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Seismic regime of south Sakhalin before the Krillon earthquake 23.04.2017 (LURR and SDP models)

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Abstract. In the present work we show a fundamental possibility of a short-term prediction of strong shallow-focus earthquakes in the Southern Sakhalin (on the Krillon earthquake example, 23.04.2017, Mw=5.0). Retrospective modeling of earthquakes sequences from 2013 to 2017 based on the method of self-developing process (SDP) and the catalogue data of the local network has required. An auxiliary tool was used to improve the accuracy of the SDP estimates. It is a medium-term earthquake prediction method called LURR (load-unload response ratio). The previous results were improved using different sample data in the zones of active fault structures. This avoids ambiguity in the choice of the computational domain for SDP calculations. The zone of maximal anomalous levels of LURR coincides with that one we obtained a solution by the method of SDP. It happened 77 days before the earthquake. When compared with average estimates by the LURR method (two years), the prediction time was concluded to go down by 11 times.

1. Introduction

In the last few years, several seismic areas have become noticeably more active on Sakhalin [1]. Undoubtedly, it causes concern of society as are still fresh in memoirs of the tragedy in Neftegorsk (1995, M=7.2) and Nevelsk (2007, M=6.2). Material damage from the oil and gas earthquake amounted to more than 4 billion rubles. More moderate in strength Nevelsk Earthquake in 2007, destroyed the city of Nevelsk, which led to material damage in the amount of more than 6 billion rubles. Despite this, the work of Russian and foreign researchers in a very important area of long- and medium-term seismic hazard assessments in the far East, mainly associated with Kamchatka and the Kuril Islands.

Against the background of practically non-developing networks (on Sakhalin) of monitoring points of a number of potentially interesting geophysical parameters (EM field, radon, groundwater level, GAE, etc.), the study of earthquake sequences remains the only tool for studying the seismic regime. A number of successful works on the study of the seismic regime on Sakhalin are associated with good registration capabilities of the seismological network (Sakhalin Branch of the Geophysical Survey of Russian Academy of Science). Such works [1-4] were carried out in Institute of Marine Geology and Geophysics (IMGG) of FEB RAS in the last 5-10 years on the basis of LURR algorithms [5, 6] and SDP [7]. These methods, based on the analysis of seismic catalogs, allow us to determine the main points of transition of the seismic regime to a state close to the readiness for dissipation of a significant part of the accumulated elastic energy, and the time of assessment of the peak (for reduce) are comparable with the medium-term estimates and sometimes take several months. Note that the two predictions were made not in retrospect and were registered in the Sakhalin branch of the Russian expert Council on emergencies. It is prediction of Onor 14.08.2016 (M=5.8) and Krillon 23.04.2017 (M=5.0) earthquakes. Both have been done several months in advance of the event date according to the method of LURR. Today, there is a real prediction for the area of Central Sakhalin fault (CSF) on the period up to 2020 [8]. In [9] the SDP method was applied to the retrospective prediction of strong seismic event: 2 August, 2007 Nevelsk earthquake.

LURR method and SDP method were successfully applied in the IMGG since the 2014 year to detect the final stages of preparation of strong earthquake.

SDP technique allows construct adequate models of seismic process on the basis of the nonlinear differential equation of the second order called the equation of self-developing processes. At the same time, the prediction of earthquake occurrence time is days – the first months before the main shock. Good accuracy of the algorithm is achieved so far only retrospectively with the appropriate setting, which involves the selection of the boundaries of the zone and the calculation period. There is the presence of parameters that are obtained by direct selection, and it causes a reasonable share of criticism. LURR method can help to make the approach of parameter selection in the SDP more specific. The boundaries of the earthquake preparation zone with a magnitude above 5 can be localized according to the seismotectonic model of the region on the nearest lineament within 50-100 km.

In this paper, retrospectively on the Krillon earthquake example (23.04.2017, Mw=5.0), we have used the LURR and SDP methods successively. In [10] we have already carried out a similar calculation, but the position of the region of anomalous values of LURR was not sufficiently detailed, and the calculation of SDP was carried out only for one sample (the region of maximum values of the parameter LURR). It is proposed to improve the calculation detail by using different samples in both methods in the field of the object of study (Krillon earthquake).

