Numerical Analysis Of Friction Laws. Application To Induced Seismicity

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Abstract

It's known that the rate-state friction law could be used to reproduce the seismic activity generated by tectonic fault sliding. The authors previously showed that the spring-block system with two-parametric friction law exhibits various types of chaotic motion. In the same time, the results of numerical experiments showed that used variant of the friction law did not allow to describe correctly some modes of the block movements. To solve this problem, several modifications of the friction law were considered, and numerical modeling of the spring-block system with modified friction law was conducted. By varying the model parameters, the various slip patterns were obtained, which were different from the patterns obtained using the "general" two-parametric friction law. The numerical results were compared with measurements of the slider-block movements in laboratory experiments; the comparisons were conducted for several variants of the friction law modifications. The modifications allowing to achieve the best matching with the experimental measurements for the different slip modes were found. But , the additional member used in the modification significantly affects the possibility of obtaining chaotic motion. The periodic motion obtained in laboratory experiments can be reproduced accurately, but chaotic motion can be reproduced only in terms of average values.

The resulting friction law was used for modeling slip induced by fluid injection. For this purpose 2-D model was considered. Fluid is injected near the fault in a homogenous medium. The remote stresses are constant. Influence of form of friction law was analyzed and resulting slip was compared.

1. Numerical analysis of friction laws and laboratory experiment

In the report[1] "Seismological grand challenges in understanding Earth's dynamic system" (2009) the first among the most important issues is formulated as:

"How do faults slip?". Several factors are considered, but the number of them are related to friction law. Various semi-empirical relations are used, but there are no convictions that one or the other type of law is applicable or not in the particular case. The most widely used classical one-parameter rate-state equation can not allow one to simulate correctly some features of the laboratory experiments. Besides, it's not possible to get the full range of the sliding modes (from slow sliding to high frequency events) by using this equation.

Using a numerical simulation, we compare the behavior of the sliding fault described by various friction laws. We consider spring-block slider system with one block (Fig.1). The equation of motion and general form of friction law:

$$\begin{cases} m\ddot{x} = k(u_0 t - x) - \tau_{fr} \\ \mu_{fr} = \mu_0 + a\ln\left(\frac{v}{v_*}\right) + F(\theta_i) \\ \dot{\theta}_i = G(v, \theta_i) \end{cases}$$

The most popular law is rate-and-state law, θ is parameter of state. There are a few different forms of this law (e.g. slowness and slip laws), but numerical modeling shows that the concrete form isn't essential. A General idea of this friction law can be obtained from Fig. 2. Corresponding form of friction law is:

$$\mu = \mu_0 + a\ln\left(\frac{v}{v_*}\right) + \theta_1 + \theta_2$$

$$\dot{\theta}_i = -\frac{v}{L_i}\left[\theta_i + b_i \ln\left(\frac{v}{v_*}\right)\right]$$

Change of friction coefficient with change of sliding velocity during stable slip is shown on the figure.

$$\mu = \mu_0 - (B_1 + B_2 - A)\ln\left(\frac{v}{v^*}\right)$$ - friction coefficient during stable sliding

But there is a problem: model with standard R&S law doesn't allow to describe some types of motion observed in laboratory experiments (Fig. 3, 4). Besides, model with classical one-state law does not allow to reproduce the form of velocity profiles and repeatability of events simultaneously (Fig. 5). For these reasons modification is needed.

Two forms of modification were considered. The first is introduction of an additional viscous component

$$\tau = \tau_* + \sigma_n\left(A\ln\left(\frac{|v|}{v^*}\right) + \theta_1 + \theta_2\right) + \eta^* v$$

The second is change of evolution law of state variable (compositional law)

$$\dot{\theta}_i = e^{-\frac{v}{v_c}} - \frac{v^*\theta_i}{L_i}\ln\left(\frac{v^*\theta_i}{L_i}\right)$$

The first type of modification is more fruitful. Modeling with use of the other did not give satisfactory results (Fig. 6). There is one disadvantage of first modification: chaotic motion could be observed for the two-parameter law (Fig.7), but with increase of additional term the probability that a chaotic motion could be "caught" is less Fig. 8. But, nevertheless, this modification allows to reproduce exactly periodic motion and qualitatively chaotic motion (Fig. 9-11).

