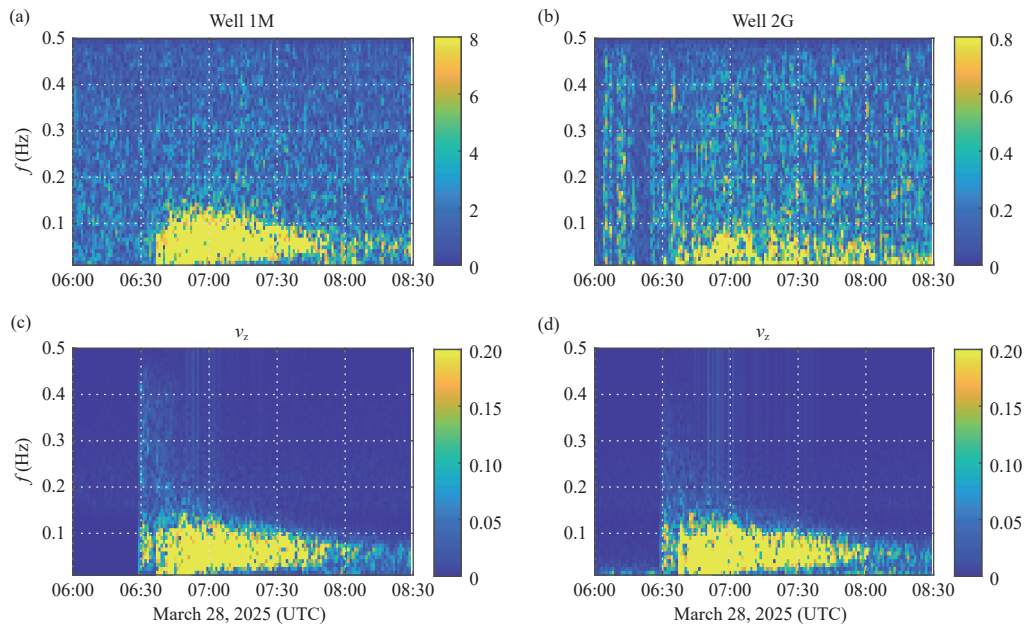


Figure 4. Spectrograms of particle velocity (c, d) and groundwater fluctuations (a, b) at Mikhnevo (a, c) and Gubkin (b, d) sites. Data were band-pass filtered at 0.01–0.5 Hz.

normalized to the background recorded 2 h before the earthquake. At the Mikhnevo site, local extrema in the particle velocity and groundwater levels of the weakly confined aquifer in well 1M coincided and appeared at 0.022 and 0.04 Hz (Figure 5a, b). At the Gubkin site, located 150 km closer to the earthquake epicenter in Myanmar, the maximum particle velocity ranged from 0.045–0.053 Hz. Local maxima in the groundwater fluctuations of the confined aquifer in well 2G were recorded at 0.032, 0.045, and 0.055 Hz (Figure 5b).

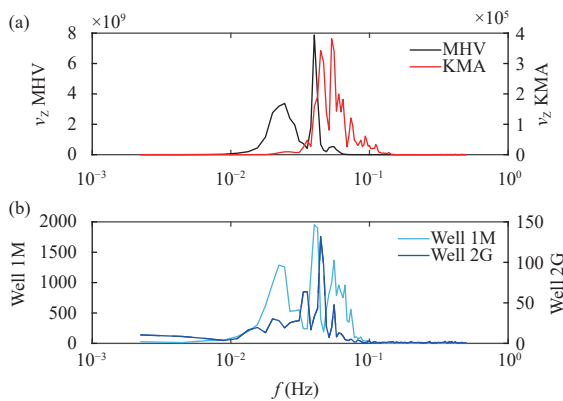


Figure 5. Normalized power spectral densities of particle velocities and groundwater fluctuations recorded at the Mikhnevo (a) and Gubkin (b) sites during the *M*7.9 Myanmar earthquake on March 28, 2025.

