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Mass-movement and seismic processes study using Burridge-Knopoff laboratory and mathematical models

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Abstract

Simple models of mass movement and seismic processes are important for understanding the mechanisms for their observed behavior. In the present paper, we analyze the dynamics of a single-block and Burridge-Knopoff model on horizontal and inclined slope with Dieterich–Ruina and Carlson friction laws. In our experiments, the slip events are distinguished by acoustic emission bursts, which are generated by slider displacement. Also acceleration was recorded on each sliding plate using attached accelerometer. In the case of the inclined slope experimental model a seismic vibrator, which produces low periodic impact (forcing) was attached to the sliding plate. This was a numerical simulation of dynamic processes occurring at one- and four-plate Burridge-Knopoff system.

Introduction

The aim of the study was the selection of optimum methods to monitor landslides and develop practical methods of reducing the risk of landslides. For many countries around the world landslides are one the most severe of all natural disasters, with large humanitarian and economic losses. The earth surface is not static, but dynamic system and landforms change over time as a result of weathering and surface processes (i.e., erosion, sediment transport and deposition). The fast mass-movement has a potential to cause significant harm to population and civil engineering projects. Large-scale experiments and field observations show that the landslide may reveal stick-slip motion [Helmstetter et al., 2004, Fabio Vittorio De Blasio, 2011]. When the friction between two solids shows velocity weakening behavior, stationary motion becomes unstable and stick-slip motion appears [Nasuno et al., 1998], which repeats stopping and fast moving states. 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 [Dieterich 1979, Ruina 1983]. The rate and state dependent friction can be quantified as follows [Dieterich 1979, Ruina 1983]:

$$\tau = \sigma_0\left(\mu_0 + a ln\left(\frac{V}{V_0}\right) + b ln\left(\frac{V_0\theta}{D_0}\right)\right), \quad (1)$$

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:

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

To study the stick-slip process a mathematical model proposed by Burridge-Knopoff is also used [Burridge R. and Knopoff L. 1967, Erickson et al.,2010, Matsukawa, H., Saito, T., 2007] (Fig.1). Plates are arranged on a massive platform and pulled by the upper platform. The upper plate moves with a constant loading velocity *v*. The blocks of mass *m* are connected to the upper plate by linear springs with spring constant k_p. The blocks are also connected to each other by linear springs with springs of natural length *a* and the constant k_c,. Frictional force acts between the lower plate and each block.

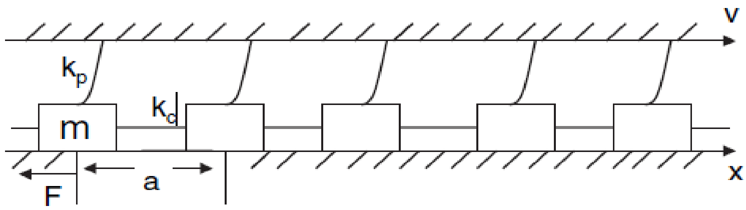


Fig.1. The schematic presentation of Burridge-Knopoff model

The Burridge-Knopoff model is convenient as it allows us to simulate many scenarios of rupture without being too expensive in regard to computing time. Thus we have the ability to explore the parameter space of the system more broadly and observe the emergent dynamics introduced by the friction law.

Experimental setup

Experiments were conducted on a Burridge-Knopoff laboratory device for the models consisting of one and three basalt plates (Fig.2). Registration was made with the help of accelerometers and piezo sensors. On one plate model three accelerometers were attached on the plate, which recorded x, y and z components. Plates were pulled via the upper platform at a speed of 1 mm/s. The experiments were also conducted for the model of the three plates. Each plate was attached on one accelerometer, which measures the x component of the acceleration. Accelerations and acoustic emissions recording are presented in Figure 3. In experiments Tri-axis accelerometer MXR9500G/M and piezo sensors were used. Mass of the each sliding plate $\approx 335\ g$, spring constants $k_c \approx 360\frac{N}{m}$ and $k_p \approx 155\frac{N}{m}$. Dragging velocity was $v \approx 1\frac{mm}{s}$.