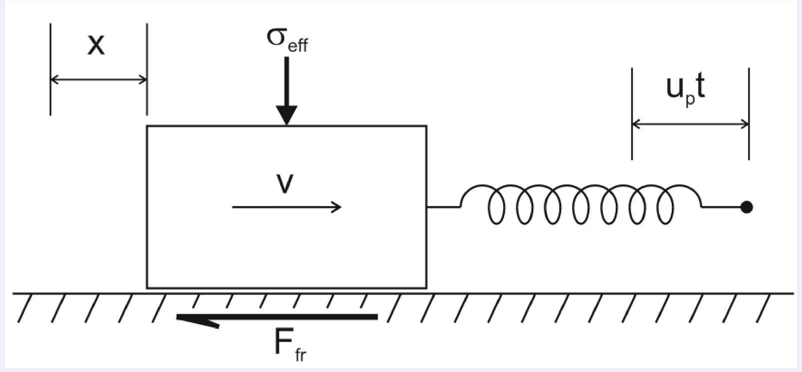


Fig.1 Spring–block model

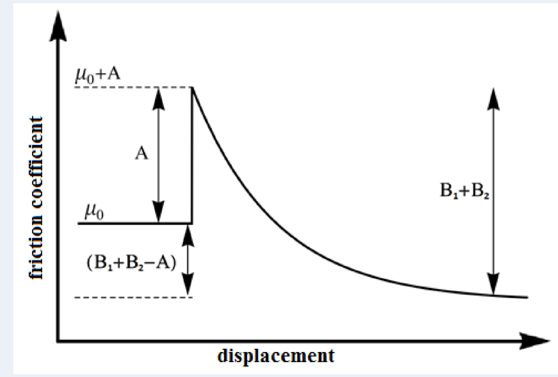


Fig.2 Behavior of friction coefficient after change of sliding velocity

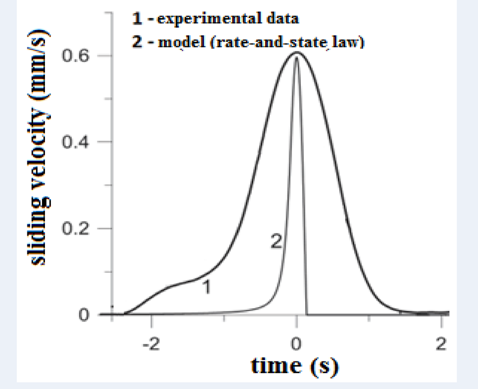


Fig.3 Sliding velocity vs time

Fig.4 Laboratory setup

Composite law

• New parameter v_{cr2} (in the framework of this model) has a little effect on the duration of episodes of failures

Form of the law with a component of viscous type η^*

• Viscosity allow to effectively change duration of sliding events.

• Shape of plot (time dependence of velocity) is changing with the change of value of η^*

