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Correlated Impacts Optimizing the Transformation of Block Medium Dynamics into Creep Regime

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Abstract—This study continues the mathematical justification of a promising concept of the initiation of displacements in fault-block media for providing a local decrease in the elastic energy and reduction of the seismic danger. The system is numerically simulated within the framework of a minimalistic variant of the model formulated previously based on an analysis of the dynamics of one tectonic platform moving on another. The proposed model well describes the known statistics of behavior of the relevant geological media and reveals correlations in the propagation of a dynamically active front. These correlations have been used to select optimum scenarios of the necessary weak local energetic action. This approach significantly increases the efficiency of this type of initiation for the transformation of the block dynamics from the stick-slip to the creep regime, as a result of which the average energy of seismic shocks significantly decreases. This makes the "suppression" of strong earthquakes possible in principle.

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Recently, we proposed [1] a mechanical model that quite adequately described the laws of deformation for a block system and the temporal correlations typical of self-organized critical systems. The proposed model differs in principle from those studied previously (see, e.g., [2–11]) by taking into account the real topology of the creep of a continental platform on a thinner oceanic platform. The concept of this model can be outlined as follows. An external force $F_{\rm ext}$ moves a platform on an elastic plate. The boundary between the plate and platform is sloped at an angle of α, which determines the ratio of the vertical force component $F_{\rm ext}\cos(\alpha)$ (acting against the Archimedean buoyancy force $F_{\rm arch}$, which holds the platform floating on the magma) and the horizontal component, which produces a shift and deformation of the whole system along the x axis.

For numerical modeling, the plate is represented by a set of discrete elements connected by nonlinear elastic forces. A realistic three-dimensional (3D) model has been developed that takes into account the y coordinate of the moving front. In this variant, faults appearing in the (x, z) planes interact with each other. To the first approximation, we can assume that the 3D system consists of a set of equivalent 2D systems, which only interact via the common front at the contact with the (continental) platform. In this approximation, a minimalistic model has been formulated, in which the interactions between (x, z) layers is taken into account in the rules determining the motion of fragments. It was demonstrated that this model reproduced the main features of the 3D model and, furthermore, is sufficiently compact to make it possible to conduct a large volume of numerical experiments. The model has proved to be robust with respect to the variation of parameters in a broad range.

The proposed model allows for the method of induction of local jumps inherent in the 3D model to be retained; that is, the period and distance between the external impacts can be selected so as to initiate a wave of small jumps leading to the almost regular propagation of the step of displacement for the entire front. The simplicity and numerical efficiency of this model can be used for obtaining the statistics of correlations in the motion of separate blocks at the front. These correlations, in turn, can be used for selecting an optimum scheme of external action leading to the transformation of the system dynamics into a creep regime. This study was devoted to an analysis of these issues.

Consider a 2D front in the (x, y) plane, each segment of which is moved forward by an overdamped external force $F_x^{\rm ext}$. Let us assume that every subsequent "tectonic" jump of each segment takes place upon its displacement (with respect to the end of the previous jump) by a certain distance $\varepsilon^{(1k)}$, which is generated by a random number generator with zero mean ($\langle\varepsilon^{(k)}\rangle = 0$), so that

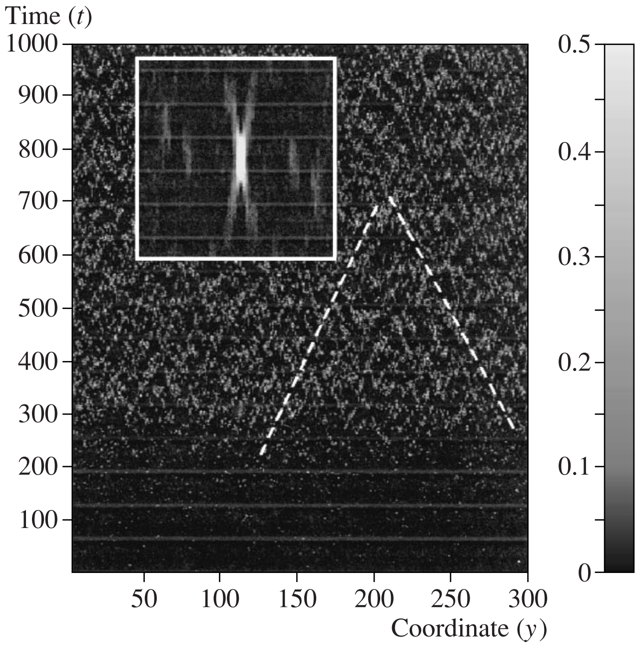

Fig. 1. Spatiotemporal map of jump distribution represented by the $M(t, y)$ matrix, with the intensities indicated by gray tint scale on the right. The initial stage corresponds to establishment of a stationary process. Dashed lines correspond to the characteristic velocities of wave propagation (pre- and aftershocks). The inset shows the corresponding $G(t, y)$ correlation function.