2. Methods

The starting point of LURR method is equivalence of load-unload response rates during elastic state deformation. Since damage of material becomes more serious and goes beyond the bounds of elastic limit, the parameter starts to increase. This relation grows as the rock is approaching to fast microcracking phase. We can consider that near critical behaviour prior damage. The main concept and details of LURR method are expounded in the author's articles [5].

The method involves solving the equations of elasticity theory to determine the components of the stress tensor at the site in which the slip vector for a single earthquake is located. This considers the displacement from the tidal effect at a given point. The use of the lunar-solar tides method is justified by the fact that it is impossible to find another such ideal calibrated load/unload indicator in the earth. Tectonic and lithostatic components are not considered, as their rate of change by orders less then tidal.

To divide earthquakes into "loading" and "unloading" the Coulomb–Mohr criterion is calculated. If an earthquake occurred during the growth of the value of this criterion, it is defined as "positive", otherwise as "negative". The investigated parameter (LURR) is identified with the ratio of the total deformation of the Benioff of all positive earthquakes to all negative for a certain period of time (in mathematical processing, this is the value of the sliding window). In elastic-plastic media before destruction, the phenomenon of fluidity is observed, when at constant stresses the deformation continues to grow. Obviously, in this state of affairs, the calculation of the ratio of the response to the load to the response to unloading does not make sense (there is no reaction as such), and mathematically the parameter LURR again becomes close to one.

In the area of transition from elastic to inelastic deformation, this parameter will begin to grow and reach its maximum values near the destruction of the medium. That is why in an environment where brittle fracture is realized one can expect the main (predicted) event after the curve reaches the maximum values, and in an environment where plastic effects may occur, there is a return of the parameter to the background level and some delay (time lag from the moment of determining the predicted trait) in time. This delay can range from several months to several years. This decrease is hardly explicable within the framework of the continuum representations used by the authors of the LURR method. Obviously, this delay depends on geological conditions. It was experimentally established [2, 3, 11] that seismic events in the region with the dimensions of hundreds of kilometers and periods of time in 360 days should be considered in the calculations by the LURR method for Sakhalin.

The seismic process is possible to distinguish between the main shocks, foreshocks and aftershocks, swarms and background seismicity. Also, the seismic process can be divided into stages of activation, attenuation and stationary development. As the level of seismic activity in work [9] the parameter which characterizes development of seismic process in time and its first derivative in time is used. It is assumed that the activation sequences are such sequences for which the second derivative is positive. The mathematical equivalent of the attenuation process will be a negative value, and the equivalent of stationary development is a zero value. The problem of modeling seismic flow before and after strong earthquakes in the SDP method is solved on the basis of the equation of self-developing processes of the second order [9]. If the dynamics of a nonlinear seismic process has significant deviations from the stationary state, then in this particular case the equation of self-developing processes is solved analytically. Its decisions are quasi-linear form: they either represent an actual linear relationship, or are reduced to a linear dependence for the logarithm.

We have used our own software the “Seis-ASZ” created in the IMGG [12] in our calculations. The “Seis-ASZ” software consists of the original algorithms of LURR method and tides computational block. Calculations using the SDP method were performed in the software package provided by the author of the method Malyshev A.I. ‘SeisDynamicsView”.

3. Results

The 2017 earthquake prediction for Sakhalin was the second consecutive successful after the Onor (2016) earthquake [2]. The calculations were carried out in the IMGG in early 2017, and in March 2017, were presented at the meeting of the Sakhalin branch of the Russian expert Council on emergencies (Protocol № 2 from 16.03.2017). The precursor indicated that before April-May 2017, an earthquake with a magnitude above 5.5 is likely to occur in the area of the West Sakhalin fault (to the West from cape Krillon). After a month (23.04.2017) earthquake (named Krillon earthquake), but with a magnitude of only Mw=5, and there it was in the expected area.