Differences in the detected frequencies at which local maxima appeared in the normalized spectra at the Mikhnevo and Gubkin sites were confirmed by analyzing coherence functions between seismic and hydrogeological

responses. The highest coherence (> 0.8) was obtained at a frequency of 0.02–0.03 and 0.045 Hz at the Gubkin site and at frequencies of 0.008, 0.022, and 0.04 Hz at the Mikhnevo site (Figure 6a). During the passage of seismic waves from the Myanmar earthquake, high coherence values were recorded for the particle velocities and groundwater fluctuations of different-aged aquifers at frequencies of 0.020–0.026 and 0.040 Hz (Figure 6b). Based on correlation analysis of seismic and hydrogeological data, high correlations (> 0.8) were obtained at the Mikhnevo and Gubkin sites under natural conditions (Figure 7a) during a 10-minute passage of a group of surface waves (in the time interval 6:50–7:00). The time shift between the seismic and hydrogeological parameters at the two sites was approximately zero during this time

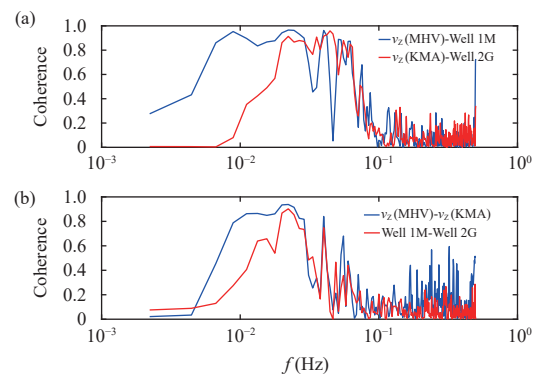


Figure 6. Coherence functions calculated between seismic and hydrogeological parameters inside each site (a) and between the same parameters at both sites (b). Abbreviations: G, Gubkin; M, Mikhnevo.

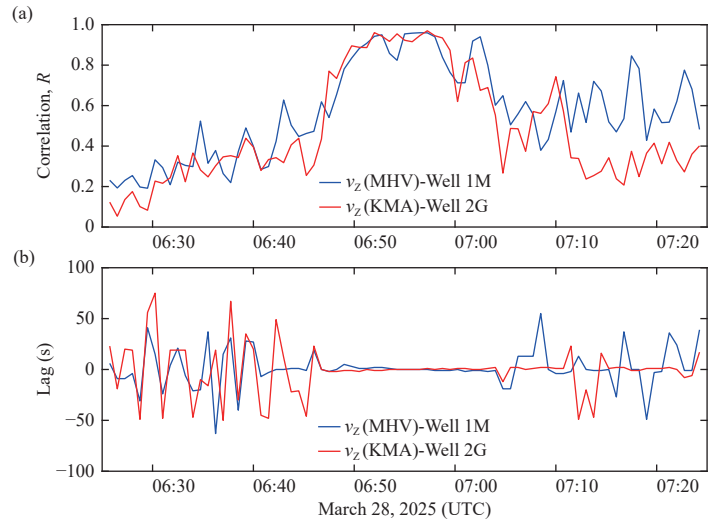


Figure 7. Correlation coefficients (a) and time shifts (b) between seismic and hydrogeological parameters registered at the Mikhnevo and Gubkin sites.

interval (Figure 7b).

4.2. Hydrogeological effects of remote earthquakes in the central Trans-Asian Seismic Belt

From 2014–2025, coseismic responses to 14 earthquakes in the central Trans-Asian Seismic Belt with magnitudes of 6.3–7.9 were detected in groundwater data at Mikhnevo and Gubkin sites at epicentral distances of 3140–6100 km (Table 3). Earthquake foci were grouped according to regional tectonic zones (Figure 8). We compared the hydrogeological effects of these events at the Mikhnevo and Gubkin sites within each identified tectonic

zone (Table 3). The obtained data were supplemented with information from published articles on groundwater responses to earthquakes (Lai GL et al., 2016; Yan R et al., 2016; Chelidze et al., 2019; Yun SM et al., 2019; Sun XL et al., 2019; Huang XD and Zhang Y, 2021; Zhang SC et al., 2023). Emphasis was placed on the type of seismic waves that caused coseismic fluctuations in water level.

Four shallow earthquakes were examined in this study, the epicenters of which were located within the southern segment of the collision zone of the Eurasian Plate. Under the natural conditions of the Mikhnevo site, dynamic variations in the level of well 1M, with amplitudes ranging

Table 3. Hydrogeological responses to earthquakes in the central Trans-Asia Seismic Belt recorded at IDG RAS test sites.

