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Stick-slip process and solitary waves

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Abstract

The mechanism of seismic and various engineering processes are explained well by the theory of stick-slip. We investigated stick-slip process in experimental spring-slider system by recording acoustic emission, accompanying the slip events. In the onset of expanded acoustic recordings can be seen a pulse, which is repeated in other records also. We think that its existence must be associated with solitary waves. Soliton wave arises in the process of stick-slip, propagates along the contact surface between the plates and produces a maximum effect on the upper plate at its end point in the direction of sliding. These impacts may affect triggering of new stick-slip events. It is important to generalize the above considered phenomenon for the earthquake event and to use it for explanation of triggering mechanism of the earthquake.

Keywords: friction, stick-slip, triggering, soliton, earthquake

Introduction

The problem of friction between two surfaces which are in moving contact is very important scientific problem. When the frictional force is nonzero, the friction generally displays two different regimes: a stick-slip motion at low driving velocities and smooth sliding at high velocities. Stick-slip is caused by the surfaces alternating between sticking to each other and sliding over each other, with a corresponding change in the force of friction. This type of sliding has been studied at different scale levels. It seems that the more we learn about friction the more complex it appears (Urbakh et al. 2004). Recent advances in friction reveal that it plays a major role in diverse systems and phenomena. A stick-slip with friction at the contact of blocks is considered by many researchers as one of the most simplified analogs of the earthquake source. Earthquakes occur due to an instability in the deformation of rocks in the earth's crust. The two sides of the fault are driven laterally, in opposite directions, characteristic of a strike-slip fault. Two directions by which we try to understand the physics and complexity of earthquakes are in laboratory studies of rock friction and mathematical dynamic rupture modeling (Scholz, 1998., Marone, 1998). In the last decades increased interest in stick-slip instabilities present in laboratory rock experiments as a means of understanding earthquake ruptures. It is known that, likewise in stick-slip experiments (Ohnaka and Kuwahara 1990, Sobolev 1993, Shibazaki and Matsu'ura 1998), the local deformation effects related to a lower friction on an irregular contact between blocks can cause solitary waves along the contact.

It is well-known that the major portion of earthquakes occurs in accordance with the scenario corresponding to the model of unstable stick-slip on regularly shaped ruptures with the asperities of different size and strength. However, the reported theoretical slider-block models, that is, simple mechanical models of an earthquake fault, describe stick-slip as a motion of sliding blocks at a smooth stiff surface (Carlson and Langer 1989, Carlson 1991, Dieterich 1992, Hahner and Drossinos 1998).

The principal goals of the study are as follows: (i) modeling the mechanism generating solitary waves; (ii) modeling the observed stick-slip effects; (iii) attempt to explain the effect of stick-slip in the frame of solitary wave theory.

Models of stick-slip

The modern concept of seismic process relays mainly on the model of frictional instability, which develops on the preexisting tectonic fault (Brace and Byerlee, 1966) in contrast with the earlier assumptions on the brittle fracture of the crust material at attaining the critical stress. Modeling dynamic earthquake rupture at multiple scales requires combining many ingredients representing the physics at each scale. Traditionally, this is accomplished using a friction law. These relations, also known as constitutive laws, determine the shear stress on the fault, usually dependent on quantities such as the slip, slip rate, or other dynamic variables quantifying the internal state of the fault.

