Creepex as a parameter of seismo-geodynamic studies based on geo-information systems

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Abstract

The GIS-EEDB (the Expert Earthquake Database) and GIS-ENDDB (the Earth's Natural Disasters DataBase) geoinformation systems implement methods for spatial-temporal analysis of both classical and new characteristics of the seismogeodynamic process. One of the new characteristics is a normalized creepex parameter that can be used in the statistical approach to studying of seismicity to assess a relative contribution of "soft" (creep) and "hard" (explosion) movements to the overall process of focal radiation. In this paper, the following modifications of the creepex parameter are proposed and compared: 1) $Cr_0 - Cr_{0\_world}$ and $Cr_N - Cr_{N\_world}$ as the result of reducing the parameters Cr_0 and Cr_N of each event to the world average values of the creepex, obtained from the polynomial dependence of Cr_{i_world} ($i = 0, N$) on M_{S_world}, where Cr_{i_world} are calculated based on the world average estimates of M_{S_world} and m_{b_world} at uniform intervals of the seismic moment (NEIC catalog), 2) C_{r_bji} as the result of reducing Cr_N of each event to Cr_{N_bji}, i.e. to the average for the studied in this work BJI catalog creepex values obtained from the polygonal trend $Cr_N(M_S)$ of all the catalog events. The advantage of using the creepex parameter, reduced to the trend of averaging the magnitudes of the catalog in question, is revealed, since the smallest linear dependence of the creepex on the magnitude is achieved (in comparison with the classical and normalized creepex) and the symmetry in the maximum amplitude of the deviation of the parameter relative to zero is preserved. Examples of the application of the compared parameters in specific seismic-geodynamic studies of aftershock processes of the Molucca and Simushir earthquakes also demonstrate the advantage of the parameter C_{r_bji} in the observed correspondence of the variations of the latter to the known physical processes in the focal zone of the Kashmir event, studied by the seismic-geodynamic methods of the GIS-EEDB geographical information system.

Keywords

Catalogs and databases of earthquakes, seismic and geodynamic processes, tectonic environments.

1. Introduction

At the present time, several modifications and prototypes of GIS-EEDB (the Expert Earthquake Database) and GIS-ENDDB (the Earth's Natural Disasters DataBase — a database of disastrous events: earthquakes and impact structures) [1] are functioning in various scientific and educational organizations. Its implement methods of statistical spatial-temporal analysis of the characteristics of the seismogeodynamic process: both the classical (parameters of the repeatability graph, the total number of earthquakes, the total seismic energy, methods of transformation of geophysical fields, etc.) and the new (the relative total seismic energy and

its gradients; maximum earthquake depths, the total slip direction in seismic foci, methods of grouping events into seismolineaments, swarms, clusters; methods of correlation analysis, etc.). Recently, a method for calculating the normalized creepex was implemented in the GIS system, which complements the complex seismogeodynamic analysis with maps and graphs of changes in this parameter in order to identify the relationship of seismic events with the tectonic environment (by the distribution of its anomalies in space), as well as the regularities of the seismogenesis processes before and after a strong event (by a change in the parameter in time).

2. The concept of creepex, its applicability and modifications

A formally constructed parameter of creepex (creep & explosion) is determined by the ratio of magnitudes M_S and m_b:

— by the difference $Cr_0 = M_S - m_b$ [2] (other types of magnitudes for volume waves are also allowed [3]);
— by the residual of these magnitudes in the orthogonal regression $Cr = M_S - k \cdot m_b - l$ [4].

From a mathematical point of view, a creepex is a difference of quantities of the same dimension, but with a different physical content. In fact, it is a normalized logarithm of the ratio of different estimates of the earthquake energy. The energy parameters of MS and mb are determined by different types (surface and volume) waves at different frequencies (a low-frequency range for MS: usually with a period of 20 s; and a high-frequency range for mb: usually with a period of 1 s). The ratio of MS and mb indicates the predominance of low or high frequencies in a spectrum, indicating macroseismic processes with the creep or the explosion effect, respectively. This allows the parameter to be used, for example, for reliable explosions identification on the background of seismic events of natural and anthropogenic origin. The spectral characteristics of the processes of fast and slow disruptions of the geophysical environment continuity act as an information carrier in the identification criteria. The extremely fast destruction by explosion is accompanied by the emission of high-frequency seismic vibrations, the extremely slow one is by a plastic flow, i.e. a creep, which in the extreme case is not accompanied by the high-frequency seismic emission (episodic tremor and sliding). But the information content of the creepex is much broader, since M_S and m_b are evaluated by seismologists based on the spectral characteristics of the wave forms associated with an earthquake, each reflecting the specific features not only of an earthquake itself, but also the conditions of its origin and propagation in the "muddy" (according to [5]) geophysical environment.