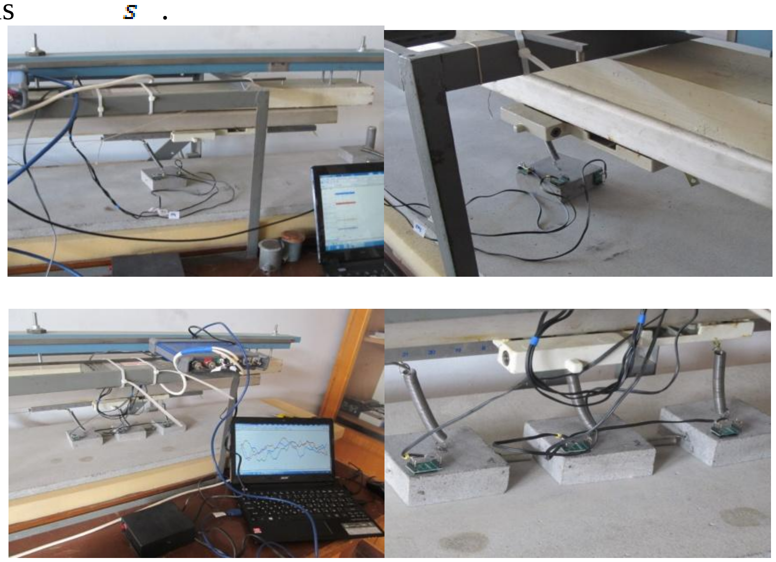


Fig.2. The Burridge-Knopoff one- and three plate experiments

a) b)

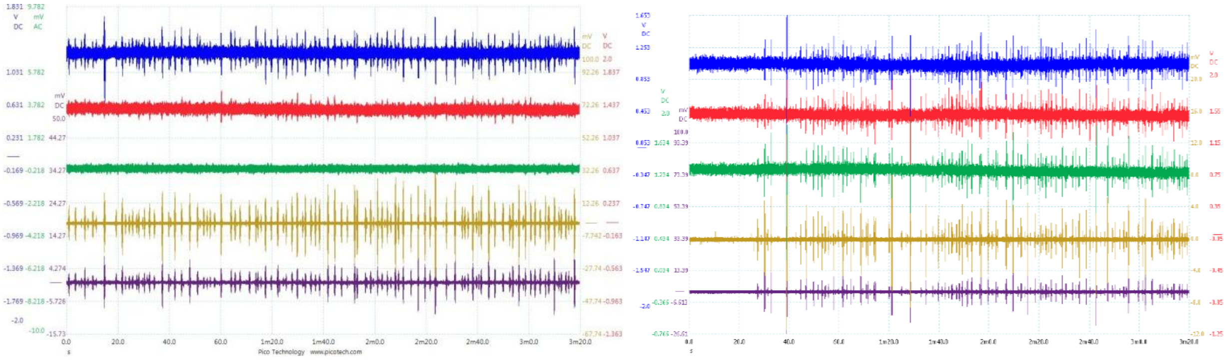


Fig.3. The Burridge-Knopoff system experiments accelerometers and acoustic emission data recordings: a)one plate and b)three plate experiments.

Burridge-Knopoff stick-slip experiments were conducted for the horizontal position of fixed and sliding plates with clean surfaces and with a layer of sand between the sliding plates (Figure 4).

Fig.4. The Burridge-Knopoff experiments with clean surfaces plates and with a layer of sand between the plates

In experiments the upper platform moved at a speed of 1 mm/sec. To the each sliding plate was attached an accelerometer, which measures the acceleration of the plate. Also was recorded acoustic emission using piezo sensor. The information was recorded on a 8-channel PicoScope 4824. These records are shown in Figure 5.

