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Elastic waves induced transport along slab-like solid-gouge interfaces

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ABSTRACT

Theoretical derivation of the perturbed transport due to a sudden weak impact in a presumed slab-like region filled with solid-gouge and vacancies was conducted. The induced transport which is of the second order is created by a small-amplitude surface elastic wave propagating along the flexible interface by considering the weakly nonlinear coupling between the interfaces and the slip effect. **We simplify the original system of lower-order partial differential equations (related to the momentum and mass transport) to one single higher-order quasi-linear partial differential equation in terms of the unknown stream function.** Via numerical searching we identify the possible critical threshold values for zero-flux states corresponding to certain Navier-slip parameter and wave number which could be relevant to the possible seismic reversal or disappearance of moving of solid-gouge. Our numerical results are useful to the seismic pattern recognition together with synthetic earthquake catalogs.

1. Introduction

Human local activities like removal of forest cover, mining, reservoirs, forestry, agriculture, and urbanization can cause spatio-temporal variations or changes in discharge regime and sediment flux leading to morphological adjustments. Nevertheless the influence of the latter or the interactions with the earthquake triggering are yet open question. An applicable model of an earthquake is based on the presence of an unstable fault in the crust that, under stress concentration, will eventually slip generating the earthquake [1].

1.1. General Problems

Recently the methodology of selecting and processing of useful information about the possible occurrence of potentially damaging or strong earthquakes [2–4] has reached a reasonable level of maturity. Nevertheless, the problem we encountered still lacks a comprehensive and generally accepted solution [5]. For example the investigation of a strong earthquake (which will destruct water resources as well as vegetation like agriculture and forest) is linked to the following observations and spatio-temporal patterns (reflecting the changes in the basic characteristics of seismicity), such as the rise of response to excitation, reversal of territorial distribution of seismicity, rise of earthquake clustering in space and time, transformation of frequency–-magnitude relation (which favors relatively stronger earthquakes), rise of irregularity in space and time, etc. [6] Therein a reversal of territorial distribution of seismicity or seismic reversal (SR) will consist of the rise of activity in the areas (e.g., faults), where average activity is relatively low, and vice versa, drop of activity on the relatively active faults; while an earthquake clustering concerns the tendency of the earthquakes to occur closely in time and space. We remind the readers that the SR pattern has been found in seismicity of Lesser Antilles [6].

1.2. Seismic Reversal and Mass Movement due to Defects

Furthermore there might be the Riecke effect–increasing of solubility of rocks due to an imposed pressure. This specific effect can thus lead to a mass movement: Solid material is dissolved under high enough stress and will be carried out in solution along the stress gradient to regions of smaller stress where it precipitates. [6]. Meanwhile possible petrochemical transitions tie up or release the fluids, as in formation or decomposition of magnesium silicate hydroxide (serpentines), respectively. Others would cause a rapid drop of density, such as in transformation of calcium carbonate (calcite) into aragonite or vaterite. This might create a vacuum and unlock the fault; the vacuum will be closed at once by hydrostatic pressure, but the rupture could then be triggered [6]. Note also that in order to identify the time of occurrence and the magnitude of an impending stronger earthquake (e.g., the main-shock location and occurrence with sufficient accuracy), some methods have been applied to foreshocks with varying successes: for example, M8 together with its algorithmic derivations, and pattern informatics (see, e.g., [6–8]). The latter is related to seismic spatio-temporal pattern recognition [9] as well as synthetic earthquake catalogs approaches [10].

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1.3. Relevant Previous Contributions

Theoretical (using the kinetic approach) and experimental studies of interphase nonlocal transport phenomena which appear as a result of a different type of non-equilibrium representing propagation of a surface elastic wave have been performed since late 1980s [11,12]. These are relevant to induced perturbed transport flowing along deformable elastic slabs with the dominated parameter being the rarefaction parameter: N_s = mean − free − path$/L_d$, mean-free-path (mfp) is the mean free path of particles, L_d is proportional to the distance between two slabs [11]. The role of the rarefaction parameter is similar to that of the Navier slip parameter Kn [13,14]; here, $\text{Kn} = \mu S_0/d_i$ is the dimensionless Navier slip parameter; S_0 is a proportionality constant as $u_s = S_0\tau$, τ: the shear stress of the bulk velocity; u_s: the dimensional slip velocity; for a no-slip case, $S_0 = 0$, but for a no-stress condition. $S_0 = \infty$, μ is the viscosity, d_i is one half of the distance between upper and lower slabs.

1.4. Objectives

In this paper the perturbed mass movement driven by the wavy elastic slab-like interface or due to a sudden weak impact will be presented by numerical calculations. The flat slab-like region is presumed and the corresponding matter is filled with solid-gouge and vacancies with the interface being flat-plane like. The (net) gravity forcing is neglible due to the slab or interface is rather thin. Our numerical results will show that for certain time-averaged perturbed transport of the matter there might be existence of reverse states (the speed of the matter becomes zero and even negative at the center-line). The latter could be relevant to the possible seismic reversal or disappearance of moving of solid-gouge. Our numerical results are also useful to the seismic pattern recognition [9] together with synthetic earthquake catalogs [10].

