Features of Fluid-Dynamic Processes in a Seismically Active Region (Case Study of Kamchatka Peninsula, Russia)

Galina Kopylova and Svetlana Boldina

Abstract
The effects of 19 earthquakes ($M_w = 6.8{-}9.0$, epicentral distances 80–14600 km) are considered on data of long-term precision water level observations in the YuZ-5 well, Kamchatka Peninsula. Four types of water level variations were identified: I—oscillations, II—oscillations with short-term rise, III—short-term rises, IV—long-term decreases. Manifestations of the selected types of water level variations are determined by the intensity of seismic impact corresponding to the ratio of magnitude and earthquake's epicentral distance, the calculated values of specific density of energy in seismic wave, maximum velocity and amplitude-frequency composition of maximum phases in the earthquake record, obtained from broadband seismic waveforms at the nearest station. Dynamic deformation of water-bearing rocks during the passage of seismic waves is accompanied by different hydrogeodynamic processes in the "well—water-bearing rock" system including amplification of water pressure variations in the wellbore, short-term impulses of pressure near the wellbore, water pressure decrease at distances up to hundreds of meters from the well due to increased permeability of water-bearing rocks during intense shocks. Based on water level variations modelling, we show evaluation criteria for possibility of their occurrences. These criteria include the presence of certain frequencies in composition of seismic wave (oscillations), values of amplitudes and relaxation times of water pressure impulses (short-term level rises), presence of geological objects with variable permeability in the vicinity of the well.

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Well · Water level · Earthquakes · Kamchatka peninsula

1 Introduction

Generation of seismic waves is accompanied by different disruptions of the hydrodynamic regime of ground—and surface waters in the form of changes in discharges, pressure and water levels [12]. During the strongest earthquakes with magnitudes of 8–9, the effects of seismic waves are recorded at distances up to tens of thousands of km from the epicenter, reflecting the planetary scale of the impact of such earthquakes on the hydrodynamic regime of the Earth's hydrosphere. Below, the vibration effects of seismic waves in water level changes in wells are called hydrogeoseismic variations or HGSV. Different types of HGSV reflect aggregative changes of groundwater pressure due to dynamic deformation of water-bearing rocks and attendant filtration processes caused by changes in properties of water-bearing rocks, mainly their permeability [12]. Mechanisms of permeability change under vibration impact of seismic waves may include the development of fracture dilatancy in water-bearing rocks [2, 3, 6], the groundwater degassing [11], the decolmatisation of fracture-pore space [3], the effects of cumulative accumulation of interblock deformations [7].

This paper presents HGSV data of water level changes in the YuZ-5 well, Kamchatka Peninsula, recorded by digital equipment with a measurement interval of 5 min. Observations have been carried out by the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS) since 1997 for the purposes of studying hydrogeodynamic precursors of earthquakes and other seismicity effects in the water level changes [9]. In 1997–2017 19 HGSV caused by earthquakes with M_w = 6.8–9.1 at epicentral distances d_e = 80–14600 km were recorded in the well (Fig. 1, Table 1). These data allow dividing HGSV into four types (I–IV). The dependence of the selected type of HGSV manifestation on intensity of seismic impact and amplitude-frequency composition of maximum phases of the Earth's surface motions are considered in the records of the PET seismic station. For example, the processes of HGSV formation are discussed on the base of modelling.