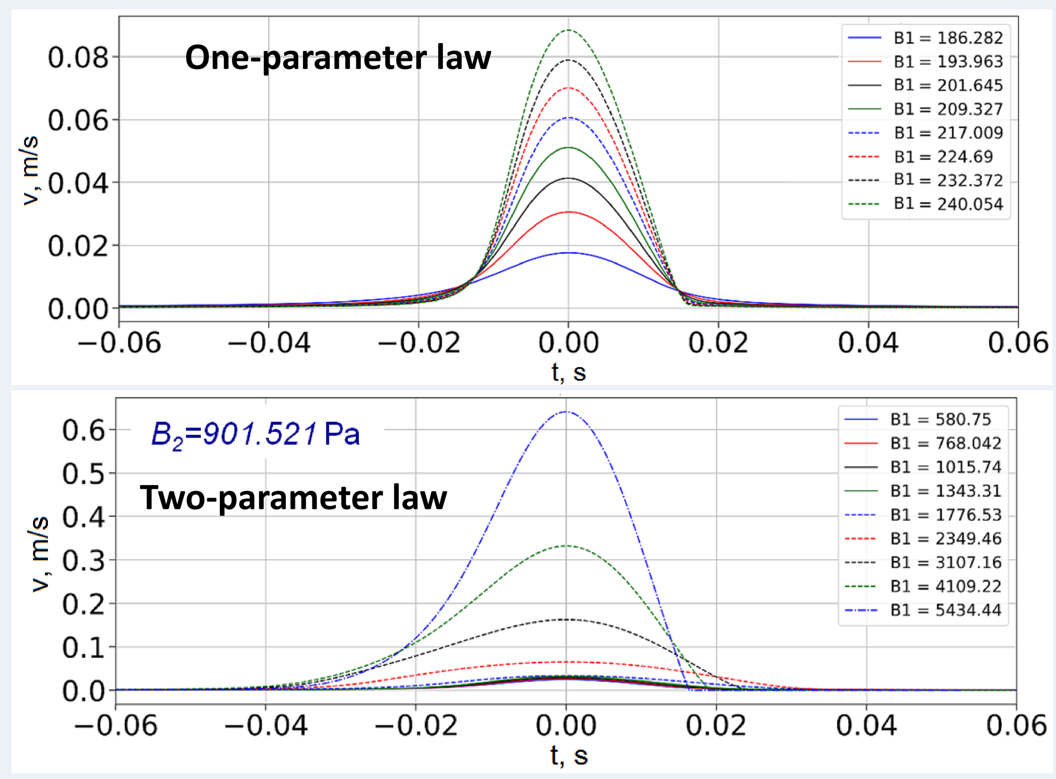


Fig.5 Dependence of form of velocity profile on value of parameter B

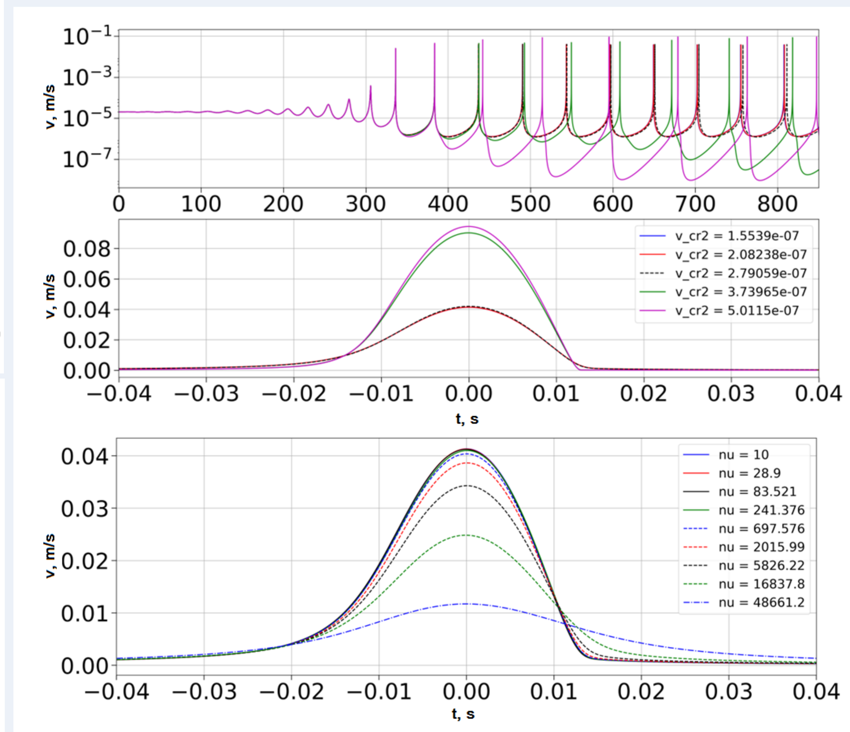


Fig.6 Dependence of form of velocity profile on additional parameter for two modifications of law