Then only one method was used for the prediction and its early confirmation was associated only with a delay in the calculations. Indeed, the harbinger itself appeared on LURR's curve in mid-2015, and the calculations were made in early 2017, that is, a year and a half later. This discrepancy is acceptable for the first steps, testing the method, but in the future, with continuous monitoring of the parameter for the Sakhalin, the appearance of anomalies should be recorded without delay. Next, we show the order of calculation by this (LURR) method with detail by different computational samples (figure 1) and in the same way we show the search for foreshock activations by the SDP method.

The seismic catalogue for the LURR calculations includes earthquakes in the period from 2010 till the 12-th of April of 2017, this is the last entry before main shock. The calculation parameters are standard for all our works: window – 360 days, shift 60 days, the range of magnitudes 3.3-5. Areas for the calculation were initially selected in the size of one-degree latitude and longitude in the semi-axis of the ellipse. Ellipses were selected with an overlap of 1 degree. These dimensions satisfy the original work and our experience [4, 5]. By sorting out the smaller rectangular areas (figure 1), the position of the area of the precursor was established. We had revealed the anomaly of LURR in May of 2015. It returned to the background level only at the beginning of 2016.

The results of calculations in areas of smaller size, including the zone of the West Sakhalin fault (WSF) showed that a precursor was formed in the zone of responsibility of the WSF but very close to CSF. This information is used to work with the SDP algorithm (retrospectively in comparison with LURR results). In this area according to the SDP method, we used a catalogue of earthquakes in the magnitude range from 2 to 3 for the period from 2003 to April 2017. In the southern part of Sakhalin, WSF plays a major role in the generation of strong earthquakes. In order to identify the main stages of development of the seismic process in this period, first analyze the seismic activity of the fault (area on the figure 1b). The graph of the accumulation of events during the investigated period for the WSF area (46°N-47°N) on the figure 2 is shown. When calculating the activity to identify self-developing processes (the SDP method), earthquake catalogs limit the magnitude to a range of values from 2 to 3 (weak seismicity).