Thus, Cr_0 and Cr are those simple parameters of the spectral characteristics of the earthquakes that can be used in the statistical approach to studying of seismicity to assess a relative contribution of "soft" (creep) and "hard" (explosion) movements to the overall process of focal radiation. Thus, the dominance of increased values of the creepex in the region under study, reflecting the predominance of low frequencies in the earthquake spectrum, is a sign of tectonic "softness" [3]. Indeed, in [6, 7], it is confirmed that in transform faults with a shift deformation or spreading zones, the tectonic movement in which generally exhibits the property of "aseismic creep", seismic sources have a much higher value of the creepex than in subduction zones

characterized by a "cold" brittle fracture. On the other hand, the reason for the local differences in the creepex distributions "be sought for in different conditions for generating seismic waves in specific foci — the type of strength or mechanism of the focus" [2, 3]. This means that local Cr deviations are "a measure of the specificity of the focal zone", and spatial-temporal changes in the parameter will be "due to the conditions variations in the focal zone on the radiation of compression and shift waves" [7]. However, a "balanced" approach is also necessary here, since the accuracy of the Cr estimate for an individual event, determined by the error in calculating M_S and m_b, can be "both objective and subjective" [7, 8].

There are many factors leading to the dependence of the radiation efficiency of a seismic source on the scope of events, for example, the effect of absorption and scattering of high frequencies during the oscillations propagation [9]. In addition, there are some methodological problems in estimating the seismic energy of earthquakes, for example, its systematic overestimation in an elastic medium in comparison with a viscoplastic one [10], etc. Such factors can be the reason for the long-discovered nonlinearity of relationships between magnitudes of different types [11]. Thus, studying earthquake catalogs created by many agencies has shown that the difference between the magnitudes M_S and m_b depends on the earthquake magnitude M_S according to the linearly growing law [3, 8]. This dependence complicates the use of the creepex parameter in statistical studies, making it difficult to adequately interpret its anomalies without a special consideration of the magnitude of each event in a sample.

To solve this problem, a modified (normalized to the arithmetic mean of M_S and mb of each event) estimate of the creepex parameter $Cr_N = 4(M_S - m_b)/(M_S + m_b)$ was proposed in [8] which somewhat reduced its systematic dependence on the earthquakes magnitude M_S (especially pronounced for large events), but did not completely eliminate this dependence, transforming it from linear to logarithmic (Figure 1).

In this paper, the following modifications of the creepex parameter are proposed and compared.

1. $Cr_0 - Cr_{0\_world}$ and $Cr_N - Cr_{N\_world}$ is the result of reducing the parameters Cr_0 and Cr_N of each event to the world average values of the creepex, obtained from the polynomial dependence of Cr_{i_world} $(i = 0, N)$ on M_{S_world} (Figure 2, a), where Cr_{i_world}
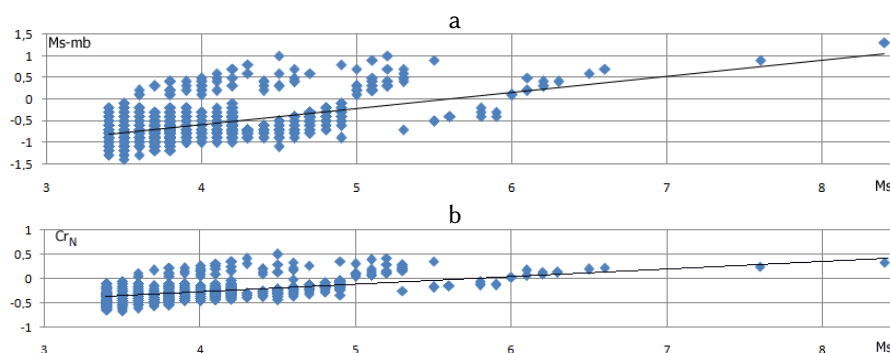