Date	Original / Arrival Time at OBN (UTC)	Mw / D (km)	Distance, R (km)		Velocity at OBN, V_{P-P} (mm/s)	Groundwater Response (mm)				Region	Seismic energy density, $\varepsilon \cdot 10^{-4}$ (J/m ³)
						Mikhnevo		Gubkin			
			Focus OBN	Focus KMA		1M	2M	2G	3G		
Southern Segment of the Collisional Margin of the Eurasian Plate											
07.12. 2015	<u>07:50:0.6</u> 07:56:09.0	<u>7.2</u> 12	3206		0.82	35.0	5.0			Tajik.	0.71
26.06. 2016	<u>11:17:09</u> 11:23:10.6	<u>6.4</u> 16.9	3145		0.11	4.4	-			Tajik.	0.05
08.08. 2017	<u>23:27:49</u> 23:34:10.0	<u>6.3</u> 27.6	3459		0.33	13.7	-			North Xinjiang	0.03
22.01. 2024	<u>18:09:05</u> 18:15:19.3	<u>7.1</u> 16.1	3419	3304	0.70	35.0	-	0.86	0.61	Kyrgy- Xinjiang	0.42
Tibetan Subplate & Northern Border – Altyn Tagn Fault											
12.02. 2014	<u>09:19:48</u> 09:26:55.8	<u>6.9</u> 18.3	4052		0.14	6.0	-			South Xinjiang	0.13
03.07. 2015	<u>01:07:44</u> 01:14:20.4	<u>6.4</u> 15.6	3668		0.23	10.2	-			South Xinjiang	0.03

Continued

Date	Original / Arrival Time at OBN (UTC)	Mw / D (km)	Distance, <i>R</i> (km)		Velocity at OBN, <i>V</i> _{P-P} (mm/s)	Groundwater Response (mm)				Region	Seismic energy density, <i>ε</i> · 10 ⁻⁴ (J/m ³)
			Focus OBN	Focus KMA		Mikhnevo		Gubkin			
						1M	2M	2G	3G		
Kunlun Fault (Transform)											
08.08. 2017	<u>13:19:48</u> 13:28:51.8	<u>6.5</u> 16.2	5646		0.08	3.9	-			Gansu	0.01
21.05. 2021	<u>18:04:14</u> 18:12:42.2	<u>7.4</u> 12	5184	5131	0.75	31.0	3.0	0.50	*	Qinhai	0.32
Frontal Thrust Zone of the Indian Plate											
25.04. 2015	<u>06:11:24</u> 06:19:30.5	<u>7.9</u> 12	4918		0.66	29.2	4.9			Nepal	2.00
26.04. 2015	<u>07:09:06</u> 07:17:22.1	<u>6.7</u> 20.6	4986		0.22	10.3	-			Nepal	0.03
12.05. 2015	<u>07:05:17</u> 07:13:32.0	<u>7.2</u> 12	4985		0.87	38.1	-			Nepal	0.19
26.10. 2015	<u>09:09:31</u> 09:15:19.7	<u>7.5</u> 209.4	3240		0.39	14.2	-			Afghan (Hindu Kush)	1.87
07.01. 2025	<u>01:05:16</u> 01:13:31.1	<u>7.1</u> 10	4987	4823	0.30	14.0	-	*	-	Tibet	0.13
Indo-Burmese arc											
28.03. 2025	<u>06:20:52</u> 06:30:22.5	<u>7.9**</u> 20.1	6102	5951	0.75	37.0	4.0	1.00	-	Myanmar	0.53

*Registration data are unavailable.

**Magnitude from the China Earthquake Network Center.

from 4–35 mm were caused by the passage of a group of surface waves. Hydrogeological responses to the arrival of shear waves were also recorded during earthquakes in Tajikistan (December 7, 2015) and Kyrgyzstan–Xinjiang (January 22, 2024), which had magnitudes > 7.0 (Figure 9). During the earthquakes in Tajikistan, which occurred at the smallest epicentral distances from the Mikhnevo site of all earthquakes analyzed in this study, the extrema in the groundwater level of well 1M and particle velocity appeared at frequencies of 6.2×10^{-2} and 6.5×10^{-2} Hz, respectively. Under the anthropogenically disturbed conditions of the Gubkin site, located 50 km closer to the epicenters of the earthquakes in Kyrgyzstan–Xinjiang and Myanmar, the amplitude of dynamic variations in groundwater during the passage of surface waves did not exceed 0.6–0.8 mm.

Similar hydrogeological effects have been observed in the seismically active regions of Georgia in Eastern Europe. For instance, the amplitudes of the hydrogeological responses to the passage of shear and surface waves in the Nakalakevi well were 15 and 24 mm, respectively, at a distance of 2526 km from the epicenter of the Tajikistan earthquake on December 7, 2015

(Chelidze et al., 2019). During the earthquake in northern Xinjiang, China, which occurred at the intersection of the Liushugou–Hongyanchi thrust fault and a subsidiary fault on August 8, 2017, an abrupt change and oscillations in the groundwater level of a Chinese confined aquifer at well X-10 were observed, with an amplitude of up to 70 mm, a seismic energy density of 1.2×10^{-3} J/m³ and an epicentral distance of 390 km (Sun XL et al., 2019).

