
# Book of Proceedings

The Ninth International Congress
of the Serbian Society of Mechanics
July 5-7, 2023, Vrnjačka Banja, Serbia

**The Ninth International Congress of the Serbian Society of Mechanics, July 5-7, 2023, Vrnjačka Banja, Serbia – Book of Proceedings**

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9th International Congress of the Serbian Society of Mechanics
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# MODELLING OF LANDSLIDE DYNAMICS: ROLE OF DISPLACEMENT DELAY AND NATURAL BACKGROUND NOISE

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## Abstract

Novel stochastic landslide model is suggested and analyzed within this paper. The effect of delay in displacements of the neighboring blocks and the influence of random background noise is included, for the first time, in the explicit mathematical model and examined. Such setup of landslide model is considered as close to natural conditions since delayed displacement among different parts of the unstable slope occurs due to changes in friction, while ambiental seismic noise represents continuous background factor affecting the landslide dynamics. Type of noise as linear stationary stochastic process with Gaussian inputs (random noise) is determined by surrogate testing of the recordings of ambiental noise before and after the small seismic event at the location of Zavoj dam in Serbia. Two explicit mathematical models are suggested for landslide dynamics: two-block model with time delay in displacement of the neighboring blocks and model of n all-to-all coupled blocks with included delay and random background noise. Both models exhibit small displacements of constant velocity in equilibrium state, which mimics well the dynamics of creeping landslides. Dynamical analysis of both models is conducted numerically using Runge-Kutta 4th order numerical method. Results obtained indicate that landslide dynamics is not affected by the introduced time delay for certain friction conditions, while background random noise has surprisingly positive stabilizing effect. In particular, it appears that the increase of time delay in a two-block deterministic landslide model for certain friction conditions does not lead to onset of instability. On the other hand, the increase in intensity of random background noise in a landslide model near the bifurcation point composed of n globally coupled blocks "pushes" the bifurcation curve further thus making the examined dynamical system stable. These findings, although provided on a theoretical level of the mechanism behind the landslide dynamics, could have important implications in further research on landslide dynamics.

**Keywords**: landslide, noise, time delay, bifurcation.

## 1. Introduction

Inspection of slope stability and identification of its main controlling factors represents an obligatory task in any design work. Commonly, landslide stability and conditions for triggering instability are examined by invoking the limit equilibrium methods [1] or finite element method [2]. In recent years, smooth particle hydrodynamics also found its place in the contemporary slope stability analysis, primarily due to the fact it enables the analysis of the post-failure behavior [3]. Although all these methods provide satisfying results, the dynamics of the land sliding itself remains relatively uninvestigated, which further prevents proper identification of the (de)stabilizing factors. One attempt in this direction is the representation of landslide dynamics as dynamics of the spring-block model on an inclined slope.

The idea of representation of landslide dynamics as a dynamics of spring-block model is not new and it originally comes from Davis [4], who proposed a model for an accumulation slide in a form of connected two block on an inclined slope (Fig.1). In this original model, motion of the two-block system was accurately described by three ordinary differential equations, where connection between feeder (lower) and accumulation (upper) slope is assumed to be both elastic and viscous (through differences in velocities and acceleration). Frictional strength was represented by conventional effective stress model, where friction is assumed to be the function of piezometric elevation, slope angle and angle of internal friction.

Apart from the original setup and a new model of a landslide dynamics, Davis [4] also pointed out the existence of time delay in displacement between the feeder and accumulation part of the slope (Fig. 2).