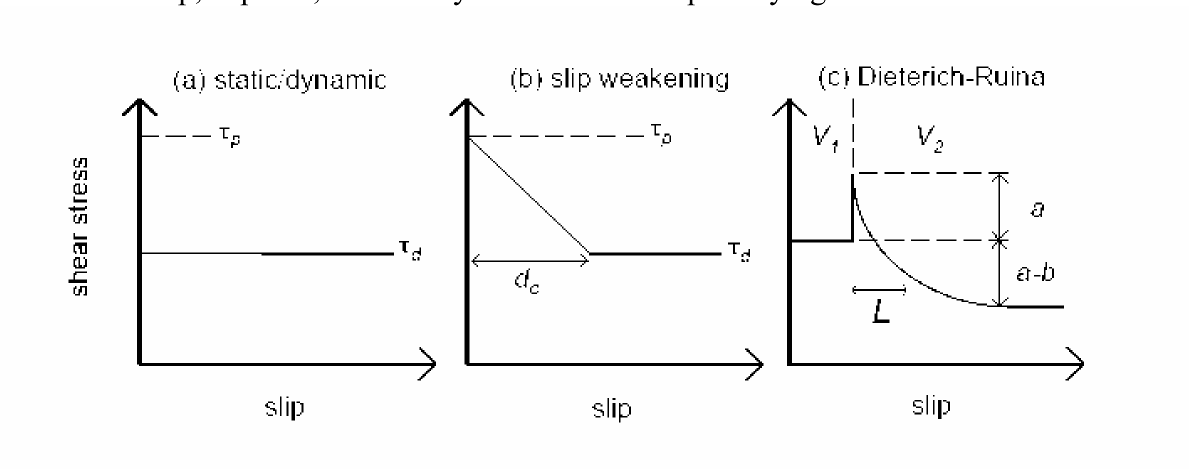

Fig.1. Friction laws for earthquake faults. (a) Static/dynamic friction. (b) linear slip weakening and (c) Dieterich-Ruina Rate and State law (Daub, 2009)

The simplest example of a friction law is the static/dynamic friction law from introductory physics. The shear stress is always proportional to the normal stress, and the proportionality constant μ (i.e. the coe_cient of friction) takes on two different values. While the two sides of the fault are in stationary contact, the coefficient of friction is the static coefficient of friction $\mu = \mu_s$ and once the surfaces begin to slip the friction drops to the dynamic coefficient of friction $\mu = \mu_d$. Linear slip-weakening has been used extensively to study dynamic rupture (Ohnaka, Kuwahara, 1990). The slip-weakening law is intentionally simple, and serves as a first approximation for how stress weakens with slip.

Analysis of the experimental data, obtained by investigating of spring-slider system motion, has lead to empirical law, named rate- and state-dependent friction law. The rate- and state dependent friction law assumes dependence on a single dynamic state variable in addition to the slip rate. This state variable captures the entire history dependence of friction through its evolution. The fundamental progress was made by experiments of Dietrich and theoretical analysis of Ruina, which show that the friction strength is rate-state dependent (Dieterich, 1979; Ruina, 1983):

$$\tau = \sigma_0\left(\mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)\right), \qquad (1)$$

where μ_0 is the initial coefficient of friction, V is the new sliding velocity, V_0 is the initial sliding velocity, θ is the state variable and D_0 is the critical slip distance, a and b are two experimentally determined constants.

The state variable varies according to:

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_0} \qquad (2)$$

Experiments to study the inhomogeneous friction were carried out on a spring-block model, whose scheme is shown in Fig.1.

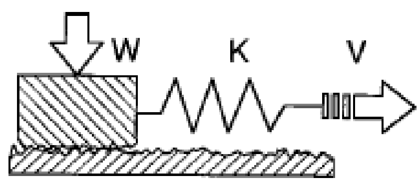

Fig.2. Schematic representation of spring-slider model. W is the weight of the sliding plate, K is the stiffness of spring and V is the velocity of the sliding plate

Depending on conditions (spring stiffness *k*, velocity of drag *V,* normal stress σ_n, slip surface state θ) three main types of friction are observed by displacement recording – stick-slip, inertial regime and stable regime, correspondingly, a, b and c in Fig.3.