$$\langle \varepsilon^{(k)}(t)\varepsilon^{(k')}(t')\rangle = D_\varepsilon \delta_{kk'}\delta(t-t'). \quad (1)$$

The jump magnitude $\psi(k)$ is also assumed to be a random quantity with zero mean ($\langle\psi(k)\rangle = 0$) and is set by average noise intensity ($D_\psi < D_\varepsilon$) as follows:

$$\langle \Psi^{(k)}(t)\Psi^{(k')}(t')\rangle = D_\Psi \delta_{kk}\delta(t-t'). \quad (2)$$

The angle brackets $\langle\ldots\rangle$ in Eqs. (1) and (2) denote averaging over the ensemble of events, $\delta(\ldots)$ is the Dirac function, δ_{xz} is the Kronecker symbol, and $D_{\psi,\varepsilon}$ is the intensity of noise that has to be reconstructed a posteriori from experimental data. Following [1], we assume that points $X^{(k)} = X(y_k)$ at the front are related by the elastic force

$$f_\varepsilon = K[X^{(k+1)} + X^{(k-1)} - 2X^{(k)}]. \quad (3)$$

Further details of the model are also as described in [1].

The initial condition was selected in the form of a planar front, the motion of which was described in detail previously (see [1, Fig. 4)] and related comments). The spatiotemporal map of jump length distribution along the front is depicted in Fig. 1. At every step of the numerical procedure, system (1)–(3) is solved and a set of tectonic displacements $\delta X^{(k)}$ (including zero shifts) distributed along the y coordinate is obtained, which represents a row of the $M(t, y)$ matrix at the given time. This procedure is repeated and the entire geological history of the system is recorded in the form of an $M(t, y)$ matrix mapped against the scale of gray tints (Fig. 1, intensity scale). This spatiotemporal map exhibits a clear initial transition period. A particular scenario is determined by the initial configuration (here, a planar front). As can be seen from Fig. 1, the stationary regime reveals a well-pronounced correlated character. The neighboring regions at the front interact by means of the elastic force (3), so that large jumps of one segment induce several jumps in the neighboring segment that propagate as decaying waves in both directions from a strong local "earthquake."

Arriving at a certain "weak" segment, i.e., a segment potentially close to a spontaneous break, such waves can initiate this break, thus inducing a new coarse "tectonic shear" with accompanying waves and so on. In other words, each significant event in the system is sur-

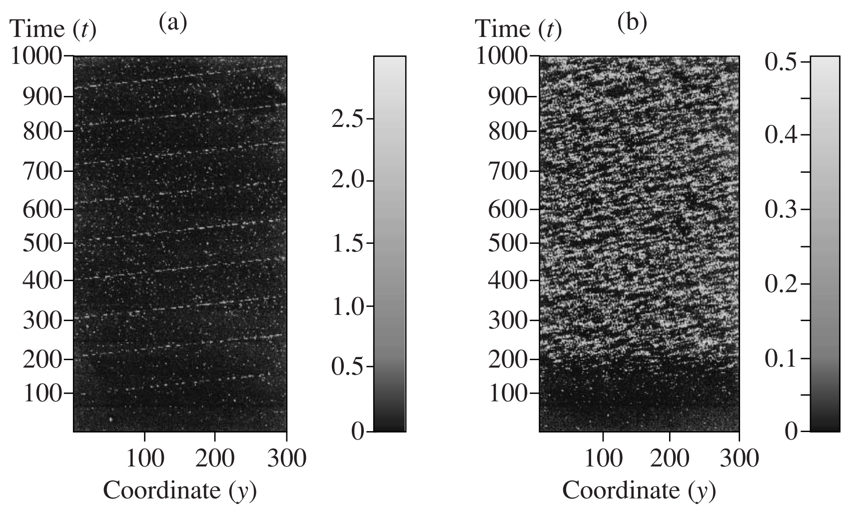

Fig. 2. Same as in Fig. 1, but in the presence of artificial impacts initiating local jumps of the front segments in the case of (a) regular shift of the impact site along the entire front and (b) adaptive reaction to events selected using the $G(t, y)$ correlation function.

