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Sine-Gordon modulation solutions: application to macroscopic friction, regular and slow earthquakes and fault dynamics

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The Frenkel-Kontorova (FK) model and its continuum approximation, the sine-Gordon (SG) equation, are widely used for modeling various phenomena. In many practical applications the wave-train solution, which includes many solitons, is required. In such cases the system of Whitham's modulation equations, superimposed on the SG equation, provides such a solution. Here we consider several applications which use the SG modulation solutions [1-3].
Fault dynamics in the earth's crust, i.e. the nucleation and development of regular and slow earthquakes, is a complicated multidisciplinary problem which has been investigated using diverse approaches. Our approach, inspired by dislocation dynamics in crystals, is based on the FK model introduced to describe plasticity. In the model we propose, sliding occurs due to the movement of defects of a certain type (i.e. areas on the frictional surface with locally stressed material, known as a macroscopic dislocation or slip pulse) nucleated by shear stress in the presence of asperities. The spatial translation of a dislocation requires only a small fraction of the stress necessary for the uniform relative displacement of frictional surfaces. This is a fundamental distinction between our approach to macroscopic dry friction and those of others such as the Burridge-Knopoff and rate-and-state types of models.
We show how this model can be applied to the qualitative and quantitative description of fault dynamics in general, and slow and regular earthquakes in particular. The three fundamental speeds of plate movement, earthquake migration, and seismic waves are shown to be connected in the FK model. The velocity of nonelastic stress propagation along faults is a function of accumulated stress. It changes from a few km/s during earthquakes to a few dozen km per day, month, or year during afterslip and inter-earthquake periods. The distribution of aftershocks in this model is consistent with both the Omori law for temporal distribution and a 1/r low for spatial distribution. We also discuss how the model explains the difference between the scaling laws for regular earthquakes and slow slip events, the periodicity of episodic tremor and slip (ETS), and the diverse tremor migration patterns during ETS events. Finally, we consider the nature of non-volcanic tremor, both ambient and accompanied by ETS.

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