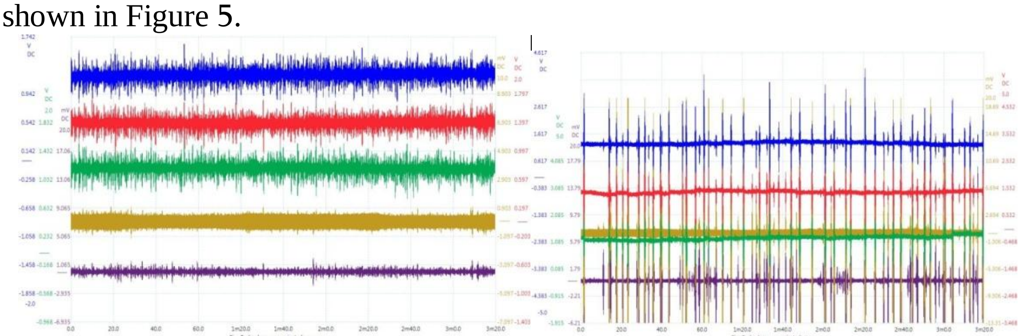


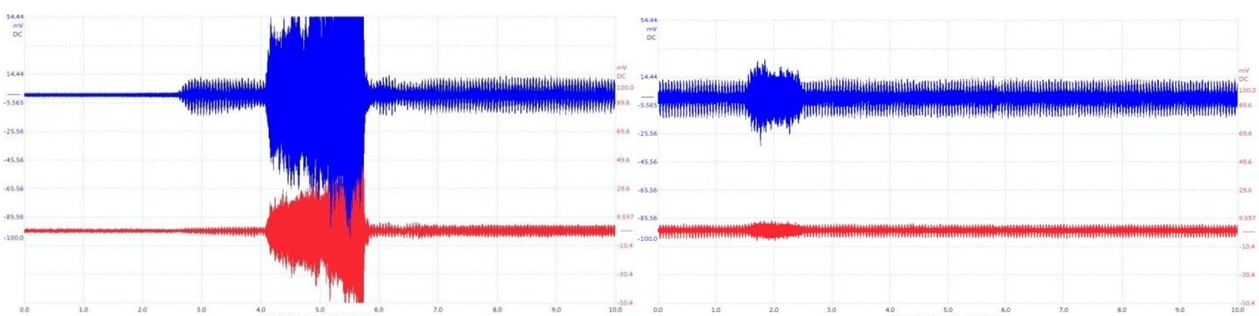
Fig. 5. Records of accelerations and acoustic emissions arising during the Burridge-Knopoff experiments with clean surfaces plates (a) and with a layer of sand between the plates (b). Blue, red and green channels, show respectively accelerometer records attached to the first, second and third sliding plate. Yellow and purple channels present the piezo sensors records.

To study the phenomena of stick-slip and triggering of Burridge-Knopoff model under the influence of gravitational forces we accembled laboratory equipment with an inclined plane (Fig. 6). These settings may help to learn the process of landslide stick-slip motion triggering under different conditions on the sliding surface between basalt plates and under the influence of gravitational forces. The acoustic emission arising during sliding of upper plate was recorded. To this goal piezo sensors were attached to the upper and lower corners of the large (fixed) plate. At the critical angle of inclination of the system triggering forcing was applied by a seismic vibrator attached to the sliding plate. The information was recorded on a 8-channel PicoScope. In experiments the inclination slope of boards was measured.

Fig. 6. Laboratory model for series of Burridge-Knopoff experiments, under the influence of gravitational forces. Middle figure shows the seismic vibrator attached to sliding plate.

Experimental results for one- and three plate models under the influence of gravitational force are presented in Fig.7. The critical angle of slip is different for one- and three plate models. Triggering of sliding close to the critical slope but still stable occurs by a seismic vibrator. Namely, the system was left close to the critical angle for 45 minutes. Then, on the attached seismic vibrator a forcing of 20 Hz frequency and 1.6 V intensity was applied. The information was recorded on a 8-channel PicoScope. As can be seen from Fig.7 during the experiment several intermediate slips took place. The beginning of sliding of system of plates was caused by influence of the seismic vibrator. The seismic vibrator played the role of a trigger in slip.

a) b)



c) d)