The epicenters of earthquakes within the Tibetan subplate, were confined to tectonic sutures with lengths > 1000 km and the seismically active transform Altyn and Kunlun faults. For two Altyn-based earthquakes in south Xinjiang, China (February 12, 2014 and July 3, 2015), with magnitudes of 6.9 and 6.4, respectively, the same type of dynamic variations in groundwater level (amplitude: 6–10.2 mm) were observed, though the intensities of their oscillations differed. The maximum amplitudes of the hydrogeological responses to Kunlun-based earthquakes on August 8, 2017 (northern Xinjiang), and May 21, 2021 (Qinhai, China), with magnitudes of 6.5 and 7.4, respectively, reached 31 mm. Groundwater fluctuated in the weakly confined aquifer in well 1M at the Mikhnevo site in response to the arrival of shear waves during an

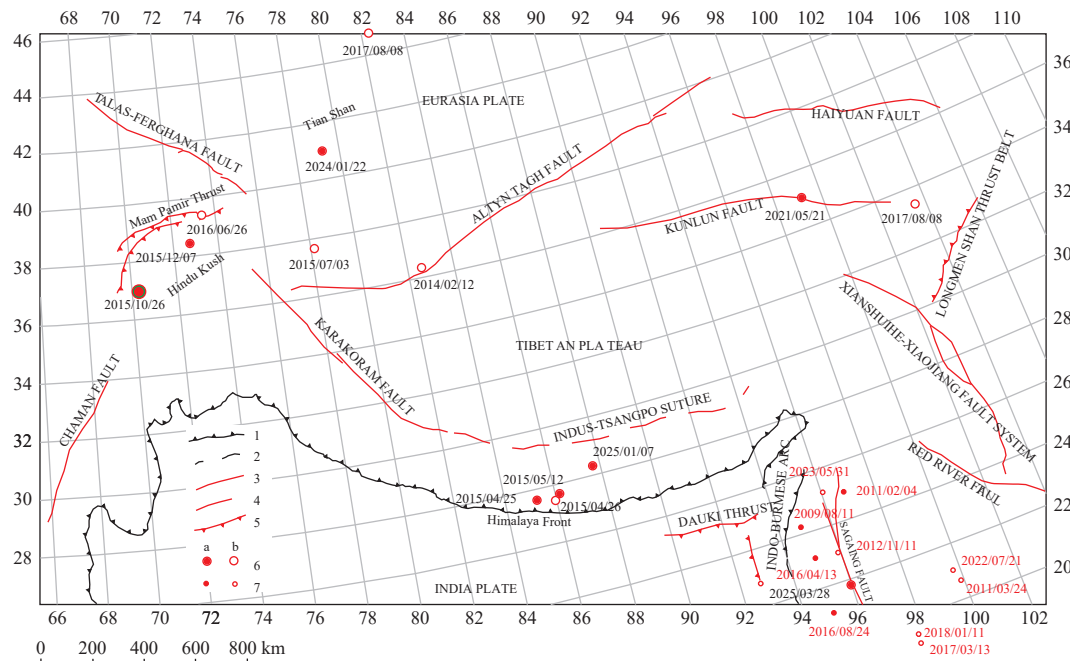


Figure 8. Tectonic regime of the central Trans-Asian Seismic Belt (after Turner et al., 2014) (1, 2—plate boundaries: 1—subduction, 2—other; 3—large active fault; 4—suture; 5—thrust; 6–7—earthquake epicenters: 6—responses recorded in groundwater fluctuations at IDG RAS test sites (magnitude: a > 7, b < 7); 7—earthquake epicenters within the Indo-Burmese arc (depth of focus [km]: a $\geq$ 80; b < 80). Earthquake $M7.5$ on October 26, 2015, with a depth of 215 km, is shown as green-red circles.