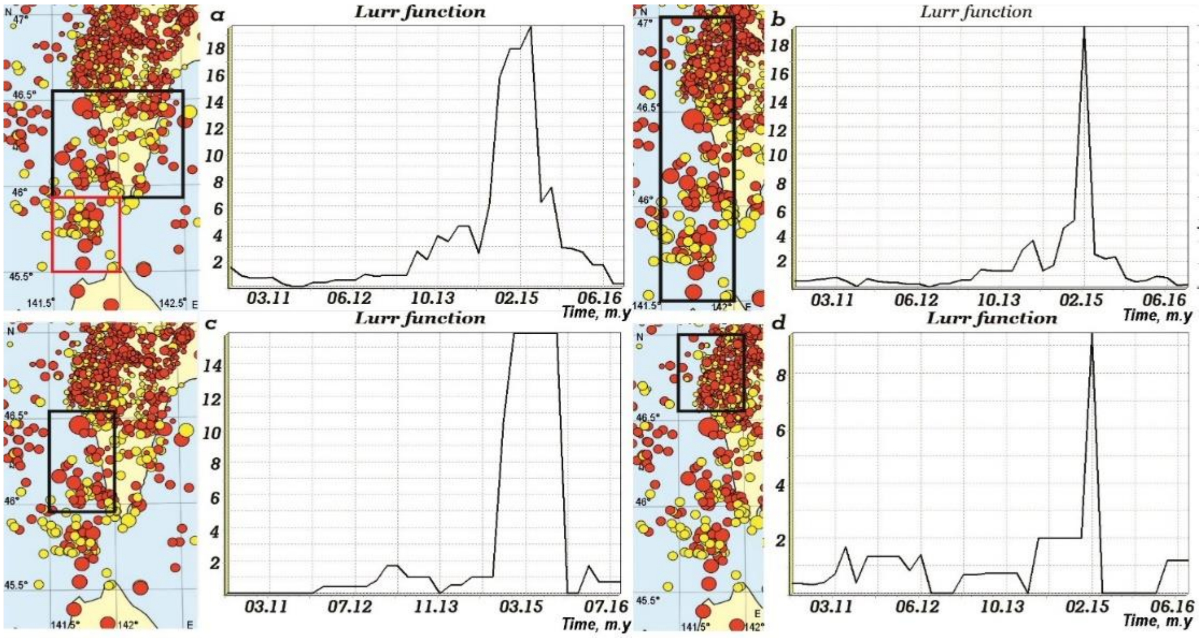

Figure 1. Areas for calculation and LURR plots.

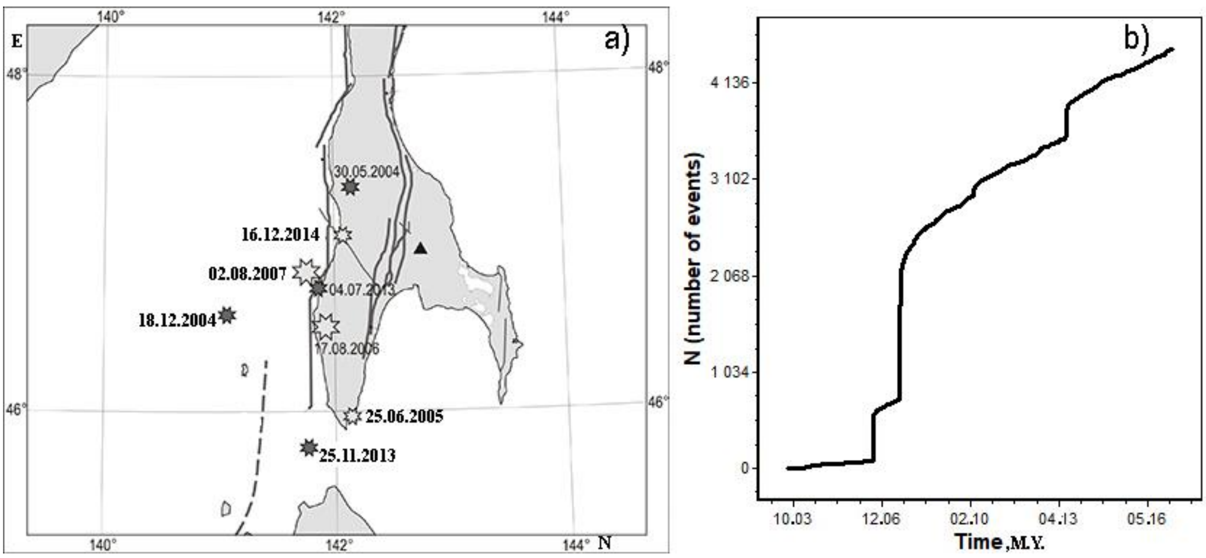

Figure 2. a) Map of south Sakhalin with main faults and significant earthquakes for the last twenty years, b) seismic activity of West Sakhalin fault.

This chart reflects the significant events for WSF: strong earthquakes (2006, 2007, 2013 years), post-relaxation processes and periods before these earthquakes. The last mentioned could be interested as a foreshocks or SDP periods. Our mission is to analyze the seismic regime after LURR anomaly of 2015 year. So, it clear, that the period since the last relaxation process after earthquake 2013 till 2017 year is what we need.

In agreement with the LURR results, the final catalogue is limited from the North (46.6°N). Figure 3 shows the solutions in this period for different areas. Figure 3a corresponds to area on the figure 1a without a separate area bounded by a red line. Figure 3c corresponds to full area on the figure 1a. Figure

3b corresponds to area on the figure 1a inside a separate area bounded by a red line. A significant effect on the series of activations was observed in the South-Western part of the Krillon with the marine part of the WSF and the La Perouse Strait (figure 3b). However, the unique solution for SDP (figure 3d) is obtained in other area (45.9°N-46.6°N). This area coincides with the zone of maximum values of LURR (figure 1c). The remaining areas have stable trends of activity (figure 3a-b).