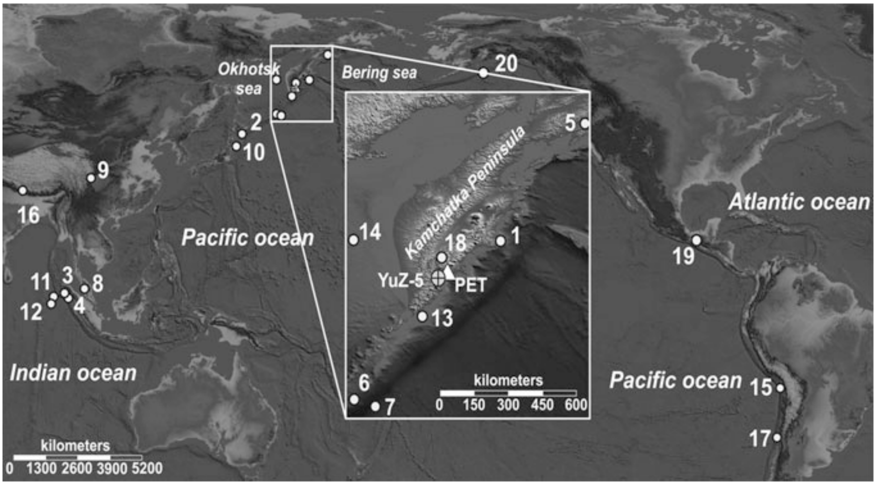

Fig. 1 The location Scheme of earthquake epicenters (Table 1), YuZ-5 well and the PET seismic station (inset)

2 HGSV Types and Their Dependence on the Intensity of Seismic Impact and Amplitude-Frequency Composition of Seismic Waves

Among the registered HGSV (Table 1) we distinguish four types based on the morphological characteristics and duration (Fig. 2): type I—forced and free oscillations within hours; type II—oscillations with short-term rises (minutes to hours); type III—short-term rises (hours); type IV—long-term (1.5–3 months) water level decreases.

To estimate seismic impact intensity in the well area, the values of specific energy density of the seismic wave e, J/m^3 [12] and maximum velocity of ground motion V_{m}, cm/s were used. The values of V_{m} were determined as average estimates from (1)–(2) [5]:

$$V_m = 81/(0.9 + d_e/D)^2, \tag{1}$$

$$V_m = 21/(d_e/D)^{1.5}, \tag{2}$$

where D is the maximum linear size of the earthquake source in km, calculated by the equation $lgD = 0.44M_{\text{w}}–1.289$ [10], where M_{w} is the earthquake magnitude.

Figure 3 shows the distribution of the selected HGSV types depending on the ratio of M_{w}, d_{e} and e (Fig. 3a) and M_{w}, d_{e} and V_{m} (Fig. 3b). One can see there is a change in water level response to seismic waves, depending on the intensity of

Table 1 Earthquake data (https://earthquake.usgs.gov/earthquakes) and characteristics of HGSV according to observations in the YuZ-5 well in 1997–2017. Earthquake numbers correspond to numbers in Fig. 1

No	Date, dd. mm.yy	Time, hh:mm:ss	Coordinates, degrees		M_W	H, km	Epicentral distance, d_e, km	Area	Character of water level variations	Type
			Lat,°N	Lon, °E						
1	05.12.97	11:26:54	54.84	162.04	7.8	33	200	Kamchatka	Decrease with an amplitude of 1 m for 3 months	IV
2	25.09.03	19:50:06	41.81	143.91	8.3	27	1670	Hokkaido Isl.	Oscillations for 1.5 h with an amplitude of $\geq$1.7 cm, rise for 1.5 h with an amplitude of 1 cm	II
3	26.12.04	00:58:53	3.30	95.98	9.0	30	8260	Sumatra Isl.	Oscillations for 12 h with an amplitude of 5 cm, rise for 8 h with an amplitude of 2 cm	II
4	28.03.05	16:09:36	2.09	97.11	8.6	30	8290	Sumatra Isl.	Oscillations for 5 h with an amplitude of at least 1 cm	I
5	20.04.06	23:25:02	60.95	167.09	7.6	22	1018	Koryakia	Rise for 6 h with an amplitude of 1.8 cm	III
6	15.11.06	11:14:13	46.59	153.27	8.3	10	812	Simushir Isl.	Rise during the day with an amplitude of 6.5 cm	III
7	13.01.07	04:23:21	46.24	154.52	8.2	10	810	Simushir Isl.	Oscillations for 3.5 h with an amplitude of $\geq$3 cm, rise for 3.5 h with an amplitude of 1 cm	II
8	12.09.07	11:10:26	4.44	101.37	8.5	34	7770	Sumatra Isl.	Oscillations within 3.5 h with an amplitude of $\geq$0.9 cm	I
9	12.05.08	06:28:00	31.08	103.27	7.9	10	5176	China	Rise for 3 h with an amplitude of 0.9 cm	III
10	11.03.11	05:46:24	38.8	142.37	9.1	29	2000	Japan	Oscillations for 18.5 h with an amplitude of $\geq$6.6 cm, rise for 20.5 h with an amplitude of 4 cm	II
11	11.04.12	08:38:38	2.35	93.07	8.7	33	8560	Sumatra Isl.	Oscillations for 24 h with an amplitude of $\geq$1.5 cm	I
12	11.04.12	10:43:09	0.77	92.45	8.2	16	8760	Sumatra Isl.	Oscillations for 22 h with an amplitude of $\geq$0.7 cm	I
13	28.02.13	14:05:51	50.93	157.34	6.8	45	260	Kamchatka	Decrease with an amplitude of 28 cm for 1.5 months	IV