1.5. Present Approaches

We adopt the macroscopic or continuum-mechanic approach and simplify the original system of lower-order partial differential equations (related to the momentum and mass transport) to one single higher-order quasi-linear partial differential equation in terms of the unknown stream function (Ψ). In present study, we shall assume that the Mach number $Ma \ll 1$, and the governing equations are the incompressible Navier-Stokes equations which are associated with the relaxed slip velocity boundary conditions along the interfaces [15]. We then implement the boundary perturbation technique so that we can obtain the related boundary-value-problem solutions approximately. To consider the originally external-force-free state for simplicity, due to the difficulty in solving a fourth-order quasi-linear complex ordinary differential equation (once the wavy interface or boundary condition being imposed), we can finally obtain approximately perturbed solutions and numerically calculate those physical quantities we have interests, like, time-averaged transport or entrainment, perturbed velocity functions, critical forcing corresponding to the freezed or zero-volume-flow-rate states.

2. Theoretical Formulations

In general the lithosphere of our Earth can be characterized as a hierarchy of specific volumes, from tectonic plates to grains of rock. Their relative mass movement against the forces of friction and cohesion is realized to a large extent through earthquakes. In fact the mass movement is controlled by a wide variety of independent processes, concentrated in the thin interface or boundary zones between specific volumes [16].

2.1. Preview of Mesoscopic Approach

The effects of elastic or deformable interfaces, like surface elastic waves (SEW) interacted with volume and surface phonons (propagating along the elastic boundaries), upon the entrained transport of fluids have been studied previously [11,12], however, the mathematical difficulty is essential therein. The role of elastic macroscopic walls resembles that of microscopic phonons. As presented in Borman et al. [12], for the description of the transport processes in the non-equilibrium gas-solid system including the processes occurring in the case of propagation of an elastic wave in a solid, we need to solve

$$\frac{\partial \bar{f}\,(\mathbf{x}, \mathbf{v}, t)}{\partial t} + \mathbf{v}\cdot\frac{\partial \bar{f}\,(\mathbf{x}, \mathbf{v}, t)}{\partial \mathbf{x}} = I_g(\{\bar{f}\,\}),$$
$$\frac{\partial n(\mathbf{x}, \mathbf{k}_j, t)}{\partial t} + \mathbf{c}_j\cdot\frac{\partial n(\mathbf{x}, \mathbf{k}_j, t)}{\partial \mathbf{x}} = I_v(\{n\}),$$
$$\frac{\partial H(\mathbf{r}, \mathbf{K}_\xi, t)}{\partial t} + \mathbf{c}_\xi\cdot\frac{\partial H(\mathbf{r}, \mathbf{K}_\xi, t)}{\partial \mathbf{r}} = I_s(\{f, n, H\}),$$

and the associated boundary conditions (scattering and interacting laws near the interface)

$$|v_r|\bar{f}^{\,+} = \int_{v_i<0} d\mathbf{v}_i|v_i|\bar{f}^{\,-}(\mathbf{v}_i)W(\mathbf{v}_i \to \mathbf{v}_r), \frac{|c_r|}{L_t}n^-(\mathbf{k}_j)$$
$$= \sum_{\mathbf{k}_{1j_1}(c_i>0)}\left[\frac{c_i}{L_t}n^+(\mathbf{k}_{1j_1}) + \overline{N}_g(\mathbf{k}_{1j_1}) + \overline{N}_p(\mathbf{k}_{1j_1})\right]V_p(\mathbf{k}_{1j_1} \to \mathbf{k}_j;\, \omega).$$

$\bar{f}$, n, and H denote the distribution function for gases, volume phonons, and surface phonons, respectively. I_g, I_v, and I_s are the corresponding collision integrals. Here, the kernel W represents the probability density of a transition of a molecule from a state with a velocity $\mathbf{v}_i$ to a state with a velocity $\mathbf{v}_r$ when the molecule is scattered by the surface, V_p is the probability of a transition of a phonon $\hbar\omega$ from a state $(\mathbf{k}_1, j_1)$ to a state $(\mathbf{k}, j)$ when the phonon is scattered by the surface and L_t, is the thickness of the solid. Please see the details in Borman et al. [12] for other notations or symbols. To escape from above (many-body problems) difficulties, we plan to use the continuum-mechanic approach and adopt the slip boundary condition which is a complicated extension of previous approaches [15] because we still consider the mean free path of the dilute vacancies corresponding to the nonzero slip velocity along the interfaces (which is similar to the incomplete accomodations of the momenta or energy for collisions or reflections of particles from the slab-like interface) which are approximated and represented by the Navier slip parameter or the slip velocities [13,14] here. Note that we use the same solving procedure for earth matter movement by earthquakes as in [15]. To be specfic, such a movement may be caused by different reasons (e.g., pressure redistribution by solidification of rock materials). Nevertheless we presumed that for actual rocks, the proposed mechanism is the dominant one.

2.2. Slab-like Interface Treatment

We consider a two-dimensional slab-like region of uniform thickness filled with a homogeneous matter (solid-gouge with vacancies). The equation of motion is

$$(\lambda_L + \mu)\text{grad div }\mathbf{V} + \mu\nabla\mathbf{V} + \rho\mathbf{p} = \rho\frac{\partial^2\mathbf{V}}{\partial t^2}, \tag{1}$$

where λ_L and μ are Lamé constants, $\mathbf{V}$ is the displacement field (vector), ρ is the mass density and $\mathbf{p}$ is the force for unit mass. The Navier-Stokes equations, valid for Newtonian matter, has been a mixture of continuum fluid mechanics ever since 1845 following the seemingly definitive work of Stokes and others [17], who proposed the following rheological constitutive expression for the fluid deviatoric or viscous stress (tensor) $\mathbf{T}$: $\mathbf{T} = 2\mu\nabla\mathbf{V} + \lambda_L\mathbf{I}\nabla\cdot\mathbf{V}$. The flat-plane boundaries of this matter-region or the slab-like interfaces are rather flexible and presumed to be elastic, on which are imposed traveling sinusoidal waves of

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