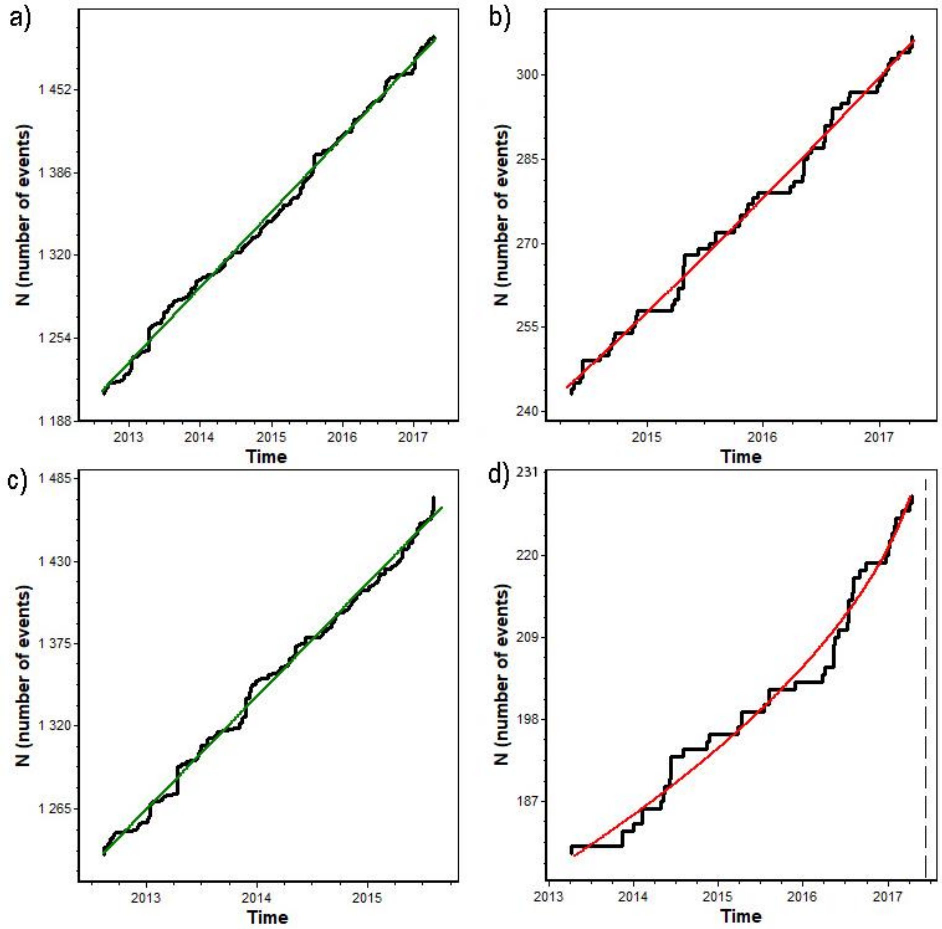

Figure 3. SDP curves for different segments of seismic catalogue (green line – stationary mode, red line – increase mode, dotted line – asymptote).

This solution has been completed on date 6 of February 2017 (figure 3d). The delay for estimated earthquake from this date is 77 days.

Concluding the discussion of the results, we will focus on the most general aspect for short-term predictions. The hypothesis of practical unpredictability of earthquakes, put forward more than 20 years ago [13], has not received convincing evidence from seismological data. And the attempts to justify this hypothesis by the ideas of self-organized criticality face the following contradiction.

For the systems described by the methods of nonlinear dynamics (among them can be attributed the earthquake source as a complex multiphase system), it is really possible the emergence of "deterministic chaos" with the entanglement of trajectories in phase space [14]. Self-organized criticality is the good example of such chaos and unpredictable behavior. However, in the nonlinear dynamics of the systems, the presence of the "prediction horizon", i.e. the ability to predict only events close in time and the practical unpredictability of events beyond this horizon. For earthquake foci, it follows that medium-term forecasts should be even worse than short-term ones, but this is clearly contrary to seismological practice.