(continued)

Table 1 (continued)

No	Date, dd. mm.yy	Time, hh:mm: ss	Coordinates, degrees		M_W	H, km	Epicentral distance, d_e, km	Area	Character of water level variations	Type
			Lat,°N	Lon, ° E						
14	24.05.13	05:44:48	54.89	153.22	8.3	611	348	Okhotsk Sea	Rise for 7 days with an amplitude of 9 cm	III
15	01.04.14	23:46:47	−19.61	−70.77	8.2	25	13300	Chile	Oscillations within 4.5 h with an amplitude of ≥ 0.4 cm	I
16	25.04.15	06:11:26	28.15	84.71	7.8	15	6810	Nepal	Oscillations for 4 h with an amplitude of ≥ 0.5 cm	I
17	16.09.15	22:54:33	−31.57	−71.65	8.3	25	14600	Chile	Oscillations within 6.5 h with an amplitude of ≥ 0.5 cm	I
18	30.01.16	03:25:10	54.01	158.51	7.2	180	80	Kamchatka	Decrease with an amplitude of 40 cm for 3 months	IV
19	08.09.17	04:49:21	15.07	93.72	8.1	70	7400	Mexico	Oscillations for 1–2 h with an amplitude of ≥ 2 cm	I

seismic impact on the “well—water-bearing rock” system. With increase in values of e and V_m, the type of HGSV changes from I to IV. Using filtered earthquake records in different frequency ranges, we can estimate maximum velocities of the Earth’s surface motion and the corresponding center frequencies. Distribution of HGSV types (I–IV) depending on the amplitude-frequency composition of maximum phases in velocity records of BHN, BHE, BHZ channels at the PET seismic station are shown in Fig. 4. The position of types I–IV along the horizontal axis corresponds to the central frequencies in which the maximum velocities of ground motion were registered. In this case, low-frequency and low-amplitude seismic signals during the passage of surface waves are accompanied by oscillations in the water level (type I HGSV). With amplitude increase, water level short-term rises are superimposed on the oscillations (type II HGSV). Relatively high-frequency seismic signals of the surface waves are accompanied by short-term rises in the water level (type III HGSV). In cases of local strong earthquakes accompanied by tangible shakes with the intensity $I_{msk\text{-}64}$ = 5–6 points, the long-term water level decreases are observed (type IV HGSV).

3 Assessment of Criteria for the Occurrence of Various HGSV Types

The study of HGSV types of I–IV was carried out by comparing the observed water level variations with its calculated behavior according to mathematical models [3, 4, 11] taking into account the parameters of water-bearing rocks and geometric dimensions of the well. This approach allows to obtain quantitative criteria for the emergence and development of various hydrogeodynamic processes cased by seismic impact and to construct phenomenological models for the HGSV of various types.

As shown [4], water level oscillations in the well (HGSV of I and II types (Fig. 2) are due to two factors including harmonic changes of water pressure in the “well—water-bearing rock” system and vertical displacements of the Earth’s surface. The degree of water level response to seismic waves is determined by geometrical characteristics of the well, the value of transmissibility of water-bearing rocks and depends on the type and period of seismic waves. To describe water level oscillations in the YuZ-5 well, an analytical expression was used for the amplitude ratio between the water level variations x_0 and the head h_0, taking into account the effect of groundwater pressure amplification in the “well—water-bearing rock” system during the passage of surface seismic waves [4]. The example of the earthquake on December 26, 2004, M_w = 9.1 (№ 3, Table 1) describes the conditions for the occurrence of the water level oscillations in the YuZ-5 well, exceeding the vertical displacement of the Earth’s surface ($x_0/h_0 > 1$), and it was shown that amplification of water level oscillations in the well occurs during the passage of surface waves with a period of ω = 44.6 s at the value of the parameter $T/r_w^2 \geq 1\ s^{-1}$ [8]. In this work, the parameters for the YuZ-5 well are presented.

