Control of variations in the stress-strain state based on monitoring the apparent resistivity in the well

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Abstract. The article gives an example of the application of a new approach to the search for short-term earthquake precursors based on the analysis of the data of three-year monitoring of the apparent resistivity in a water-saturated well on board a reservoir near a hydroelectric power station. The analysis also involved data on atmospheric pressure, water level and temperature in the well. The effects were estimated in a linear approximation, neglecting transients. The method of principal components was used for data processing. The results obtained in the time and frequency domains indicate that a new method for controlling localization variations and searching for short-term precursors of earthquakes is promising.

1. Introduction

1.1. A new paradigm for short-term precursor research

This paper provides a practical example of the application of a new paradigm of short-term precursor research, which is based on five simple concepts.

The first of which is that the most common precursors are due to small variations in the stress-strain state of the fractured medium. Anomalies in apparent resistivity, gas emanations, and level are associated with changes in the capacity and permeability of the fracture space. EMP, acoustic emission and seismoelectric signal (SES) anomalies are caused by variations in fractures that are natural stress concentrators.

The second idea is that anomalies of short-term precursors at a considerable distance from the source arise due to the propagation of a slow deformation wave generated by the dynamic pre-fracture phase known from the LNT theory [1] associated with the concentration of cracks in the area of the future fault and unloading of the outer part of the consolidated heterogeneity.

The third idea is that for short-term forecasting, formalization of signal separation from interference is required, which can only be based on understanding the nature of the signal and interference, and formalization of signal anomaly extraction, which requires preliminary separation of the signal from the registered mixture of signal and interference.

The fourth idea is that it is more correct to speak not about a short-term forecast, but about diagnosing the presence of a dynamic pre-fracture phase, the duration of which is the sum of the time of propagation of the deformation wave to the point of observation and the time of prediction.

Fifth, short-term precursors are divided into two types according to the nature of their use for short-term forecasting. The first includes bright precursors with a significant amplitude, which are rarely
observed and do not have a repeatability. They are caused by a nonlinear, often irreversible response of the medium to a small variation of the stress-strain state (SSS) and are associated with the unique features of the local geological structure. The second type is low-amplitude, caused by a linear response of the medium to a small variation of the SSS, which are observed always and almost everywhere, do not cause irreversible phenomena and have repeatability.

All the precursors registered in historical chronicles and most of the known short-term precursors belong to bright short-term precursors, since highly sensitive and noise-immune techniques are required to identify low-amplitude precursors. Bright rare short-term precursors, due to the accumulated significant number of facts of their registration, inform us about the existence of local variation of the SSS associated with the dynamic phase of destruction of the heterogeneity, but cannot be used for practical forecasting due to the rare occurrence and lack of repeatability. Low-amplitude precursors can be used for forecasting, but they require careful development of techniques and methods of measurements and processing, which can be realized only on the basis of understanding the nature of the signal and interference.

1.2. Brief description of the experimental technique and technique
The choice of monitoring the apparent resistivity to control low-amplitude variations in the SSS of the array is associated with the clarity of the physics of the phenomenon [2, 3] and the high tensosensitivity of this parameter, confirmed by field measurements and laboratory experiments [4, 2, 5, 6].

The task of monitoring variations in the stress-strain state (SSS) near HPP dams is of great practical importance, since any dynamic phenomena near the dam can have catastrophic consequences. This problem is also of scientific interest, since seasonal changes in the reservoir level create a significant variation in the SSS of the host environment, which makes it possible to observe the reaction of the environment to a powerful controlled impact.

This work evaluates the possibility of monitoring variations in the local stress-strain state of the massif based on the analysis of data from a more than three-year series of observation of apparent resistivity (AR) using the "Georesistor" precision station [7] in a well drilled to monitor lateral water filtration from the reservoir during the period of its filling.

The idea of this method for measuring AR, the choice of the observation site and its hardware implementation belong to Shamil Idarmachev's group, Ibragim Idarmachev provided monitoring, Evgeny Chirkov's contribution is in the method of processing the measurement results using some additional data.

The Vener electrode array is located in a well drilled to monitor the lateral filtration of water from the reservoir during the filling period and is always at least 40 meters below the water level in the well. The depth of the location of its electrodes from the wellhead is from 90 to 99 meters (A-90, M-93, N-96, B-99).

Due to the high sensitivity of the geometry of the fracture space to external influences, one can expect here a tensosensitivity comparable to that known for tuffs [5, 3, 8].