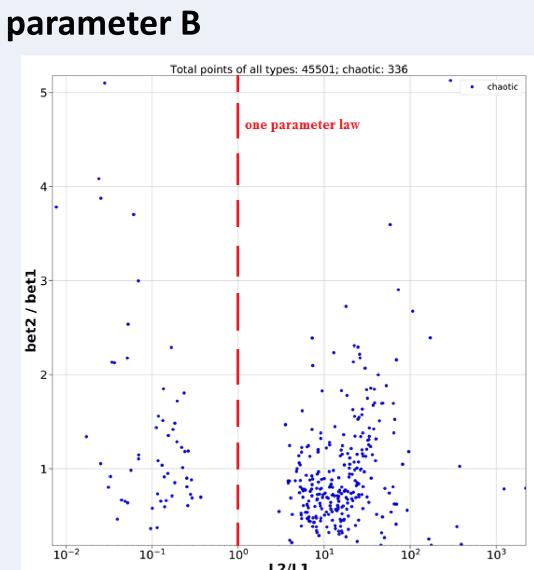


Fig.7 Blue points – values of dimensionless parameters at which there is a chaotic movement

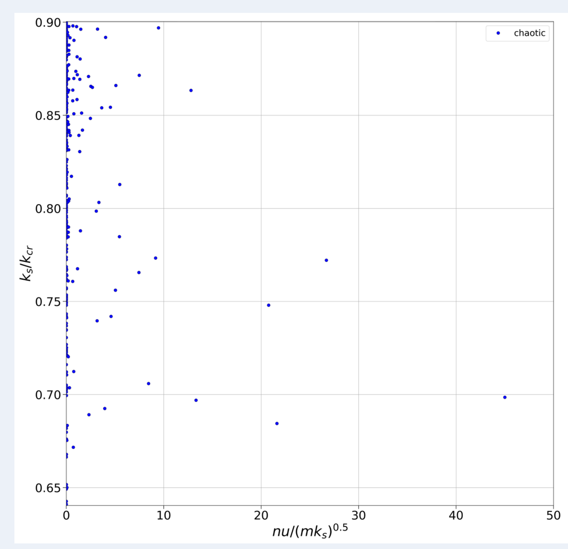


Fig.8 Blue points – values of dimensionless parameters at which there is a chaotic movement

$$\mu = \mu_0 + a\ln\left(\frac{v}{v_*}\right) + \theta_1 + \theta_2$$

$$\dot{\theta}_i = -\frac{v}{L_i}\left[\theta_i + b_i \ln\left(\frac{v}{v_*}\right)\right]$$