However, the contradiction loses importance if we consider the subject of discussion is not the predictability or unpredictability of earthquakes, but the potential of a particular method for a particular seismic region (considering the limitations due to the volume and quality of the initial geophysical data and the speed of their production).

4. Conclusions

It is shown that the combined application of LURR and SDP methods, each of which was previously adapted for Sakhalin earthquake catalogs, allows to improve the accuracy of determining the time of the expected event (from several years according to LURR data to months-days according to SDP data with a significant decrease in the number of false alarms characteristic of SDP).

Only the one SDP decision was received in area of LURR anomaly on the south Sakhalin. It happened 77 days before the earthquake. When compared with estimates by the LURR method, it can be concluded that the prediction time decreased by 11 times.

The proposed scheme demonstrates the promising outlook (at least for Sakhalin) and its application in the near future is important and interesting.

References

[1] Levin B W, Sasorova E V, Zakupin A S and Kamenev P A 2018 Local Occurrence of the Relationship between Variations in the Earth's Rotation Rate and the Dynamics of Seismicity: Case Study of Sakhalin *Doklady Earth Science* 2. **483** pp 1575–78

[2] Zakupin A S., Levin Yu N., Boginskaya N V and Zherdeva O A 2018 Development of medium-term prediction methods: A case study of the August 14, 2016 Onor (Mw = 5.8) earthquake on Sakhalin *Russian J. Geology and Geophysics* 11. **59** 1526–32

[3] Tikhonov I N and Zakupin A S 2016 Retrospective evaluation of applicability of two-stage for short-term forecast of earthquakes (M≥5) within the Southern Sakhalin region according to detailed catalog *J. Vestnik of the Far East Branch of the Russian Academy of Sciences* **1** 58– 67

[4] Tikhonov I N, Mikhaylov V I and Malyshev A I 2017 Modeling the Southern Sakhalin earthquake sequences preceding strong shocks for short-term prediction of their origin time *Russian J. of Pacific Geology* 1. **11** pp 3–11

[5] Yin X C et al., 1995 A new approach to Earthquake Prediction: The Load/Unload Response Ratio (LURR) Theory. *Pure Appl. J. Geophys* **145** 701–15

[6] Yin X C, Wang Y C, Peng K Y, Bai Y L, Wang H T and Yin X F 2001 Development of a new approach to Earthquake Prediction: The Load/Unload Response Ratio (LURR) Theory *Pure Appl. J. Geophys* **157** 2365–83

[7] Malyshev A I and Tikhonov I N 2007 Nonlinear regular features in the development of the seismic process in time *J. Izvestiya. Physics of the Solid Earth* 6.**43** 476–89

[8] Zakupin A S and Boginskaya N V 2019 Modern seismicity in the area of the Central Sakhalin fault (south of Sakhalin Island): false alarm or postponed prediction? *J. Geosystems of Transition Zones* **3** 27–34

[9] Tikhonov I N, 2009 Prediction of strong earthquake within the southwestern shelf of Sakhalin island and its realization during the august 2, 2007, Nevelsk earthquake *Russian J. of Pacific Geology* 5. **3** 429–36

[10] Zakupin A S 2019 Medium-Term Prediction of Sakhalin's Dangerous Seismic Events in the LURR and SRP Models *IOP Conf. Ser.: Earth Environ. Sci.* **272** 022021

[11] Zakupin A S and Semenova E P 2018 Study of the process of preparation of strong earthquakes (Mw>5) on Sakhalin using the LURR method *J Bulletin KRASEC. Phys. & Math. Sci.* 25. **5** 73–88

[12] Zakupin A S, 2016 Program complex for the analysis of instability of seismic process. *J. Geoinformatika* **1** 34–43

[13] Geller R 1997 Earthquake prediction: a critical review *J. Geophysical International* **131** 425–50

[14] Zaslavski G M and Sagdeev V Z 1998 *Moscow: Nauka. The main editorial office of physical and mathematical literature* p 368