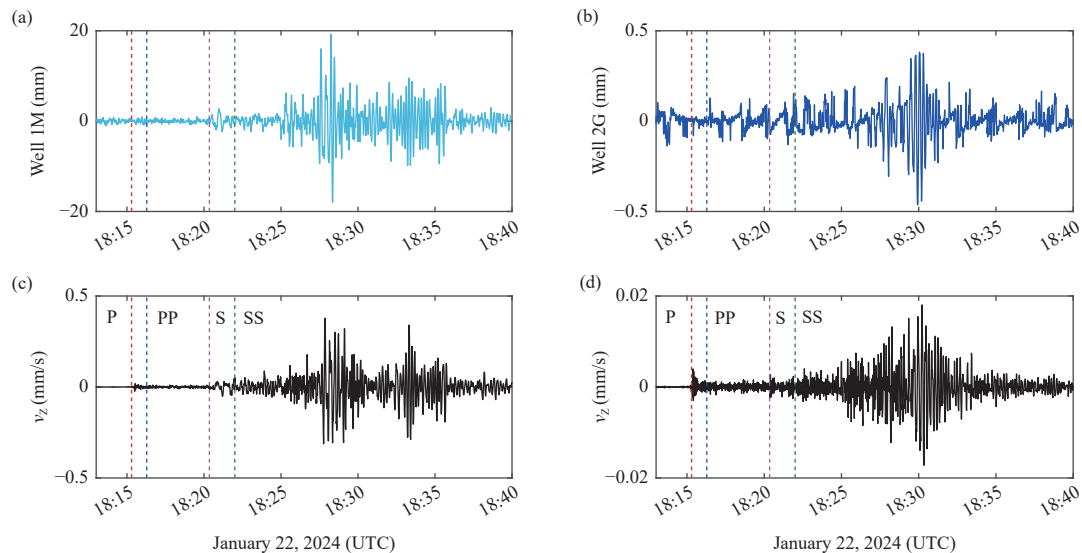


Figure 9. Waveforms of seismic (c, d) and hydrogeological (a, b) responses, recorded at the Mikhnevo (a, c) and Gubkin (b, d) sites during the Kyrgyzstan–Xinjiang earthquake on January 22, 2024. Vertical lines mark the onsets of P, PP, S, and SS-waves according to the USGS. Data were band-pass filtered at 0.01–0.5 Hz.

earthquake in Qinhai on May 21, 2021. In the normalized spectra, the extrema of these fluctuations, corresponding to the maximum particle velocities, were identified at 2×10^{-2} Hz. In well X-10 in China, 1830 km from the epicenter of the earthquake on August 8, 2017, in association with the Kunlun Fault, the amplitude of the

coseismic oscillations in the groundwater of the weakly confined aquifer was 35 mm (Sun XL et al., 2019).

Hydrogeological responses on the East European Platform to five earthquakes that occurred in the Frontal Thrust Zone of the Indian Plate onto the Eurasian Plate were recorded (Table 3). The maximum amplitude of the

dynamic variations in groundwater level during three earthquakes in Nepal, confined to the Himalayan Front, was 38.1 mm (Gorbunova et al., 2018). The extrema of the fluctuations in groundwater level in the weakly confined aquifer (well 1M) and the particle velocities during the first earthquake were synchronized over a wide frequency range ($3.8\text{--}5.2 \times 10^{-2}$ Hz); during the second and third, frequencies of 4.8×10^{-2} and 5.5×10^{-2} Hz, and 4.8×10^{-2} Hz, were detected. During the earthquake in Tibet on January 7, 2025, a reservoir–well system response was observed under natural conditions (Mikhnevo site) during the passage of surface waves (Table 3). The *M*7.5 Afghanistan deep-focus earthquake on October 26, 2015, which occurred in the Hindu Kush, drove fluctuations in the groundwater levels of the weakly confined aquifer (well 1M) with the arrival of shear waves, before coseismic oscillations were observed, and synchronously with surface waves, as was the case with the *M*7.9 Nepal earthquake on April 25, 2015. Extremes in groundwater fluctuations, synchronous with ground oscillations along the vertical component, were established at frequencies of 3.3×10^{-2} and 4.8×10^{-2} Hz; the response was observed in the form of a single train of oscillations during the passage of surface waves. In a seismically active region in Georgia, at a distance of 2449 km from the epicenter of the *M*7.5 Afghanistan earthquake, which occurred at a depth of 215 km, coseismic variations in groundwater level, with amplitudes of 4–33 mm, were identified in four observation wells drilled to depths from 255 m to 3.5 km and penetrating subartesian confined aquifers composed of fractured marls and andesite-basalts (Chelidze et al., 2019).