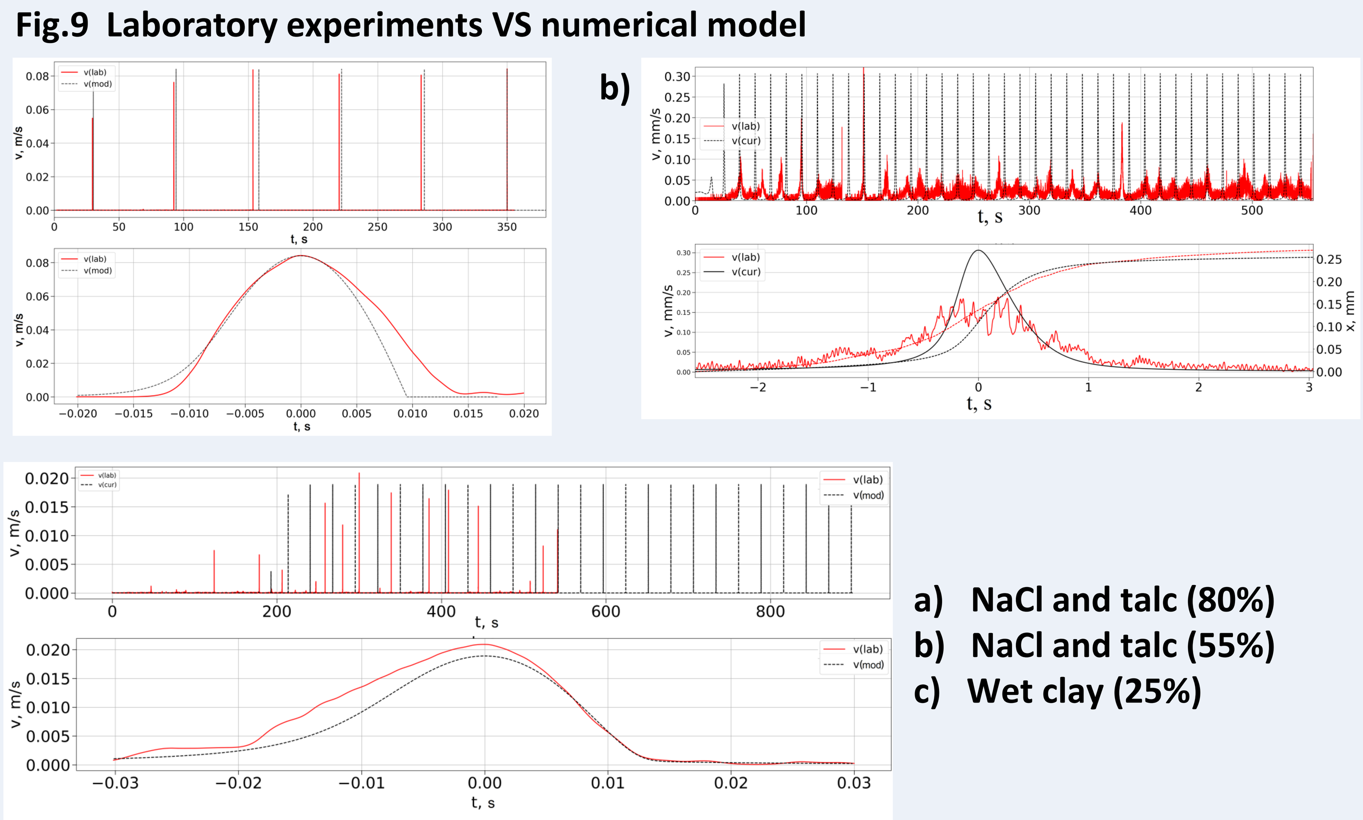
$$\rho = \frac{L_1}{L_2} \quad \beta_2 = \frac{B_2}{A} \quad \beta_1 = \frac{B_1}{A}$$

$$k_{cr} = \frac{2A}{L_1 + L_2}\left(\frac{mv^2}{L_1 A}(\rho + 1) + 1\right)\Big[(\beta_1 - 1) + \rho^2(\beta_2 - 1) + 2\rho(\beta_1 + \beta_1 - 1) + \sqrt{\{[(\beta_1 - 1) + \rho^2(\beta_2 - 1)]^2 + 4\rho^2(\beta_1 + \beta_1 - 1)\}}\Big] / (4\rho)$$

k<kcr – unstable sliding

k > kcr – stable sliding

Fig.9 Laboratory experiments VS numerical model



a) NaCl and talc (80%)
b) NaCl and talc (55%)
c) Wet clay (25%)

2. Basel EGS

We use modified friction law for modeling seismicity at Basel site. The data was taken from public sources.

The model is simplified (for now). The problems of fluid filtration and deformation of fractures are considered separately. The model is 2-D. The permeability is homogenous, but model of dual porosity is taken: as the pressure increases fractures open and permeability also increase (Fig. 10). Backflow rate was taken constant, but cumulative volume is the same (Fig. 11). For modeling MRST was used.

The model is adapted to reproduce history of bottomhole pressure (Fig. 12).

For seismicity modeling a set of randomly distributed fractures was taken. At the beginning fractures are not active, as soon as traction force on fracture exceeds force of friction it starts motion. The fracture was modeled as spring-block model with no mass. The initial state is stable sliding with law velocity. The deformation of fracture doesn't lead to change of stress state in the surrounding space. The parameters of friction law for all fracture are almost the same. Different numbers of initial fractures were considered. For fracture consisting of three blocks the governing equations are:`

$$\begin{cases} 0 = k_1(u_0 t - x_1) - k_{12}(x_1 - x_2) - \tau_{fr1} \\ 0 = k_2(u_0 t - x_2) + k_{12}(x_1 - x_2) - k_{23}(x_2 - x_3) - \tau_{fr2} \\ 0 = k_3(u_0 t - x_3) - k_{23}(x_2 - x_3) - \tau_{fr3} \end{cases}$$

$$\tau = \tau^* + \sigma^{eff}\left(a\ln\left(\frac{|v|}{v^*}\right) + \theta_1 + \theta_2\right) + \eta v$$