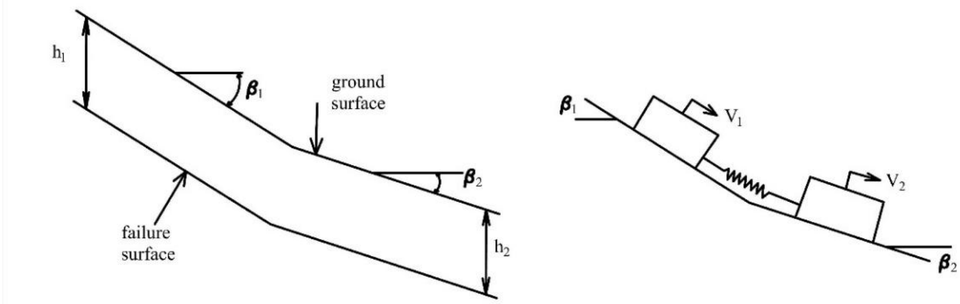


**Fig. 1.** Spring-block model of landslide dynamics, originally proposed by Davis [4]

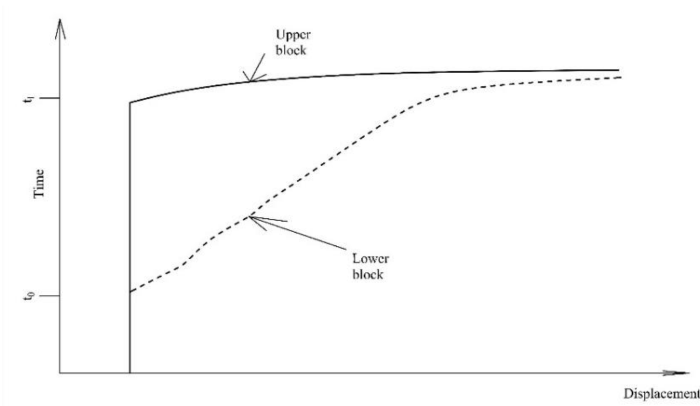


**Fig. 2.** Time delay between the movement of the lower (feeder) and upper (accumulation) part of the slope, as proposed by Davis [4]

From this point of view, such finding could be considered as avant-garde, since it is well known that existence of delay increases dimensionality of the analyzed system, which further sets a path for the onset of rich dynamical behavior. Although such finding was significant, it has not been investigated since then, mostly because dynamical systems with time delay are not easy to solve, and numerical computation in that time was not strong enough to perform computationally demanding calculations.

In 1997, Cartwright et al. analyzed spring-block (Burringe-Knopoff) model as a convenient model of frictional sliding, and, for the first time, included rate dependent friction in the analysis of landslide dynamics (Fig.3). One should note that idea of rate dependent friction came from the analysis of earthquake fault nucleation process [8].

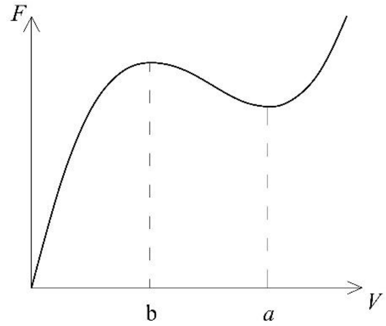


**Fig. 3.** Rate dependent friction assumed in examined landslide models.

In that time (1997), friction law associate with landslides was still on the level of Coulomb-Mohr assumptions, and scientific and engineering community was not ready to accept rate-dependent friction law as a valid assumption for friction along the sliding surface. This idea came to life again in 2012, when Viesca and Rice examined the conditions for nucleation of slip-weakening rupture instability in landslides by localized increase of pore pressure. This was further explored by Lucas et al. [7], who declared frictional velocity-weakening mechanism as applicable to small and large landslides. This paper could be considered as a starting one for a whole new direction of research of the role of velocity weakening friction law in landslide dynamics [9, 11, 12, 13].

As for the effect of noise on landslide dynamics, there are no previously conducted studies. Recordings of ambiental noise are generally used as a method to predict (estimate) landslide dynamics [14], but not as a significant landslide triggering factor. However, it has been previously suggested that significant changes of dynamics could be induced by the effect of noise [15].

Based on the aforementioned, the following is assumed in the present paper:

- Rate dependent friction law
- Time delay in displacement of neighboring blocks
- Existence of permanent background noise.

Under these assumptions, landslide dynamics is analyzed and the effect of time delay and noise is qualitatively and quantitatively evaluated.