rounded by a set of pre- and aftershocks that lead to correlations in the $M(t, y)$ matrix. Dashed lines in Fig. 1 correspond to the characteristic velocities of wave propagation. Although the velocity of these waves is not universal and varies depending on the constants in Eqs. (1)–(3), their very existence is a consequence of the structure of the system under consideration. Physically, the velocity of correlation spreading depends on the composition and strength of rocks, the level of friction forces between blocks, etc.; therefore, each geological region has a certain characteristic velocity, which can be determined from experimental statistics of local secondary shocks accompanying earthquakes. The correlation can be quantitatively described by a spatiotemporal correlation function $G(t - t', y - y') = \langle M(t, y)M(t', y')\rangle$ such as the one depicted in the inset to Fig. 1. This correlation function was calculated for a particular realization of the $M(t, y)$ matrix over the $t - t_0$ time interval (beginning with the time t_0 upon termination of the transient process). The gray scale reflects the absolute values of correlations between jumps at the front. The slopped ridges of density $G(t, y)$ on both sides of the central maximum correspond to the averaged (typical) velocities of propagation of the interacting events in the given system.

The aim of our investigations is the practical usage of a theoretically justified effect of weak controlled spatially localized impacts on a given system. Previously [1], we modeled the effect of periodic pulses of variable intensity and preset on/off ratios. If the action is localized in a single (x, z) layer, this layer gradually proceeds forward and pulls the neighboring layers behind so as to form a protrusion on the $X^{(k)}$ front. Then, increasing deviations $X^{(k+1)} + X^{(k-1)} - 2X^{(k)}$ are suppressed by the elastic coupling, so that the protrusion is gradually suppressed by the neighboring layers. Nevertheless, we succeeded in suggesting a strategy [1] that retained the applicability of the proposed method in a distributed system. For this purpose, each subsequent point of action was shifted over several (x, z) layers along the front so that a small jump would be initiated at a different site of the front, stimulating new neighboring regions. This shift was selected in both the 3D model and its reduced variant.

Figure 2a illustrates such an artificially stimulated process in the same system (and same notation) as in Fig. 1. Here, the clearly distinguished straight lines correspond to periodic impacts regularly shifted along the front, which virtually completely suppress the spontaneous jumps in the systems. Unfortunately, this scenario requires large-scale preliminary works irrespective of whether the probable earthquakes will actually take place. At the same time, the correlations of spontaneous events suggest a constructive idea; it is possible to apply the artificial impacts at the sites of statistically anticipated aftershocks rather than over the entire front, thus only producing a controlled initiation of small jumps at the sites where these jumps are stimulated by intrinsic correlations.

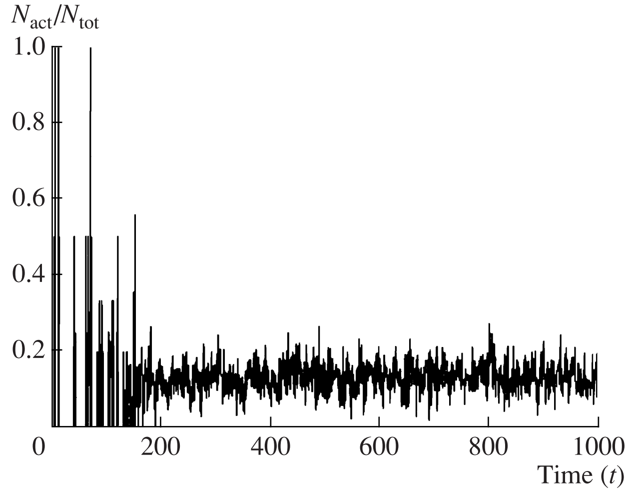

Fig. 3. Temporal variation of the fraction of spontaneous jumps not prevented by the proposed adaptive scenario (mapped in Fig. 2b). In the initial transient stage, the events are not yet correlated and the fraction of spontaneous jumps can be large (reaching unity), while in a stationary stage this fraction falls within 0.1–0.2.

Figure 2b shows the distribution of events caused by such a self-consistent action. This pattern appears as more densely filled with jumps as compared to that in Fig. 2a. However, the scales of jump lengths in Figs. 2a and 2b are also substantially different. The main consequence of this procedure is a sharp drop in the fraction of spontaneous events taking place when the system reaches the level of critical stresses. Figure 3 shows the temporal variation of the number of such events that were not prevented by the aforementioned economic adaptive scenario. As can be seen, the relative fraction of critical events is formally large (even reaching unity) only in the initial transient stage, where the events are not yet correlated. However, this stage is an evident artifact of the numerical procedure with a planar initial front (since the initial configuration was a priori not known). In a stationary stage, where the system attains a self-consistent regime, the fraction of spontaneous jumps not prevented by the economic adaptive action falls within 0.1–0.2. In other words, the economic scenario allows 80–90% of spontaneous earthquakes in the system to be prevented.

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