Figure 1: The dependence on the magnitude M_S of the creepex-parameters Cr_0 (a) and Cr_N (b) by an example of the Tohoku earthquake vicinity (1458 paired determinations: 11.03.2010–11.03.2012, 30–50°N; 140–160°E).
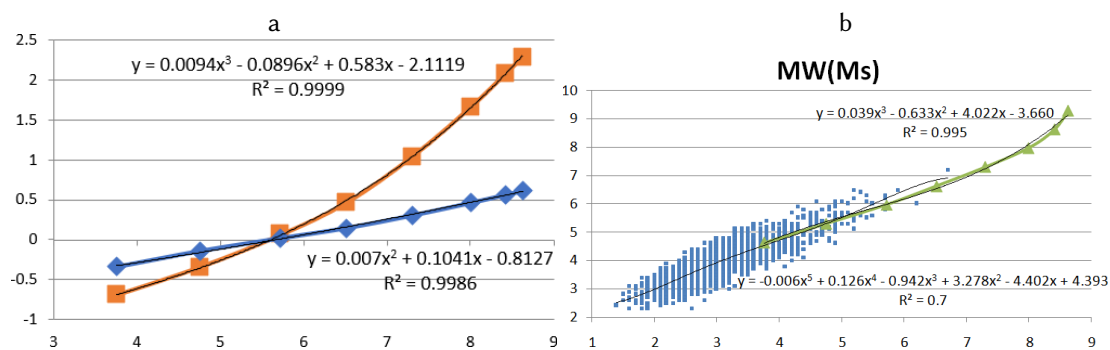
Figure 2: The polynomial dependences: a — on the average world magnitude M_{S_world} of the creepex-parameters: $Cr_{0\_world} = M_{S\_world} - m_{b\_world}$ (red) and Cr_{N_world} (blue); b —of the world average magnitude M_W on the M_{S_world} (green) and of the magnitude M_W (calculated from M_L) on $M_{S\_}$ (M_S corrected for the trend level) for all the events in the BJI catalog (blue).

are calculated based on the world average estimates of M_{S_world} and m_{b_world} [11] at uniform intervals of the seismic moment (NEIC catalog).

2. $Cr_b ji$ — the result of reducing Cr_N of each event to Cr_{N_bji}, i.e. to the average (for the studied in this work BJI catalog [12]) creepex values obtained from the polygonal trend $Cr_N(M_S)$ (black line in Figure 2, b) of all the catalog events.

3. Comparative analysis of creepex modifications, examples of their application

Comparison of the proposed parameters can be carried out both from the view point of solving the problem of the creepex dependence on magnitude, and based on the correspondence of the creepex variations to the known physical processes in the foci of specific events, investigated by different methods of a geographic information system.

The dependence M_S of different creepex versions is shown in Figure 3 using an example of the aftershock swarm of the January 21, 2007 earthquake ($M_S = 7.5$) in Molucca according to the BJI catalog. The reduced to the average trend of the BJI catalog creepex value $Cr_N - Cr_{N\_bji}$ demonstrates a less pronounced dependence on magnitude than the parameter Cr_N, while maintaining the character of monotonic growth with an increase in the magnitude of the event (Figure 3, a).