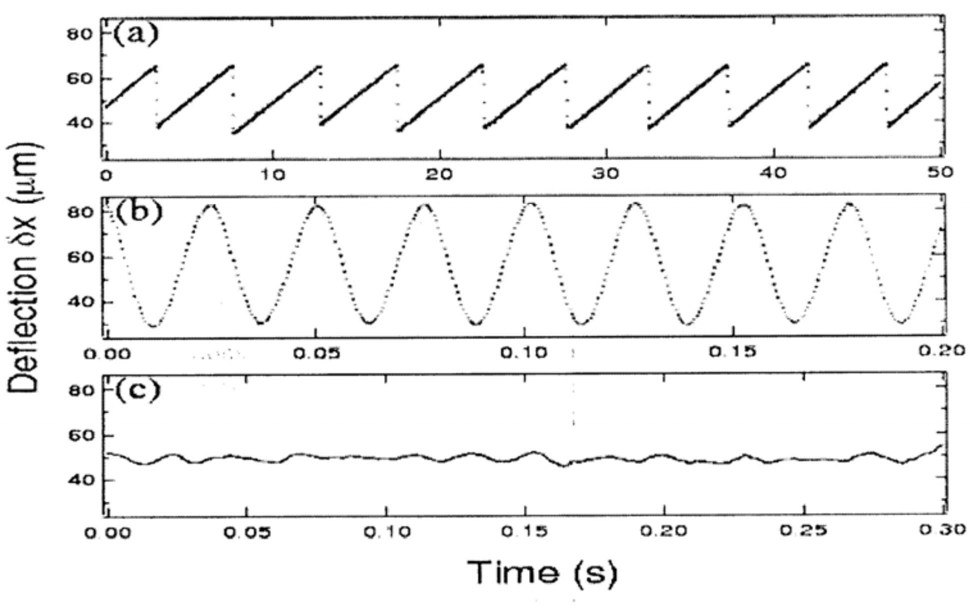

Fig. 3. (a) Stick-slip motion, (b) Inertia-dominated oscillation, (c) Steady sliding motion with fluctuations (Nasuno et al., 1998)

Fig.2 shows spring deflection δx, top plate position x and its instantaneous velocity V. Stick-slip regime is observed at relatively low velocities V and low stiffness. At higher V the transition to inertial periodic oscillations occurs; at still higher V we have the stable sliding with fluctuations.

Experimental setup

The dynamics of the sliding process in the spring-slider model depends on the dragging spring stiffness K and dragging velocity V (Boettcher and Marone, 2004). At low velocity, this process is of relaxation type, at intermediate velocity it is periodic, and at high velocity the sliding became relatively stable, with random deviations.

We investigated (mechanical) triggering and synchronization of instabilities in experimental spring-slider system by recording acoustic emission, accompanying the slip events; the setup is described in detail in Chelidze *et al.* (2006) and Varamashvili et al.,(2010). Experimental setup represents a system of two horizontally oriented plates (Fig. 4). The supporting and the slipping blocks were prepared from basalt; these samples were saw-cut and roughly finished. The height of surface protuberances was in the range of 0.1-0.2 mm.

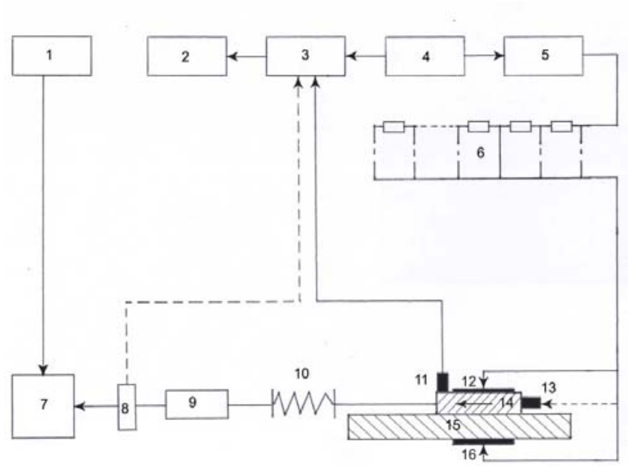

Fig. 4. Schematic representation of the experimental spring-slider model: 1 – Stabilized power source, 2 – personal computer, 3 – amplifier, 4 – forcing signal generator, 5 – external voltage generator, 6 – voltage divider, 7 – dragging device, 8 – tensometer, 9 – dynamometer, 10 – spring, 11 – piezoelectric sensor, 12 – electrode, 13 – vibrator, 14 – sliding block, 15 – fixed block, 16 – electrode.