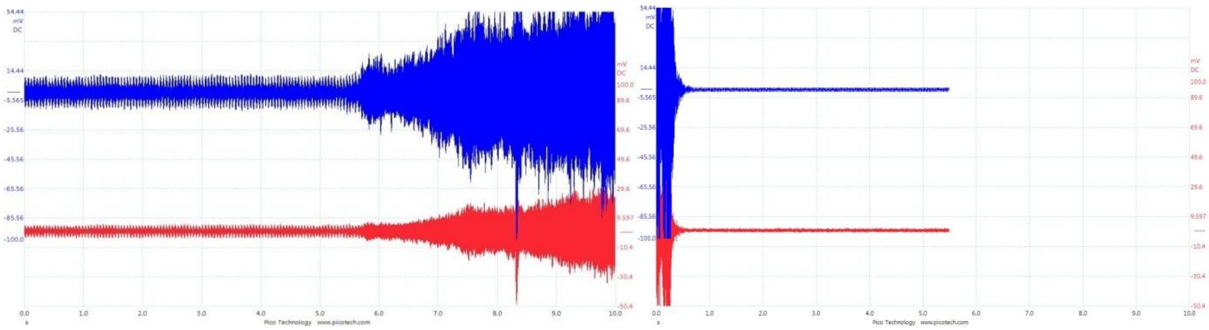


Fig.7. a) The record the acoustic emission occurred on one-plate model, b), c), d) record the acoustic emission when sliding occurred on three-plate model.

Numerical modeling

Because of the nonlinearity imposed into equation by the logarithmic term in the Dietrich-Ruina friction law, analytic integration cannot be done even in the simplest case of a single block. For this reason we proceed by implementing a numerical method as a system of 3 first order ODEs [Erickson et al., 2010]:

$$\dot{u}_j = v_j \qquad (3)$$

$$\dot{v}_j = \gamma^2\left(u_{j-1} - 2u_j + u_{j+1}\right) - \tilde{\gamma}^2 u_j - \left(\frac{\gamma^2}{\xi}\right)\left(\theta_j + \ln\left(v_j + 1\right)\right) \qquad (4)$$

$$\dot{\theta}_j = -\left(v_j + 1\right)\left(\theta_j + (1+\epsilon)\ln\left(v_j + 1\right)\right) \qquad (5)$$

Where u_j is the non-dimensional slip, $\gamma = \sqrt{\left(\frac{\mu}{m}\right)\left(\frac{D_0}{V_0}\right)}$ and $\tilde{\gamma} = \sqrt{\left(\frac{\lambda}{m}\right)\left(\frac{D_0}{V_0}\right)}$ are the dimensionless frequencies, $\xi = \frac{\mu_0 D_0}{a}$ is the dimensionless spring constant, $\epsilon = \frac{b-a}{a}$.

Numerical experiments have been conducted in the case of three blocks. At the initial time zero displacements from equilibrium were assigned to blocks and the maximum deviation of the central block - on the Gaussian distribution. Revealed the originality of the sliding of the central block. At certain intervals of instability amplified and enhanced non-linearity the central unit is experiencing periodic motion.

N=3;
γ =0.5;
$\tilde{\gamma}$=0.5;
ξ =0.5;
ϵ =0.5;
sigma=1;

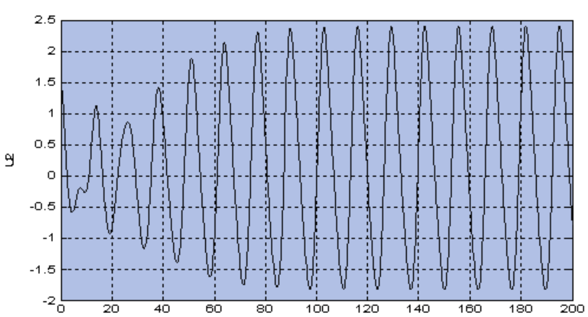


Fig.8. Numerical experiments for three-block Burridge-Knopoff model

Burridge-Knopoff model (Fig. 1) can be also described in terms of the normalized equation[Matsukawa, Saito, 2007]:
The normalized equation of motion of the model (Fig. 1) is expressed as:

$$\ddot{x}_i = (vt - x_i) + l^2(x_{i+1} + x_{i-1} - 2x_i) - \phi(\dot{x}_i), \qquad (6)$$

here $l = \sqrt{\frac{k_c}{k_p}}$, is the dimensionless stiffness parameter; x_i, t, v and $\phi(\dot{x}_i)$ are normalized dimensionless parameters. In order for the model to exhibit a dynamical instability, it is essential that the friction force exhibits a frictional weakening property, i.e., the friction should become weaker as the block slides. As the simplest form of the friction force, we assume here the form used by Carlson:

$$\phi(\dot{x}_i) = \frac{1-\sigma}{1 + \frac{2\alpha \dot{x}_i}{1-\sigma}}, \qquad (8)$$