On the contrary, the creepexes, reduced to the global data (calculated by NEIC [11]): $Cr_N - Cr_{N\_world}$ and $Cr_0 - Cr_{0\_world}$ demonstrate (Figure 3, a) the suppression of the monotonic growth at large magnitudes, resulting in distortion of information about the creepex for large events. This may be due to a systematic difference in estimates M_S presented by different catalogs (here, by BJI and NEIC ones). It is possible, of course, to find the correspondence of these estimates by the coincidence of the trends in their relationship with a more objective by defined magnitude M_W (Figure 2, b). We have estimated the latter according to the magnitude M_L presented in the BJI catalog. It was found that, in contrast to the dependence $M_W(M_L)$: $M_W = M_L - 0.4$ according to Abubakirov et al. [13], for BJI a good agreement of the trends
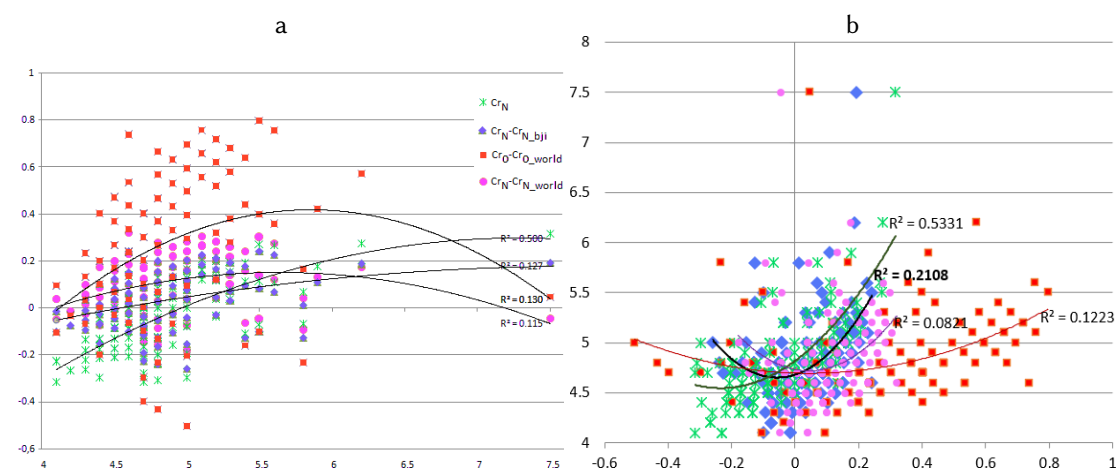
Figure 3: Dependence on the magnitude MS of various creepex parameters: Cr_N, $Cr_N - Cr_{N\_world}$, $Cr_0 - Cr_{0\_world}$ and $Cr_N - Cr_{N\_bji}$ on an example of the aftershock swarm of the earthquake of 21.01.2007, $M_S = 7.5$ in Molucca.

in the area of their intersection is given by the formula $M_W = M_L + 0.5$. If we accept $M_W = M_L - 0.4$ [13], then it is necessary to decrease the estimate M_S in the BJI catalog by 1.2: $M_{S\_} = MS - 1.2$ (Figure 2, b). For m_b in this case, a correction -0.4 is required. The introduction of such significant corrections brings about a large shift of the creepex Cr_N value (and, largely, of the value Cr_0) into the area of negative values. Conversely, reducing the values Cr_0 and Cr_N to average the Cr_{world} and Cr_{N_world} world creepexes, obtained from relatively high magnitudes, leads to a shift of the obtained estimates into the positive area (Figure 3, b; yellow and gray lines in Figure 4, a). Apparently, the events distribution shifted in one or another direction does not correspond to the equal importance of the contributions (to seismicity, in general) of two physical processes: a brittle fracture and a viscous slip. Thus, from the viewpoint of the expediency of using the creepex, it does not allow to visually classify events according to relevant two groups using the obtained parameters.

So, the idea of reducing the creepex to the average value over the world catalogs (NEIC) for the events of the BJI catalog cannot be accepted because, although it removes the dependence of the creepex on M_S, leads to a systematic shift of its normalized estimate to the area of negative or positive values. Now consider the graph in Figure 3, b showing the advisability of reducing the creepex to the trend of averaging the itself magnitudes of the catalog used, in this case: $Cr_{bji} = Cr_N - Cr_{N\_bji}$. The distribution of this parameter (its trend is highlighted by a bold line) has no displacements about the zero axis.