The results of modeling are shown on Fig. 13-14.

$$M_o = GS\Delta x \quad M_w = \frac{lg(M_0)}{1.5} - 6.06$$

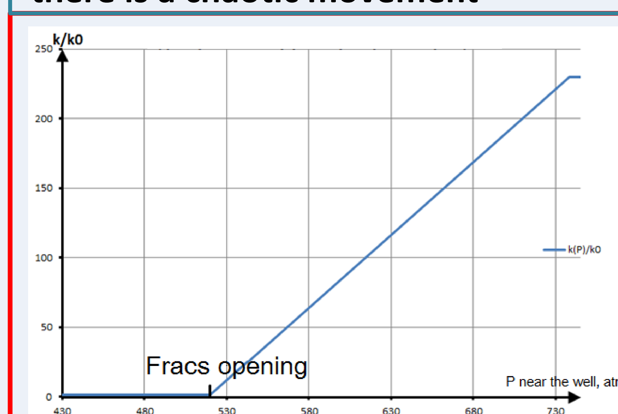


Fig.10 Permeability of cell near the well

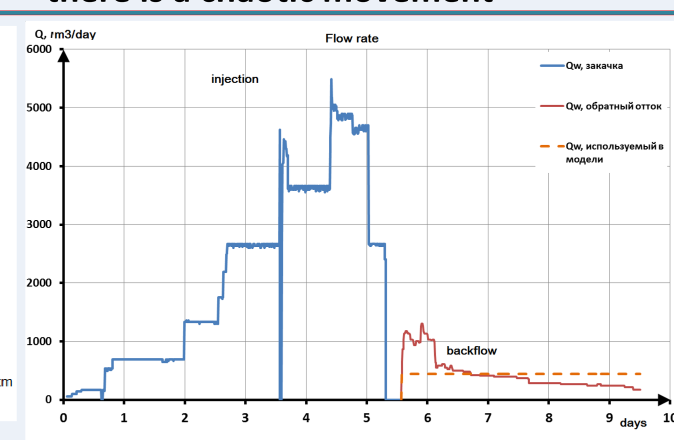


Fig.11 Injection rate

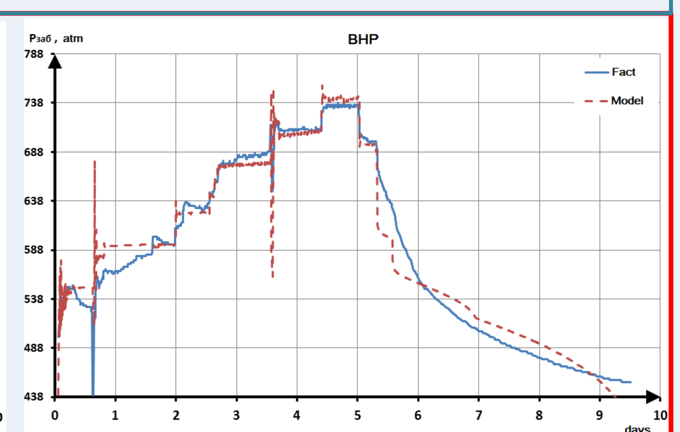


Fig.12 BHP history