Numerical experiments were conducted for one- and four plates for $l = \sqrt{60}$, a=1, $\sigma = 0.01$ and $\alpha = 4$ numeric values. The results are presented in Fig. 9.

a) b)

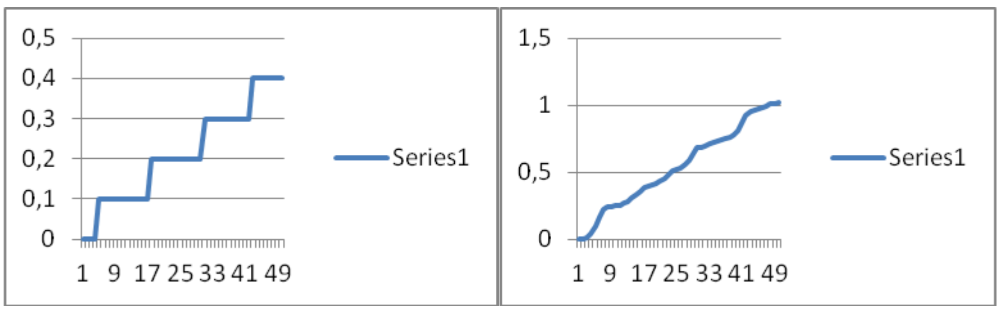


Fig. 9. a) Numerical simulation of displacement (ordinate) versus time (abscissa) for one block, b) the same calculations carried out for moving the center of gravity of the system in conditional units the Burridge-Knopoff model of four plates. (abscissa - time, ordinate - displacement).

For each experiment we have files of large volume with records of accelerations and acoustic issues. Data recording in a digital form was made at the sampling rate 2 kHz. Each experiment proceeded about 10 minutes. Gravitational experiments taking into account a parking phase (prior to influence by the seismic vibrator) proceeded about 50 minutes. At this stage our task is to transfer these accelerations to movements to compare data of experiment with data of mathematical modeling.

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ბურიჯ-კნოპოვის ლაბორატორიული და მათემატიკური მოდელის გამოყენებით მასების მოძრაობის და სეისმური პროცესის შესწავლა

ნოდარ ვარამაშვილი, თამაზ ჭელიძე, მარინა დევიძე, ზურაბ ჭელიძე, ვიქტორ ჩიხლაძე, ალექსანდრე სურმავა, ხათუნა ჩარგაზია, დიმიტრი ტეფნაძე

რეზიუმე

მასების მოძრაობის და სეისმური პროცესების მარტივი მოდელები მნიშვნელოვან როლს თამაშობენ მათი მექანიზმების შესასწავლად. წარმოდგენილ სტატიაში ჩვენ ვაანალიზებთ, ჰორიზონტალურ და დახრილ სიბრტყეზე დიტრიხ-რუინას და კარლსონის ხახუნის კანონების გამოყენებით, ზამბარა-ბლოკის და ბურიჯ-კნოპოვის მოდელის დინამიკას. ჩვენს ექსპერიმენტებში, დასრიალების გამორჩევა ხდება დასრიალების პროცესში გენერირებული აკუსტიკური ემისიის საშუალებით. ასევე ხდებოდა თითოეული მოსრიალე ბლოკის აჩქარების ჩაწერა. დახრილი მოდელის შემთხვევაში ერთ-ერთ მოსრიალე ფილაზე მიმაგრებული იყო სეისმური ვიბრატორი, რომლის საშუალებითაც ხორციელდებოდა სისტემაზე მცირე გარეშე ზემოქმედების მოდება. განხორციელდა ერთ და ოთხ ბლოკიანი ბურიჯ-კნოპოვის სისტემაში მიმდინარე დინამიკური პროცესების რიცხვითი მოდელირება.