Examples of the application of the compared parameters in specific seismic geodynamic studies on various aftershock processes (Figure 4) also demonstrate the advantage of the parameter Cr_{bji}. The first, strongest shock (marked with vertical lines in Figure 4) on the graphs of Cr_N and Cr_{bji} (red and blue colors) is marked by a regular significant increase in the creepex value (which shows a large contribution of quasi-plastic flow to the mechanism of main shocks, and sometimes of several subsequent shocks), after which a gradual (over several hours) decline occurs, characterizing the beginning of the medium conversion to brittle fracture
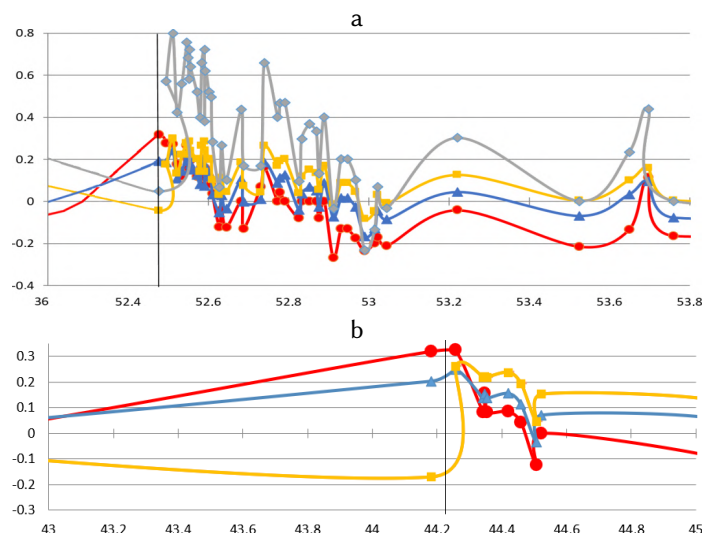
Figure 4: Changes in various creepex parameters in time. a — a 1.5-day fragment of the aftershock swarm of the earthquake of January 21, 2007, $M_S = 7.5$ in the Moluccan Sea, Indonesia (at the junction of the Eurasian plate and the Papua microplate): Cr_N (red color), $Cr_N - Cr_{N\_world}$ (yellow), $Cr_0 - Cr_{0\_world}$ (gray) and Cr_{bji} (blue); b — a 0.5-day fragment of the aftershock swarm of the Simushir earthquake of January 13, 2007, $M_S = 8.1$ (at the junction of the Okhotsk and the Pacific plates): Cr_N (red), $Cr_N - Cr_{N\_world}$ (yellow) and Cr_{bji} (blue).

(developed the next day). A similar mechanism was established as a result of a more detailed geodynamic study of the Kashmir earthquake (08.10.2005, $M_S = 7.6$) carried out by means of the GIS-ENDDB system (Figure 5).

The temporal distribution of aftershocks of the Kashmir earthquake (Figure 5, a) clearly demonstrates the relaxation process of the source in the first hours after the main shock by partial, periodic chains of events with a decreasing value of the creepex Cr_N within a chain. According to a change in the value Cr_N, the chains demonstrate the transition from quasi-plastic flow to brittle fracture, according to the general interpretation from [6]. Let us note that a number of studies [14, 15] mention periodic activations of the after-shock process of the Kashmir earthquake and the impossibility of explaining its without introducing special corrections into the seismodynamic model (in particular, the "slip variability" correction, "repeated slip", etc.) or the assumption of the existence of a highly fluid layer in the lower crust.

The connection of the initial events of each chain with quasi-plastic processes at depth is also proved by their depths: the temporal distribution of the ISC catalog events near the focal zone shows that at the beginning of each chain there is a deeper event than the subsequent ones in the chain, and the main shock of the Kashmir earthquake, although confined to the depth of the brittle layer ($H = 8.2$ km according to ISC data), is preceded by two foreshocks (3 hours before the event), which have a greater depth: 15 and 14 km (Figure 5, b). Let us also note that according to the data of the CMT global catalog [16], the mechanisms of the overwhelming number of events in the Kashmir earthquake source are an upthrust (Figure 5, c), determined by the tectonic setting of collisional compression, covering a large range of depths.