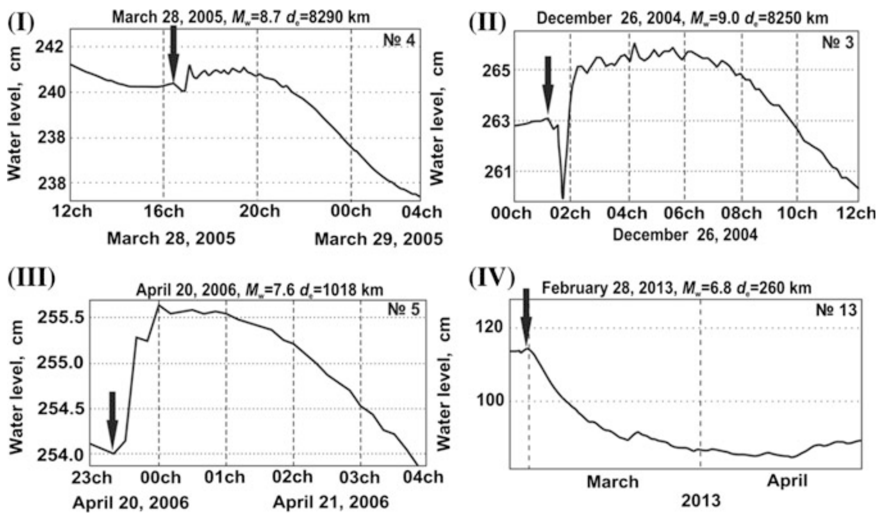

Fig. 2 Types I–IV HGSV in water level changes in the YuZ-5 well. The arrows show moments of earthquakes (numbers correspond to Fig. 1 and Table 1)

They determine the occurrence of water level oscillations: the transmissibility $T = 0.9 \cdot 10^{-4}$ m^2/s, the storage coefficient of water-bearing rocks $S = 18.7 \cdot 10^{-5}$ m^{-1}, the radius of the borehole in the area of its contact with water-bearing rocks r_w = 0.084 m, as well as the effective height of the water column in the well H_e = 494 m.

Short-term water level rises after the arrival of seismic waves (types II and III HGSV, Fig. 2) reflect the impulse increase of groundwater pressure when a non-linear filtration effect near the well is accompanied by water inflow into the wellbore. As shown in [7] the effects of non-linear filtration can occur in the presence of local inhomogeneities of the filtration properties of water-bearing rocks adjacent to the wellbore. To describe water level rise due to short-term pressure increase, a decaying exponential function was used. It characterizes the process of water flow without specifying spatial distribution of the pressure field causing water inflow into the well [11]: $u(t)= u_0(1{-}exp(-t/t_r))$, where u_0 is the maximum amplitude of the groundwater pressure increase, t is the time, t_r is the time of pressure relaxation in the "well—water-bearing rock" system. The calculated results of the water level rise within two hours after arrival of seismic waves from the earthquake on April 20, 2006, M_w= 7.6 (№ 5, Table 1) are consistent with the observed data when the increase of water pressure is u_0 = 1.6 cm and the time of pressure relaxation is t_r = 14 min.