## 2. Model setup

Model for landslide dynamics is developed starting from the model proposed by Davis [4]:

$$\begin{aligned} m_1\dot{V}_1 &= W_1 sin\beta_1 - S_1 - F \\ m_2\dot{V}_2 &= W_2 sin\beta_2 - S_2 + F \\ \dot{F} &= k(V_1 - V_2) + c(\dot{V}_1 - \dot{V}_2) \end{aligned} \tag{1}$$

where $W$ is the block weight, $g$ is acceleration of gravity, $S$ denotes the sliding resistance on failure surface, $F$ represents combined elastic and viscous forces, $k$ and $c$ are the spring and dash pot constant, and $\beta_i$ is the slope angle. Starting from model (1), a new two-block model is proposed with the included effect of time delay:

$$\frac{dU_1(t)}{dt} = V_1(t)$$

$$\frac{dV_1(t)}{dt} = \frac{1}{m}\left[k\big(U_2(t-\tau) - U_1(t)\big) - F\big(V_0 + V_1(t)\big) + F(V_0)\right] \tag{2}$$

$$\frac{dU_2(t)}{dt} = V_2(t)$$
$$\frac{dV_2(t)}{dt} = \left[k\big(U_1(t-\tau) - U_2(t)\big) - F\big(V_0 + V_2(t)\big) + F(V_0)\right]$$

where $U_i$ is the displacement of the i-th block, $V_i$ is the velocity of the i-th block, $F$ is the rate-dependent friction force, $V_0$ is the constant background velocity and τ is the delay in the position of the blocks.

Effect of noise is examined in the model of $n$ interconnected blocks:

$$dx_i(t) = y_i(t)dt$$
$$dy_i(t) = -\left[a\big(V + y_i(t)\big)^3 - b\big(V + y_i(t)\big)^2 + c\big(V + y_i(t)\big)\right]dt + (aV^3 - bV^2 + cV)dt + \sum_{j=1}^{N} k_1\left(x_j(t-\tau) - x_i(t)\right)dt + \sqrt{2D}dW_i \quad (3)$$

where $x_i$ and $y_i$ are displacement and velocity of the i-th block, respectively, and $a$, $b$ and $c$ are parameters of the cubic friction force, which according to Morales et al. [10] has the following form: $Fc(V) = 3.2V^3 - 7.2V^2 + 4.8V$. Background noise was previously investigated as a significant contributing factor for earthquake nucleation dynamics [16, 17]. In these previous studies, both random and colored nature of noise was found in the real observed recordings. In particular, nonlinear time series analysis of GPS recordings of the ground movement along the San Andreas fault in California revealed the random nature of these displacements. On the other hand, analysis of the recordings of the movement along the fault in Driny cave (Male΄Karpaty mts in Slovakia) and the noise before and after the earthquake on 8th September 2015 at the BKS station (Byerly Seismogrpahic Vault, Berkley), indicated the existence of the colored background noise. In the present paper, we analyze the ambiental noise before and after the small seismic event recorded at accelerograph station ETNA located at Zavoj dam, which is considered to be a landslide-prone area.

Next we introduce deviations from the mean field $\langle x(t)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} x_i(t)$ and $\langle y(t)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} y_i(t)$, for each element: $n_x(t) = \langle x(t)\rangle - x_i(t), n_y(t) = \langle y(t)\rangle - y_i(t)$. We assume these fluctuations are Gaussian and statistically independent in different elements. A set of moments known as cumulants or Thiele semi-invariants has an important property that all of them vanish in the Gaussian case. Therefore, we introduce the following notation for the first and second order cumulants: (a) the means $m_x(t) = \langle x(t)\rangle, m_x(t-\tau) = \langle x(t-\tau)\rangle, m_y(t) = \langle y(t)\rangle$, (b) the mean square deviations $s_x(t) = \langle n_x^2(t)\rangle, s_y(t) = \langle n_y^2(t)\rangle$ and (c) the cross-cumulant $U(t) = \langle n_x n_y\rangle$.