The location of the measuring unit in a water-saturated well allows using a serial 12-volt source for the generator, placing the measuring unit 40 meters below the water level in the well significantly reduces the influence of external climatic factors and makes it possible to evaluate the variations in stress-strain state in a selected area of finite size located inside the rock mass. Using a 24-bit ADC to measure voltage and current and calculating the average AR value per day allows achieving high accuracy and reliability in estimating the magnitude of slow SSS variations.

2. Statement of the problem and data preparation
As in most geophysical measurements, the measured value is influenced by several factors, of which we are only interested in one - the variation of the local SSS. Our task is to separate the signal in the AR due to the variation of the local SSS from the noise.

The measured apparent resistivity (AR) is determined by the resistivity of the water and the structure of the pore space of the host rocks (fractured limestones).
Water resistance is determined by its salinity and temperature. The salinity of water, as shown by the results of measuring the electrical resistance of water samples in 2015, changes greatly due to the inflow of low temperature waters and salinity during snow melting.

The water temperature in the well also depends on the water level in the reservoir and the season. The structure of the pore space is influenced by variations in the water level in the reservoir, variations in atmospheric pressure and variations in local SSS.

Seasonal changes in the water level in the reservoir create fluctuations in fluid pressure of the order of 4 atmospheres, with an increase in the level, increasing the effective porosity and permeability and decreasing the AR.

Variations in atmospheric pressure with its increase simultaneously reduce the water level in the well and compress the pore space as a result of the impact on the rock skeleton, which propagates without delays and losses to a depth of up to several kilometers [9], leading to an increase in the AR value due to the addition of the effects of both mechanisms of atmospheric pressure.

Local variations in stress-strain state applied to the rock skeleton decrease effective porosity and permeability and increase AR.

As a first approximation, all these factors (water salinity changing the AR, atmospheric pressure compressing the rock skeleton and lowering the water level, water pressure increasing the fracture space and variations in local stress-strain state) begin to affect the AR immediately.

Some doubts in this regard arose about the instantaneous connection between the change in the water level and the AR. However, they were eliminated when it was found that there were no significant peaks in the correlation coefficients between AR and water level at hourly shifts up to 24 hours.

2.1. Attracting additional data

In accordance with the above concepts and the available possibilities, additional data on the atmospheric pressure of the Buinaksk meteorological station located at a distance of about 10 kilometers (corrected for the difference in altitude) were involved in the analysis [10]. Due to the significant distance between the observation point and the Buinaksk meteorological station and the final speed of movement of atmospheric fronts, the use of a meteorological station for data processing undoubtedly introduces some error in the final result, but it is still better than not taking into account the effect of atmospheric pressure at all.

With the help of a number of methodological works, relationships were established between the course of water levels in the reservoir and two monitored wells, and series of the water level and temperature in the well with the installation were obtained, based on data on the water level in the reservoir and data on the water temperature in an adjacent, closely located well.

As you can see, after attracting additional data, the measured AR is influenced by two factors that we did not control - variations in local SSS and variations in water salinity, which are a hindrance for us.

2.2. Controlling the effect of water salinity based on measurements of its temperature

Let's try to take into account the effect of water salinity, using the fact that the water temperature in the well is an indicator of the inflow of melt water of low temperature and salinity. To do this, we first need to remove the effect of temperature on AR using the known form of this dependence, and then the remaining influence of temperature on AR will be due to the variation in mineralization.

Using the known dependence of water resistance on temperature, we solved the optimization problem to find a coefficient that minimizes the value of the correlation coefficient between the rows of the AR and the temperature of the water in the well, after which we took into account the effect of temperature on the AR using the obtained coefficient. Thus, now the temperature variation in our country reflects only the influence of the variation in water salinity and we are left with one uncontrollable factor influencing the AR - this is the local SSS variation we need.

2.3. Elimination of the error of the geoelectric model caused by the variation of the water level
However, in our data there is also a systematic error associated with the variation in the model of the geoelectric section due to the seasonal change in the water level by 40 meters. Simplified, the model of its influence can be represented as follows. Note that our supply dipole is located vertically at least 40 meters deeper than the water level in the well.

Under these conditions, it can be assumed with some error that the surface of the water level is horizontal, and the resistance of the entire half-space above this surface is equal to the resistance of dry limestones composing the controlled massif (here we neglect the difference in resistance between dry limestones and air far from contact). Under these assumptions, we have a contact model for space and can estimate the error caused by the 40-meter movement of the water level we register and subtract it from the measured data.

This was also implemented on the basis of solving the optimization problem for finding the resistance of dry limestones in the massif by minimizing the value of the correlation coefficient between the rows of the AR and the water level in the well, while limiting the variation of the resistance value of dry limestones by the interval obtained from the literature data. This error in the AR value associated with the change in the geoelectric model due to the variation in the water level was also subtracted from the measured AR value.