The long-term water level decrease as a result of strong local earthquakes (Type IV HGSV, Fig. 2) can be caused by a decrease of the groundwater pressure due to localized improvement of filtration properties of water-bearing rocks during seismic shocks with an intensity of $I_{\text{msk-64}} \geq 5$ points. Such water level decreases are

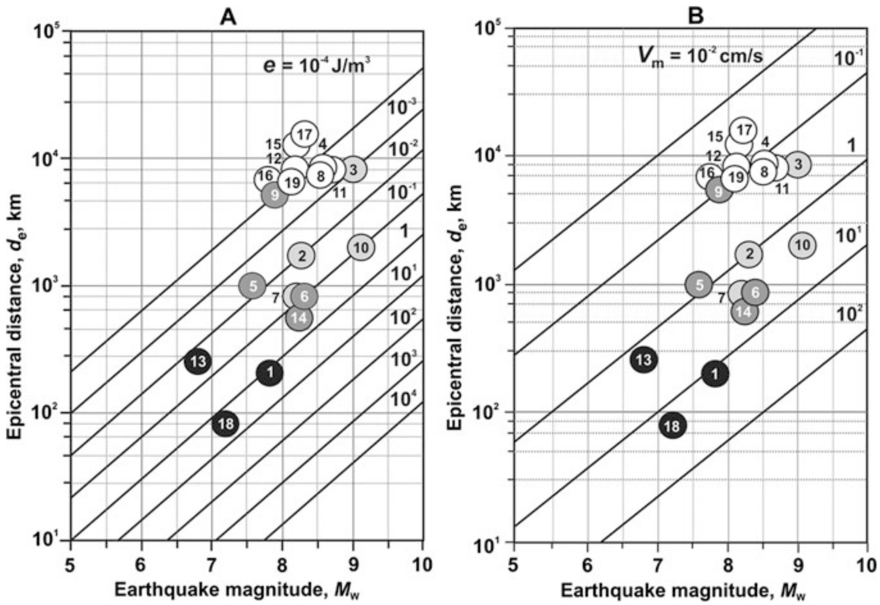

Fig. 3 Distribution of the selected HGSV types (type I— white circles, type II— grey, type III—dark grey, type IV— black) depending on the parameters of earthquakes. M_w and d_e correspond to the seismic energy density in wave *e* (**a**) and maximum velocity of wave V_m (**b**). Numbers correspond to the numbers of earthquakes in Table 1 and Fig. 1

described by a mathematical model of a distant point source of pressure disturbance in an aquifer [3]: $x = x_0 - \Delta h \cdot erfc(R/\sqrt{4ct})$, where x is water level in the well, x_0 is the initial water level in the well, R is the distance from the well to the source of head drop, c is the hydraulic diffusivity, t is the duration of level decrease, $erfc(x)$ is the addition of the $erf(x)$ error function to 1, i.e. $erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x exp(-u^2)du$. The calculated results of the water level decrease with the amplitude of $\Delta h = 0.40$ m within three months after the earthquake of January 30, 2016, $M_w = 7.2$ (№ 18, Table 1). It can occur when the hydraulic diffusivity is $c = 0.24$ m^2/s and the distance between the well and pressure drop source is $R = 450$ m [1]. The calculated results of the water level decreases after the earthquakes of December 5, 1997, $M_w = 7.8$ (№ 1) and February 28, 2013, $M_w = 6.8$ (№ 13) are consistent with the above presented results in terms of hydraulic diffusivity of water-bearing rocks and the distance to the pressure drop source. In all three cases the distances to the pressure drop source were the same $R = 450$ m. This may indicate the presence of a geological object at a distance of about 450 m from the well, for example, a fault zone or another type of hydrogeological “window”, where the permeability sharply increases during intense seismic shocks.