4.3. Responses of reservoir–well systems in platform vs. seismically active regions

At the Mikhnevo site, a linear dependence in the amplitudes of hydrogeological responses of the weakly confined aquifer on particle velocities of distant earthquakes was established under natural conditions. This dependence was characterized by a high coefficient of determination (Figure 10a). The amplitudes of the responses of reservoir–well systems to earthquakes confined to the central Trans-Asian Seismic Belt, recorded at different observation points, show pronounced data scattering depending on local hydrogeological conditions. To analyze the intensity of seismic impacts on fluid-saturated reservoirs, the seismic energy density was estimated. In general, the highest amplitudes of responses were recorded under increased seismic energy densities in all observation wells (Figure 10b). The hydrogeological response to the passage of seismic waves was detected at lower seismic energy densities in the platform region. For three horizons

of different ages tapped by wells 1M, 2M, and 2G–3G with comparable values of seismic energy density ($3\text{--}6 \times 10^{-5}$ J/m³), different groundwater responses were observed, which were associated with the filtration properties of the reservoir (see the transmissivities in Table 2). For example, in the higher transmissivity well 1M (15 m²/day) larger amplitudes of hydrogeological responses were recorded than in the lower transmissivity well 2M (4 m²/day), to the *M*7.9 Nepal (April 25, 2015), and other events.

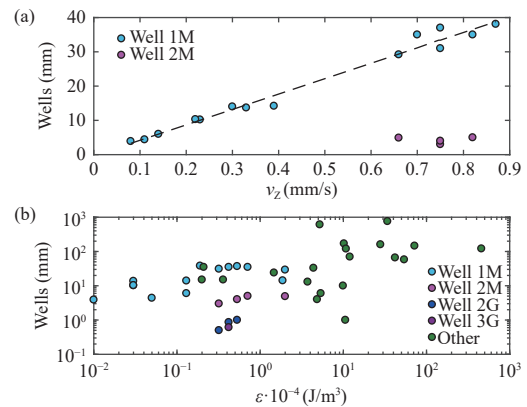


Figure 10. Amplitudes of hydrogeological responses of aquifers of different ages versus: particle velocity (a) and seismic energy density (b). Dashed line in (a): $V_z = 44.93WL - 0.30$ (coefficient of determination, $R^2 = 0.98$). Other data are from previous studies (Lai GL et al., 2016; Yan R et al., 2016; Chelidze et al., 2019; Yun SM et al., 2019; Sun XL et al., 2019; Huang XD and Zhang Y, 2021; Zhang SC et al., 2023).

The smaller values in the response of reservoir–well systems to the passage of seismic waves from distant earthquakes was also detected in wells 2G and 3G, at the technologically disturbed Gubkin site. During the *M*7.9 Myanmar earthquake on March 28, 2025, the amplitude of the hydrogeological response in well 2G (transmissivity: 3.8 m²/day), did not exceed 1 mm and in well 3G (transmissivity: 0.4 m²/day), no response was observed. Similar relationships between the responses of aquifers of different ages to seismic impacts on their filtration properties have been reported in other previous studies (e.g., Yan R et al., 2016; Sun XL et al., 2019; Huang XD and Zhang Y, 2021). The effects of different transmissivities on the amplitudes of hydrogeological responses observed in this study led to scattering in response values (Figure 10b, dark green).

The technogenic impacts at the Gubkin site manifest as a long-term water level trend that differs from natural conditions (Figure 2). Iron ore recovery using industrial explosives is accompanied by coseismic water level responses, and in some cases, post-seismic effects (Gorbunova et al., 2023). The amplitudes of the coseismic

elastic response to industrial explosions and the passage of waves from distant earthquakes are determined mainly by the filtration properties of the reservoir–well system. The post-seismic effects of lowering the water level are associated with the formation of technogenic fracturing and the renewal of existing cracks. For example, when explosions are conducted in mine chambers located in the direction of an underground stream, the amplitude of the post-seismic lowering of groundwater levels can reach 146 mm in 2–6 days (Gorbunova et al., 2023).

Data on the registration of hydrogeological effects at the Mikhnevo and Gubkin sites from remote earthquakes that occurred in the central Trans-Asian Seismic Belt are shown in Figure 11. Hydrogeological responses to earthquakes confined to the Indo-Burmese arc, which occurred at epicentral distances of 5800–6500 km and with magnitudes of 5.2–6.9 and seismic energy densities of $(0.01–1) \times 10^{-6} \text{ J/m}^3$, were not established at these sites (Figure 11). For six events with magnitudes of 6.3–6.9 at density values of $(0.1–1.3) \times 10^{-5} \text{ J/m}^3$ (Table 3), short-term coseismic oscillations in groundwater levels, with amplitudes of 4–14 mm, were observed, which indicates a poroelastic response of the water-saturated carbonate reservoir.