Thus, we got rid of the side effect associated with the variation of the geoelectric model and leading to a nonlinear dependence of the AR on the water level, and we can further consider the geometry of the geoelectric model to be fixed.

2.4. Simplified model of the geophysical situation

Note that the total relative value of the two errors (for the effect of the water temperature and the change in the water level on the AR), in the maximum value during the observation time, turned out to be less than 0.0007, and its smallness fully justifies the validity of our assumptions. However, these estimates are necessary, since in the case of applying the method in other conditions, they may turn out to be quite large, and the time variation of the sum of these errors has a complex and irregular nature.

Thus, based on an understanding of the geophysical situation, we significantly simplified the task by using the necessary data on atmospheric pressure, water level and temperature in the well [10], and by reducing the number of factors affecting the AR. First of all, due to the elimination of the effect of water temperature on the AR in order to obtain the possibility of assessing variations in salinity based on temperature variations. And also due to the elimination of non-linear side effects caused by the influence of changes in the model of the geoelectric section due to variations in the water level in the well on the measured value of the AR.

3. The applied method of data processing and the results

3.1. Principal component analysis and results of its application

In this formulation, we can try to solve this problem in a linear approximation without taking into account time shifts, since we have a measured value of the AR, three factors that influence it are controlled (variations in water level, atmospheric pressure and salinity estimated by temperature) and only one is unknown factor that we need to track (variation of local SSS).

To solve this problem, the principal component analysis (PCA) was used [11, 12]. In the PCA, one sequentially searches for independent components (linear combinations of measured values) that explain the maximum part of the remaining variance. PCA is usually used when dealing with poorly understood problems to reduce the dimension of the original data. In this case, we will be interested in the formalized partition of the total variance of the initial data into independent components in order to attempt to isolate the influence of unknown local SSS variations.

To assess the reliability of the results obtained, the original series was divided into two halves and the PCA was applied independently to two halves of the observation interval and the entire interval as a whole. In all three cases, almost identical results were obtained, which indicated their stability and
reliability. The correlation matrix for the entire observation interval is given in table 1, where the values determining this component are highlighted in bold.

Table 1. Matrix of loads of calculated components

| Measured values | 1 Component | 2 Component | 3 Component | 4 Component |
|-----------------|-------------|-------------|-------------|-------------|
| Rk              | -0.896078   | 0.193932    | 0.300184    | 0.263294    |
| Tw              | -0.881195   | -0.146848   | -0.438751   | 0.0971      |
| Hw              | 0.921412    | -0.145978   | -0.099522   | 0.346102    |
| PCh             | 0.183908    | 0.972672    | -0.141027   | 0.014107    |

As a result of applying PCA, four main components were identified, describing 100% of the variance of the data used.

The first component, which describes about 62% percent of the total variance of the initial data due to water level variation, includes 85% of the variance of the water level in the well and provides 80% of the variance of the apparent resistivity and 78% of the variance of the water salinity. At the same time, an increase in the level decreases AR more than a decrease in mineralization increases it.

The second component, which describes about 26% of the total variance of the data due to the variation in atmospheric pressure, includes 95% of the variance of atmospheric pressure and provides 4% of the variance of the AR and about 2% of the variances of the level and salinity of water.

The third component, which describes about 8% of the total variance, due to the variation in water salinity, includes 19% of the variance of water salinity and provides 9% of the variance of the AR, about 2% of the variance of atmospheric pressure and about 1% of the variance of the water level.

The fourth component, which describes about 5% of the total data variance, contains 12% of the water level variance and 7% of the AR variance and about 1% of the water salinity variance. In the fourth component, the influence of an unknown factor, in our opinion, the variation of the SSS leads to an increase in AR, despite an increase in the water level, which until now was considered a factor that has the strongest effect on the AR (Table 1). This power of the unknown factor and the physical clarity of the picture (compression of cracks by a force that overcomes the pressure of a water column, displacement of water with an increase in AR) allow us to conclude that it is caused by local variation of SSS.

3.2. Analysis of the reliability of the results obtained in the time domain

To check the adequacy of this assumption in the time domain, a formalized comparison of the identified anomalies of the fourth component was carried out with a number of earthquakes, which, according to Dobrovolsky's theory [13], create relative deformations at the observation point more than tidal deformations ($10^{-8}$). As seen from figure 1, all earthquakes have anomalies. Note that for four closely spaced events, anomalies precede earthquakes, and for three earthquakes that create the greatest relative deformations at the observation point, the amplitude of the anomalies exceeds the threshold level. Anomaly before the event that creates the greatest relative deformation is cut off by missing registration (highlighted by a straight section of the AR graph). At the same time, for two earthquakes, the sources of which are located further away, anomalies appear after the events. The width of the anomalies is inversely proportional to the magnitude of the event; therefore, the velocity of the deformation wave is directly proportional to the magnitude.
Figure 1. Comparison of the squared amplitude of the fourth component of the AR with deformations at the observation point calculated according to the Dobrovolsky theory for local earthquakes. The relative values of deformations are indicated in large print, the magnitude and distance to the earthquake source are also indicated. The gray fill indicates the level of the threshold, the probability of exceeding which does not exceed 5%.