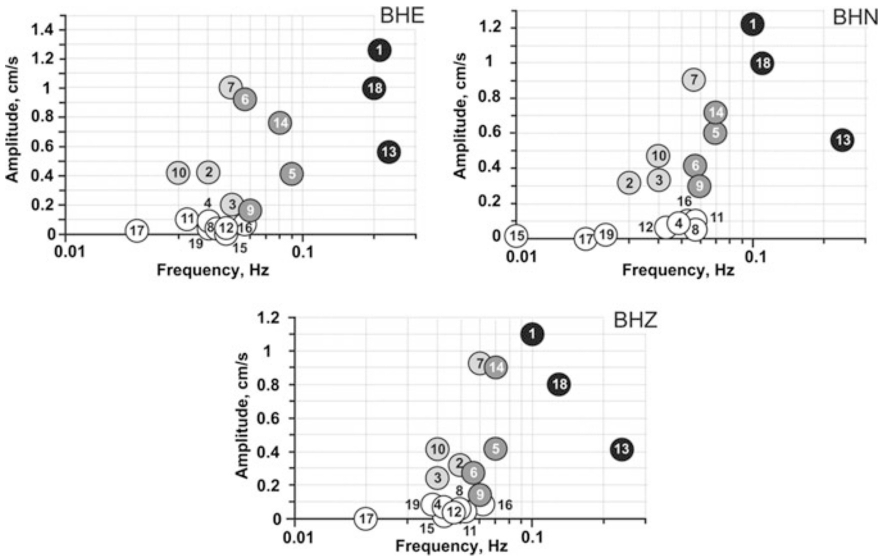

Fig. 4 Distribution of the selected HGSV types (type I— white circles, type II—grey, type III—dark grey, type IV—black) depending on the values of maximum velocity and central frequency in the records of BHE, BHN, BHZ channels at the PET station located 20 km away from the YuZ-5 well. Numbers correspond to the numbers of earthquakes in Table 1 and Fig. 1

The examples of HGSV modelling on the basis of known mathematical models and observation data with consideration of properties of water-bearing rocks and the structure of the well give evaluation of hydrogeodynamic processes interpreted in terms of different HGSV types in the observed well, and yield quantitative criteria for their initiation and development.

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References

1. Boldina, S.V., Kopylova, G.N.: Effects of the January 30, 2016, Mw = 7.2 Zhupanovsky earthquake on the water level variations in wells YuZ-5 and E-1 in Kamchatka. Geodyn. Tectonophys. **8**(4), 863–880 (2017). (in Russian)
2. Bower, D., Heaton, K.: Response of an aquifer near Ottawa to tidal forcing and the Alaskan earthquake of 1964. Can. J. Earth Sci. **15**, 331–340 (1978)
3. Brodsky, E.E., Roeloffs, E., Woodcock, D., Gall, I., Manga, M.A.: A mechanism for sustained groundwater pressure changes induced by distant earthquakes. J. Geophys. Res. **108**, 2390–2400 (2003)
4. Cooper, H.H., Bredehoeft, J.D., Papadopulos, I.S., Bennet, R.R.: The response of well-aquifer system to seismic waves. J. Geophys. Res. **70**, 3915–3926 (1965)

5. Gomberg, J., Felzer, K., Brodsky, E.: Earthquake dynamic triggering and ground motion scaling. In: 4th International Workshop on Statistical Seismology on Proceedings, pp. 45–51. Kanagawa, Japan (2006)
6. Kanamori, H., Brodsky, E.E.: The physics of earthquakes. Rep. Prog. Phys. **67**, 1429–1496 (2004)
7. Kocharyan, G.G., Vinogradov, E.A., Gorbunova, E.M., Markov, V.K., Markov, D.V., Pernik, L.M.: Hydrologic response of underground reservoirs to seismic vibrations. Izvestiya Phys. Solid Earth **47**(12), 1071–1082 (2011)
8. Kopylova, G.N., Boldina, S.V.: The response of water level in the YuZ-5 well, Kamchatka to the magnitude 9.3, Sumatra–Andaman earthquake of december 26, 2004. J. Volcanol. Seismol. **1**(5), 319–327 (2007)
9. Kopylova, G.N., Boldina, S.V., Smirnov, A.A., Chubarova, E.G.: Experience in registration of variations caused by strong earthquakes in the level and physicochemical parameters of ground waters in the piezometric wells: the case of Kamchatka. Seism. Instrum. **53**(4), 286–295 (2017)
10. Riznichenko, YuV: The source dimensions of the crustal earthquakes and the seismic moment, in Issled po fizike zemletryasenii (Studies in Earthquake Physics). Nauka, Moscow (1976). (in Russian)
11. Roeloffs, E.A.: Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes. J. Geophys. Res. **103**(B1), 869–889 (1998)
12. Wang, C.-Y., Manga, M.: Earthquakes and Water. Lecture Notes in Earth Sciences 114. Springer, Berlin (2010)