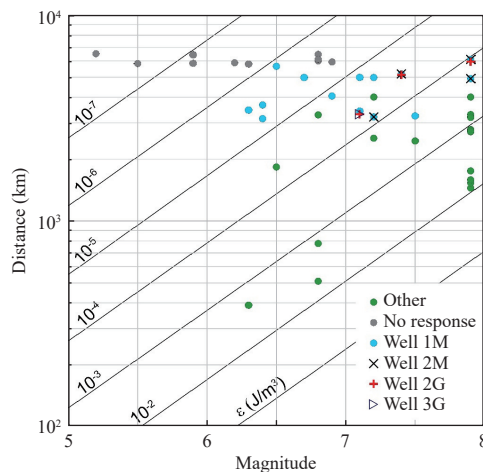


Figure 11. Diagram of hydrogeological responses to earthquakes that occurred in the central Trans-Asia Seismic Belt recorded on the East European Platform (ε is seismic energy density). Solid lines mark levels of constant seismic energy density. Other data are from previous studies (Lai GL et al., 2016; Yan R et al., 2016; Chelidze et al., 2019; Yun SM et al., 2019; Sun XL et al., 2019; Huang XD and Zhang Y, 2021; Zhang SC et al., 2023).

At a seismic energy density exceeding $1.9 \times 10^{-5} \text{ J/m}^3$ in the reservoir–well system of the weakly confined aquifer (well 1M), characterized by increased water permeability, hydrogeological responses to the arrival of shear waves were established during six earthquakes that

occurred in the fold–thrust zones of the Indian and Eurasian plates. Similar coseismic effects caused by the passage of S- and SS-waves have been observed in Taiwan (Wang CY et al., 2009), Japan (Kitagawa et al., 2011), and Kamchatka (Kopylova and Boldina, 2025), in response to the *M*7.9 Wenchuan (May 12, 2008), *M*8.8 Chile (February 27, 2010), and *M*6.6 Kamchatka (April 3, 2023) earthquakes. During the *M*7.9 Nepal earthquake (April 25, 2015), coseismic responses with an amplitude of 0.76 and 0.16 m for 109 and 97 minutes, respectively, were recorded in two wells located on the southeast Tibetan Plateau at epicentral distances of 1445–1530 km and depths of 200 and 310 m, respectively (Huang XD and Zhang Y, 2021). Based on monitoring data, short-term variations in the vertical transmissivity of weakly confined and unconfined aquifers located in marls and limestones were tracked during the first 24 h after the earthquake. The seismic energy density at the observation sites varied from 2.8×10^{-3} to $3.4 \times 10^{-3} \text{ J/m}^3$. The coseismic coherence between the vertical component of particle velocity and groundwater fluctuations in the unconfined aquifer was 0.8, and the same parameter for the weakly confined aquifer was close to 1 at $(0.9–2.3) \times 10^{-3} \text{ Hz}$. Thus, the response of reservoir–well systems to seismic impacts depends on reservoir permeability. Large amplitudes of coseismic oscillations have been observed in high-transmissivity reservoirs (Sun XL et al., 2019) and such amplitudes are greater in fault zones. Under seismic impacts in tectonically weakened zones, permeability changes have been observed in contrast to the host massif (Yan R et al., 2016; Shi Y et al., 2019).

For a carbonate reservoir in a platform region under natural conditions, the threshold values of seismic energy density have been determined at which hydrogeological responses to the passage of shear and surface waves appear. In the range of 3×10^{-6} to $1.9 \times 10^{-5} \text{ J/m}^3$, only the coseismic variations caused by the passage of a group of surface waves were distinguished in this study. At an energy density of more than $3 \times 10^{-5} \text{ J/m}^3$, the response under weakly confined conditions (well 1M) to the arrival of shear waves occurred before the hydrogeological effects associated with the passage of surface waves.

The permeability of the unevenly fractured limestones at the Mikhnevo site and metamorphosed shales and ferruginous quartzites at the Gubkin site on the East European Platform did not change after the earthquakes that occurred in Myanmar and the central Trans-Asian Seismic Belt, based on the results of preliminary processing. Instead, variations in permeability were comparable to the seasonal (background) changes.

The mechanisms underlying groundwater responses to

vibrations in S-waves are described through different approaches. One possible cause is effect of the anisotropy of the porous medium on changes in pore pressure during the passage of seismic waves generated by an earthquake. The effects of dilatation (Nikolaevskiy, 1996) and compaction of crack-like pore spaces or smoothing of grain contacts under high external stress (Lockner and Stanchits, 2002) can occur in an anisotropic medium with cracks depending on the stress–strain conditions. The growth of tensile cracks under a shear load is the basis of other models (Izvekov et al., 2020, 2023). For example, Izvekov et al. (2020, 2023) employed a thermodynamically consistent model of filtration in a medium with double porosity, considering diffuse destruction of the matrix, which was represented as a superposition of three continua (media). The first continuum was formed by the liquid saturation of the matrix (with low permeability but fairly high porosity). The second continuum was formed by liquid filling the main fractures, whose total volume was small compared with matrix porosity. The third continuum was a solid skeleton that can be rigid, poroelastic, or exhibit viscous and plastic properties (Izvekov et al., 2020).