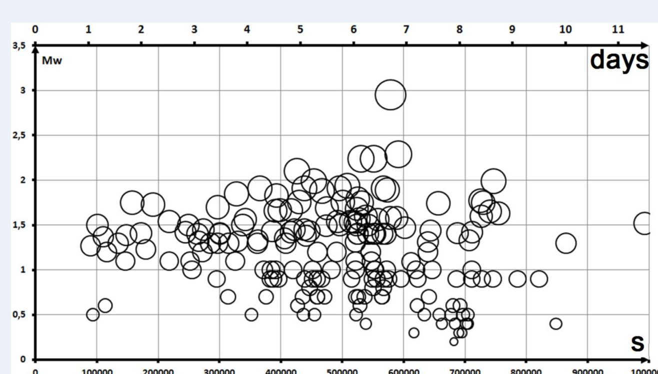


Fig.13 Seismic events, fact

Basel EGS

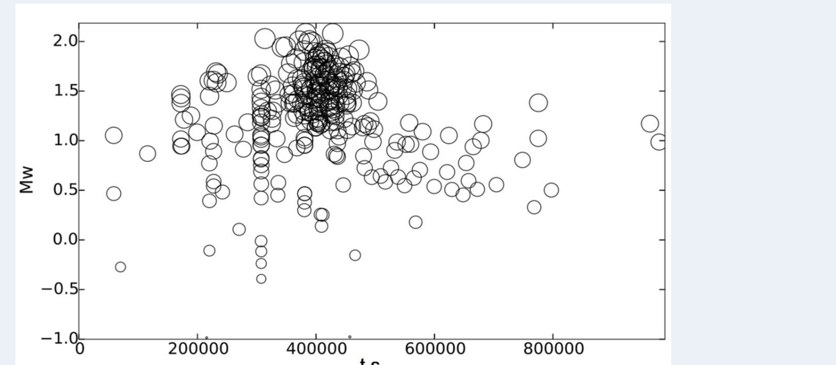


Fig.14 Seismic events, model

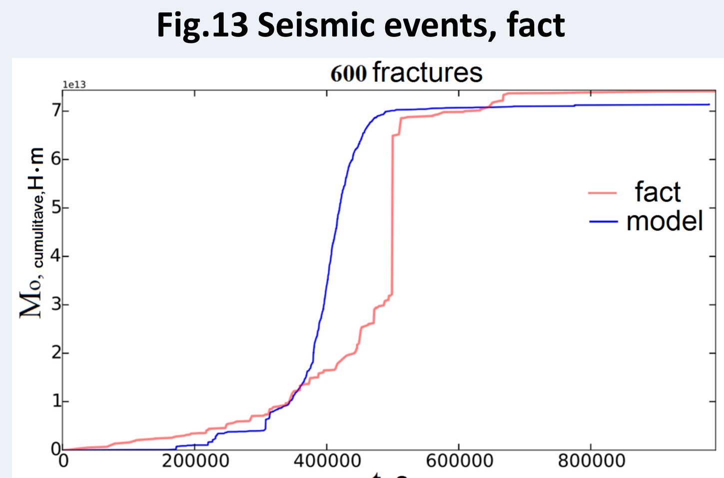


Fig.15 Cumulative seismic moment

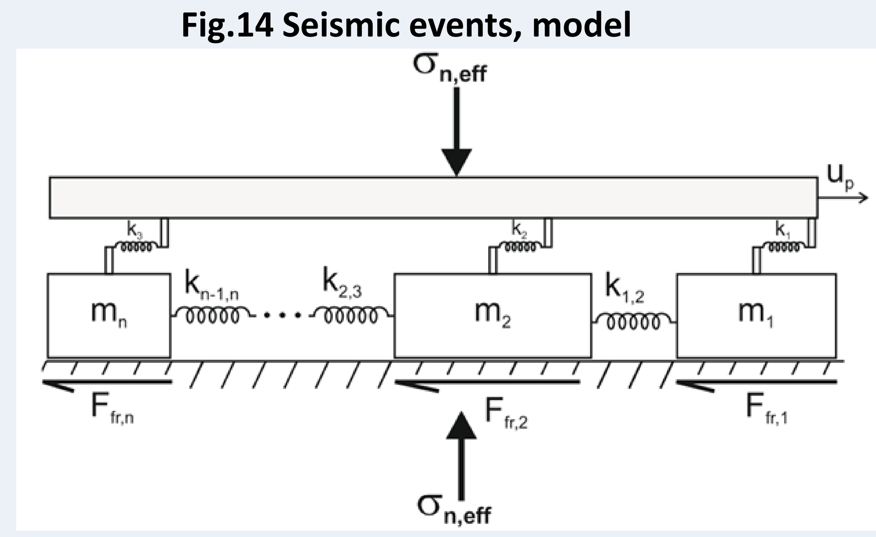


Fig.15 Fracture model

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