Verification of this result using the method of multiple regression, when the magnitude of the squared residual of the approximation of the series of AR was analyzed (using the series of data on atmospheric pressure, level and temperature of water in the well) showed a similar picture of anomalous manifestations. The formalization of anomaly detection in both cases consisted in the fact that the levels of the anomalous signal detection threshold were obtained on the basis of determining the distribution laws of the squared amplitude and choosing a threshold with a probability of exceeding it by 5% (p-value = 0.05).

Summarizing, we can conclude that the temporal dynamics of the selected fourth component is quite convincingly confirmed by the pattern of deformations calculated on the basis of the Dobrovolsky theory at the observation point from local earthquakes during the observation time.

3.3. Analysis of measured values and selected components in the frequency domain

To check the adequacy of the selected components, a spectral analysis of the series of measured data and the selected components was carried out. First, to assess the adequacy of the decomposition into components, the sums of the amplitudes of the identified peaks in the measured data and the extracted components, respectively, were compared, which coincided with an error of the order of 0.1%. Then a comparison of the spectral peaks in the measured values and the extracted components was carried out, as a result of which it was found that although the annual periodicity was present in all the measured values, in the two identified components associated with the effect of water salinity and the presumptive influence of local variation of the SSS, the annual frequency was absent. In addition, in the selected
components, some spectral peaks present in the measured values disappeared, and vice versa, spectral peaks appeared that were absent in the measured values.

These features of the spectral composition of the components isolated using PCA necessitated additional verification of the reality of the spectral peaks of the components isolated using PCA.

For lack of a better one, we used the spectrum of a series of measurements of atmospheric pressure measured daily at the high-mountain station Jungfraujoch for twenty-four years [14].

If we take into account the fact that our observation interval was less than four years and abounded in gaps, we take as identical close spectral components identified at the Jungfraujoch station with periods in days (1102, 659, 415, 321, 265, 191, 154, 128, 110) and in our experiment (1082, 649, 406, 324, 271, 191, 155, 130, 108), then we get a fairly good coincidence of both spectra. At the same time, periods 1082, 649, 406, 271, 250, 191, 155, 130, 125 were present in both spectra.

If we take into account that annual and semi-annual periods were pre-filtered from the data at the Jungfraujoch station, then we find that in our experiment only one frequency with a period of 324 was unregistered. At the same time, in our experiment, frequencies were additionally identified with the following periods of 1625, 812, 541, 231, 216, which is not surprising, since we measured not only atmospheric pressure.

The picture of the frequencies selected in the experiment will acquire relief and greater reliability if we take into account that the frequencies obtained are divided into several series with multiple periods: (1623, 812, 541, 406, 324, 271, 231); (1082, 541, 361, 180); (649, 324, 216, 130, 108); (310, 155); (250, 125). Hence it is clear that the frequency that we did not register with a period of 324 belongs to the series in which we registered the previous and subsequent members.

Finally, let us consider the frequencies that are absent in the measured values and appear in the spectrum of the components calculated using PCA. These are frequencies with periods (812, 406, 155, 130, 125). Note that all of them, with the exception of 155, belong to the series, whose members were recorded in measured values. Frequencies with periods (406, 155, 130, 125) were also independently identified in observations at Jungfraujoch station.

Based on the above, we can conclude about the reliability of the new components of the spectra, isolated using PCA. This confirms the reliability of the results obtained in the time domain for the fourth component caused by the SSS variation.

4. Conclusion

As a result, it can be concluded that, based on the application of PCA to the treatment of AR in a water-saturated well, the water level and temperature, as well as atmospheric pressure, precursor anomalies were obtained that exceeded the threshold level for three nearby earthquakes creating maximum deformations at the observation point according to Dobrovolsky's theory [13].

Analysis of the results of the method in the frequency domain showed the selection of new spectral components that were initially absent in the measured data, the reliability of which was confirmed by third-party results. Since this was obtained despite a relatively short series of observations with omissions, an assessment of water salinity based on data on its temperature and the use of data on atmospheric pressure from the remote station Buinaksk, this indicates a high perspective of the method both for controlling local variations in SSS and for short-term forecasting earthquakes.

5. References

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