To describe the changes in pore pressure associated with the anisotropic increase in matrix stiffness due to the closure of crack-like pore spaces under high external stress, Shalev et al. (2016a, b) introduced the shear strain coupling coefficient and scalar damage parameter, which allowed them to assess the degree of damage to rocks in studied reservoirs. The obtained high values of the shear–strain coupling coefficient and damage parameter indicate that fluctuations in groundwater are caused by changes in both volumetric and deviatoric deformation. In contrast, the model proposed by Kano and Yanagidani (2006) suggests that the effect of reservoir anisotropy on poroelastic deformation under seismic impact is negligible. When a shear wave propagates in a poroelastic medium, the incident SV component is believed to be partially converted into a P-wave reflected from the aquifer boundaries, which produces a change in pore pressure. The authors claimed that there was no response to Love surface shear waves (which only have the SH component of vibrations and cannot induce pore pressure changes according to this model) in the wells under study. However, groundwater responses to Love wave propagation were documented during the 2008 *M*7.9 Wenchuan (Wang CY et al., 2009), 2010 *M*8.8 Chile (Kitagawa et al., 2011), 2013 *M*8.3 Sea of Okhotsk (Shalev et al., 2016b), 2018 *M*7.9 Gulf of Alaska (Barbour and Beeler, 2021), and 2021 *M*8.2 Alaska (Boldina et al., 2022) earthquakes. To predict the effects of all seismic

phases, it is necessary to determine the full strain tensor at the site (Brodsky et al., 2003). Such measurements were taken during the 2010 Chile earthquake, using an array of strain meters located in wells in Japan (Kitagawa et al., 2011).

The response in the weakly confined aquifer (1M) at the Mikhnevo site was recorded as a Love wave from the *M*8.3 Chile earthquake in 2015 (Besedina et al., 2016). The presence of this response allowed us to assume that the main mechanism for hydrogeological responses to volumetric shear S- and SS-waves differs from the conversion of SV-waves to reflected P-waves from the aquifer boundaries (c.f., Kano and Yanagidani, 2006). We aimed to understand the response of reservoirs with double porosity (fracture-pore type) at the Mikhnevo and Gubkin test sites. Considering the types of reservoirs and the available data on groundwater responses, we can assume that the anisotropy of the fracture-pore space, which manifests in the response of reservoirs to the passage of S and SS waves, is substantial.

5. Conclusions

Analyses of the groundwater responses of natural (Mikhnevo) and natural–technogenic (Gubkin) sites on the East European Platform to the remote *M*7.9 Myanmar earthquake (March 28, 2025), associated with the Sagaing Fault, revealed the following patterns:

1. Under natural and anthropogenically disturbed conditions, the highest coherence functions between seismic and hydrogeological parameters are at frequencies of 0.022 and 0.04 Hz (periods of 40 and 25 sec);
2. Under natural conditions, the correlation coefficient between groundwater fluctuations in a weakly confined aquifer and particle velocity during the passage of seismic waves is high (> 0.8) relative to disturbed conditions, and the observed shift at the two sites was close to zero.
3. Maximum correlation coefficients were observed between groundwater fluctuations in aquifers of different ages, characterized by similar filtration parameters, during the passage of groups of surface waves.

By comparing the hydrogeological responses to remote earthquakes associated with the peripheral thrust zone of the Indian Plate, we determined that the amplitudes of coseismic groundwater fluctuations in the weakly confined aquifer (1M) are an order of magnitude higher than those under anthropogenically disturbed conditions (2G and 3G); this is consistent with the different filtration properties of the respective reservoirs.

We explored the ranges of seismic energy density at

which well-saturated carbonate reservoir–well systems responded to the arrival of shear waves and the passage of surface seismic waves. At a seismic energy density exceeding $3 \times 10^{-5} \text{ J/m}^3$, a quasi-reversible response was observed in the unevenly fractured carbonate reservoir at the Mikhnevo site with the arrival of shear waves from distant earthquakes. This seismic energy density could also be used as a threshold for detecting the responses of the confined aquifer of metamorphosed shales under anthropogenically disturbed conditions at the Gubkin site.

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Conflict of interest

The authors affirm that they have no financial and personal relationships with any individuals or organization that could have potentially influenced the work presented in this paper.

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