A constant dragging force of the order of 4 N was applied to the upper (sliding) plate; In presented Figure (Fig.5a) is showing a recording of acoustic pulses of one experiment and in Fig.5b one acoustic pulse in expanded form.

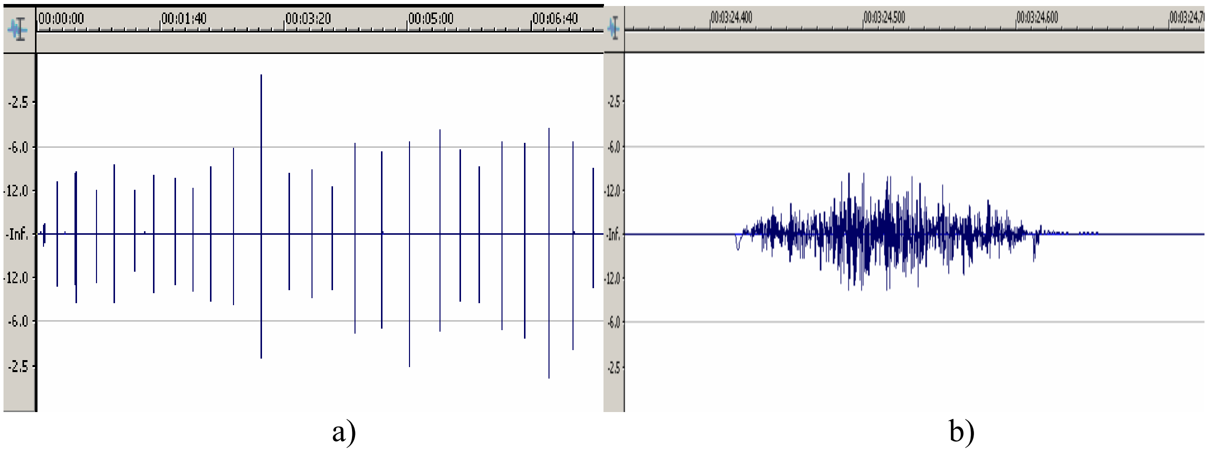

Fig. 5. The full record of AE pulses (*a*) and a separate acoustic pulse in expanded form (b)

In the beginning expanded acoustic recordings can be seen pulse, which is repeated in other records. Eexplanation of the nature of this pulse for us has always represented the great challenge.

The model

According to some authors (Bykov, 2006, 2008; Vikulin,2006; Erickson et al., 2010) in the process of inhomogeneous friction can occur soliton wave that propagates along the friction surface. There are theories of soliton waves excitation in seismic processes (Vikulin,2006; Lursmanashvili et al., 2010). It is noted from experiments that the strain waves propagating along the block contacts occur prior to the dynamic displacement which is the final stage of the stick-slip cycle. It is just at the boundary between the relatively displaced solid bodies where the generation of the strain waves of different type and scale occurs [Bykov, 2008].

According to Bykov (2008), the contacting surface of each of the interacting blocks is a homogeneous sinusoidal grained surface within asperity. The asperities of the contact surfaces of blocks stick to one another. A slip on the fault plane occurs when the stuck parts move apart.

Soliton-type solutions are also obtained by considering the Burridge-Knopoff model of earthquake. localized in space and oscillate in time however, are known as breathers. The significance of these types of solitary wave solutions was emphasized by Heaton [1990]. These types of soliton or breather solutions emerge for the nonlinear wave equation with Dieterich-Ruina friction, equation (1). These solutions can be understood as a proxy for the propagation of the rupture front across the fault surface during an earthquake and may determine a range for suitable parameter values to be used in dynamic modeling of earthquakes (Erickson et al., 2010).

Conclusion

We think that in Fig. 5 (b) expressed pulse at the beginning of acoustic burst, may be associated with a wave of soliton type. The results obtained by solving the equation sin-Gordon show that the velocity of the exciting soliton wave depends on various parameters, and may change from a few hundred microns/sec to several hundred m/sec (Bykov, 2006, 2008; Vikulin,2006).