From cumulant analysis one can find that $\langle y^3\rangle = \frac{1}{N}\sum_{i=1}^{N} y_i^3 = m_y^3 + 3m_y s_y$
$\langle y^4\rangle = \frac{1}{N}\sum_{i=1}^{N} y_i^4 = m_y^4 + 6m_y^2 s_y + 3s_y^2$, $\langle xy\rangle = \frac{1}{N}\sum_{i=1}^{N} x_i y_i = U + m_x m_y$
$\langle xy^2\rangle = \frac{1}{N}\sum_{i=1}^{N} x_i y_i^2 = m_x s_y + m_x m_y^2 + 2m_y$, $\langle xy^3\rangle = \frac{1}{N}\sum_{i=1}^{N} x_i^3 y_i = 3s_y\ U + 3m_y^2 U + m_x m_y^3 + 3m_y m_x s_y$

From cumulant analysis and by considering Ito's chain rule the following mean-field approximated model is obtained:

$$\dot{m}_x(t) = m_y(t)$$
$$\dot{m}_y(t) = (-3aV^2 + 2bV - c)m_y(t) + (b - 3aV)\left(s_y(t) + m_y^2(t)\right) - a\left(m_y^3(t) + 3m_y(t)s_y(t)\right)$$

$$\frac{1}{2}\dot{s}_x(t) = U(t)$$
$$\frac{1}{2}\dot{s}_y(t) = s_y(t)\left[(2bV - 3aV^2 - c) + 2(b - 3aV)m_y(t) - 3a\left(m_y^2(t) + s_y(t)\right)\right] - kU(t) + D \tag{4}$$
$$\dot{U}(t) = U(t)\left[(2bV - 3aV^2 - c) + 2(b - 3aV)m_y(t) - 3a(s_y(t) + m_y^2(t))\right] + s_y(t) - ks_x(t)$$

It could be easily shown that both starting stochastic (3) and mean-field approximated model (4) exhibit qualitatively the same dynamics.

One should note that both models exhibit constant background velocity which is the characteristic property of the long-lasting creeping landslides. Such examples are frequent in engineering practice, one is them is landslide "Plavinac" in Smederevo, whose displacements are being observed for over a decade (Fig. 4).

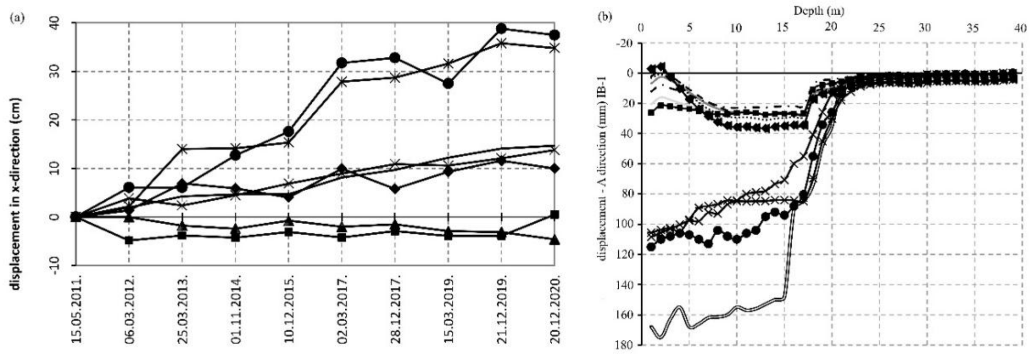


**Fig. 4.** Recorded continuous displacements of creeping landslide; example of "Plavinac" landslide in Smederevo (Serbia): (a) superficial displacements recorded at geodetic benches; (b) displacements along the depth in the installed inclinometer IB-1 (period 2016-2021).