The graph of Cr_{ISC} changes over time is more smoothed (the red line in Figure 5, d) than
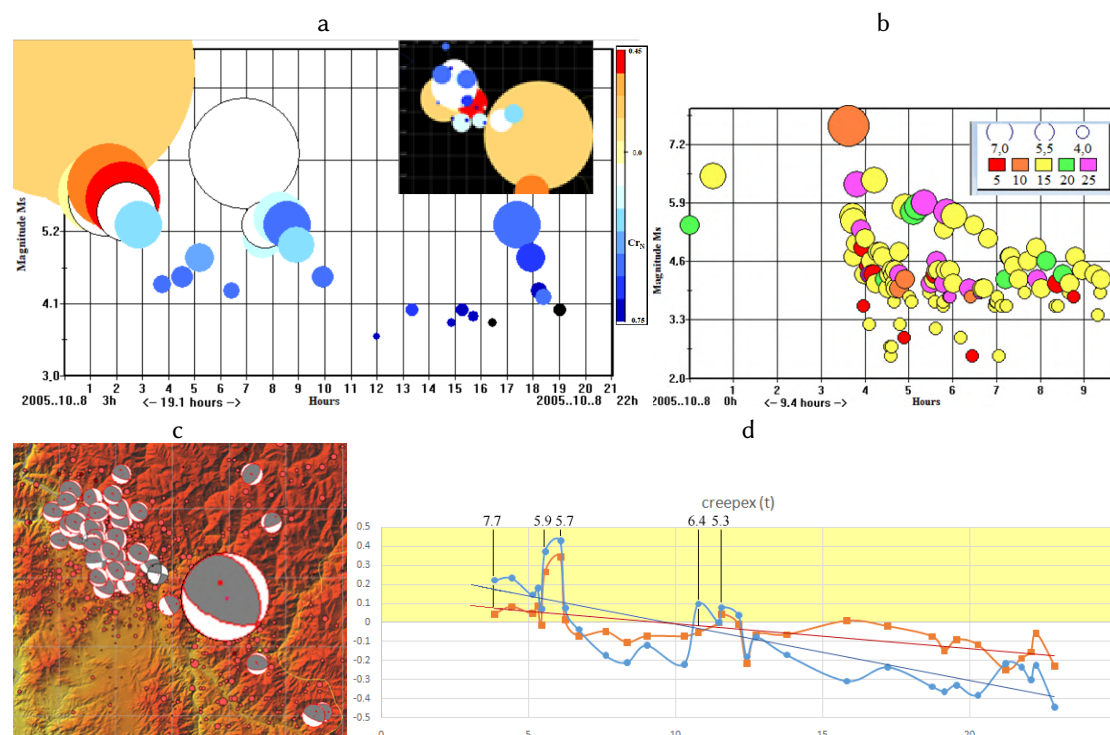
Figure 5: Development in time (the first day) of the seismogeodynamic process in the focal zone of the Kashmir shock (*lcreepex* catalog containing the paired ISC definitions of M_S and m_b): a — the events colored by the creepex value Cr_N, where the size of the circles is set by the focal zone size estimated by M_S [17]; in the inset picture: distribution of these events in the map (all the pictures were obtained by the GIS-ENDDB analysis system); b — all events of the ISC catalog in the study zone colored by depth (color and radius are determined by the legend: H in km by color, M_S by size); c — the mechanisms of the Kashmir earthquakes for 2004–2016: d — a change in the values of Cr_N (blue) and Cr_{ISC} (red) in the sample of Figure 5, a.

the Cr_N graph (the blue line), since stronger events at the beginning of each chain are not manifested here by the creepex increase (because there is no proportional dependence of the creepex on the magnitude). Apparently, the Cr_{ISC} graph more objectively reflects the physical processes in the focus: the main shock (which is marked by the first point of each chart) does not show up on the Cr_{ISC} chart as either a positive or a negative maximum. But 1.5 hours after it, the sharp maximum marks the greatest contribution of the viscous slip to the mechanism of a pair of synchronous aftershocks ($M_S = 5.9$ and $M_S = 5.7$) located along the perimeter of the focal zone of the main shock (red and orange circles in the inset picture of Figure 5, a), which can characterize a sharp change in the environment state caused by the destructive upthrust of the main shock. Another 5 hours later, an aftershock with $M_S = 6.4$ (the beginning of the second chain of aftershocks in Figure 5, a) occurs just to the northwest of the main shock, which also does not show up on the Cr_{ISC} chart as a positive maximum, but an hour after which there is a jump of Cr_{ISC} to the area of positive values (Figure 5, d). It is possible that both of these maxima show a pattern of occurrence of aftershocks with an increased creepex value after the largest aftershocks.

4. Conclusion

The creepex is an informative parameter reflecting the properties of the geophysical environment, the dynamic processes in which are manifested in the spectral features of waveforms generated by earthquakes. Obtaining a quantitative measure of information extracted from the creepex requires taking into account the peculiarities of the used information base: catalog of earthquakes. This paper shows the advantage of using the creepex parameter, reduced to the trend of averaging the magnitudes of the catalog in question, since a smaller linear dependence of the creepex on the magnitude is achieved (in comparison with classical creepex) and a symmetry is preserved in the maximum amplitudes of the parameter deviation relative to zero. The choice of the most informative modification of the creepex parameter and its implementation into the expert information and computing system GIS-ENDDB will provide the possibility: to calculate and visualize the distribution of the creepex parameter in space and time; to trace its retrospective dynamics in various regions, including that in the zones of preparation and development of strong earthquakes; to identify possible predictive patterns in the resulting anomalies. For example, the researching Kashmir earthquake (08.10.2005, $M_S = 7.6$) by means of the GIS-ENDDB system demonstrates in terms of the creepex value change the patterns of medium transition from quasi-plastic flow to brittle destruction after a major shock.

Acknowledgments

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