The generalized sine-Gordon equation can be applied for modeling peculiarities of fault dynamics. In fact, contribution of perturbation in the sine-Gordon equation in the form of friction and inhomogeneities leads to the solutions of the solitary-like waves that can be interpreted as the waves of friction activation. At definite values of friction and inhomogeneity parameters, the solitary wave “acquires” the stationary regime with the values of $V \approx 10^{-4} - 10^{-1} \frac{m}{s}$ (Bykov, 2006, 2008). These waves, migrating along the friction surface, may trigger the stick-slip events.

Stick-slip is not a periodic phenomenon. One of the reasons can be that in each case the velocity profile of arised soliton waves depends on the specific process parameters. In different cases of stick-slip events, soliton waves may be arised which have different propagation velocity and respectively, which will trigger new stick-slip events at different time intervals.

The generalized sine-Gordon equation can be applied for modeling peculiarities of fault dynamics. Our goal is to develop a mathematical model of the mechanism of excitation of soliton waves in the process of friction and with it help, in the case of our experiments, to clarify the mechanism of stick-slip. The crustal fault zones are active, nonlinear, and unstable media. Therefore, it follows from the general physical regularities of the nonlinear processes that the solitary wave generation is inevitable in the faults. The solitary wave mechanism can lead to cyclic recurrence of the seismic displacements in the fault, as one of the possible mechanisms of tectonic stress migration in the Earth.

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Процесс стик-слипа и солитонные волны

Нодар Варамашвили

Резюме

Механизми сейсмического и разных инженерных процессов хорошо объясняется в рамках теорийй стик-слип. Мы исследовали процесс стик-слип: триггерирование и синхронизацию нелинейных явлений в лабораторной системе пружина-блок с помощью регистраций акустической эмиссии сопровождающей событий проскальзывания. В начале расширенной

акустической записи выден импульс, который повторяется в других записях. Мы считаем, что его присутствие связано с солитонными волнами. Солитонная волна появляется в процессе стик-слип, распространяетя вдоль поверхности соприкосновения плиток и производит максимальное воздействие на верхнюю плиту, на краиную точку по направлению скольжения. Это может вызвать новые события стик-слипа. Важно обобщение рассмотренного выше явления для землетрясения и использование для объяснения механизма триггерирования землетрясения.

სტიკ–სლიპის პროცესი და სოლიტონური ტალღები

ნოდარ ვარამაშვილი

რეზიუმე

სეისმური და სხვადასხვა საინჟინრო პროცესების მექანიზმები კარგად აიხსნება სტიკ–სლიპის თეორიის ფარგლებში. ჩვენ ვიკვლევდით სტიკ–სლიპის პროცესს: ლაბორატორიულ ზამბარა–ბლოკის სისტემაში არამდგრადობების ტრიგერირებას და სინქრონიზაციას სრიალის შემთხვევის თანმხლები აკუსტიკური ემისიის რეგისტრაციით. გაშლილი აკუსტიკური ჩანაწერის დასაწყისში ჩანს იმპულსი, რომელიც მეორდება სხვა ჩანაწერებში. ჩვენ ვფიქრობთ, რომ მისი არსებობა უნდა ასოცირდებოდეს სოლიტარულ ტალღებთან. სოლიტონური ტალღა ჩნდება სტიკ–სლიპის პროცესში, ვრცელდება ფილების შემხები ზედაპირების გასწვრივ და აწარმოებს მაქსიმალურ ზემოქმედებას ზედა ფირფიტაზე, სრიალის მიმართულებით, მის ნაპირა წერტილზე. ამ ზემოქმედებამ შეიძლება გამოიწვიოს სტიკ–სლიპის ახალი მოვლენები. მნიშვნელოვანია ზემოთ განხილული მოვლენა განზოგადდეს მიწისძვრის მოვლენისათვის და გამოყენებული იქნას მიწისძვრის ტრიგერირების მექანიზმის ასახსნელად.