## 3. Results

### *3.1 Effect of time delay*

Results of the numerical computation of model (3) are shown in Fig. 5. As one can see a supercritical Hopf bifurcation occurs for rather strong spring stiffness k (>6) and high values of time delay $\tau$ (>1). Regarding the effect of spring stiffness, one needs to assume high spring stiffness, i.e. system under study (conditionally stable slope) needs to be observed as a system of strongly coupled accumulation and feeder slope, in order for instability to occur. As for the effect of the introduced time delay, occurrence of instability for high values of $\tau$ shows the high resilience of the conditionally stable slope to occurrence of time delay between the motion of feeder and accumulation slope. This may indicate that the time delay indicated originally by Davis [4], as shown in Fig. 6, maybe does not have significant influence on the system dynamics, for the chosen values of friction parameters.

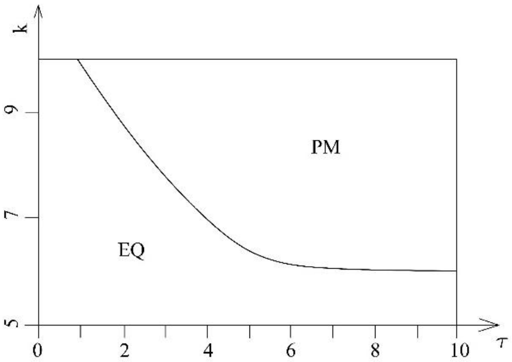


**Fig. 5.** Hopf bifurcation curve k(τ), for the fixed values of parameters $V_0$= 0.1, *a*=3.2, *b*=-7.2 and *c*=4.8. EQ stands for the equilibrium creep regime, while PM denotes unstable periodic oscillations.

If we want to examine further the effect of time delay, let us analyze the influence of the frictional parameters on the effect of τ. If one holds value of time delay and spring constant above the bifurcation curve, increase of parameters a, b and c suppress the effect of the introduced time delay (Fig. 6). This indicates that sliding surfaces with low friction parameters are more susceptible to the onset of instability.

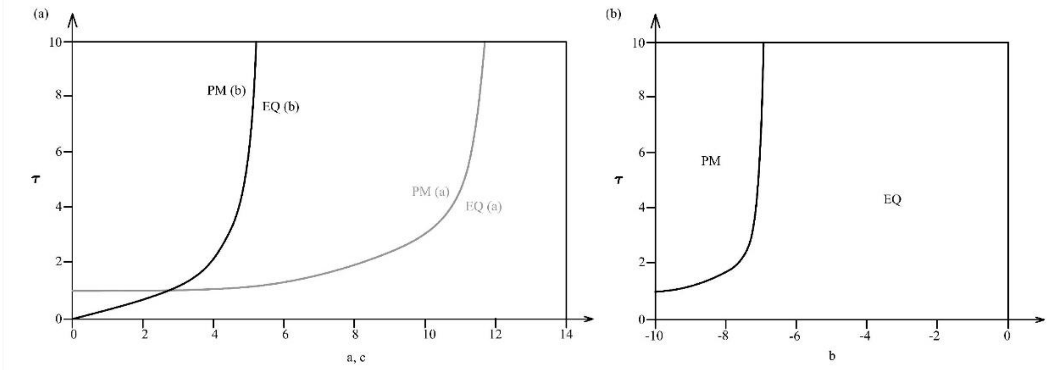


**Fig. 6.** Bifurcation diagrams regarding the effect of frictional parameters on the onset of instability: (a) τ=f(a), (b) τ=f(b), (c), τ=f(c) for fixed parameters values: $V_0$ = 0.1, K=7, a=3.2, b=-7.2 and c=4.8. EQ stands for the equilibrium state, while PM denote periodic (oscillatory) regime.

### *3.2 Effect of noise*

In order to determine the adequate type of background noise, we firstly analyze the real recordings of the ambiental noise before and after the small seismic event recorded at accelerograph station ETNA located at Zavoj dam (Fig. 7), which is considered to be a landslide-prone area. For this purpose, we invoke the method of surrogate data testing. We constructed 20 surrogate time series, and calculated the zeroth-order prediction error, which were tested against a null hypothesis that data represent a linear stationary stochastic process with Gaussian inputs. For this purpose, 20 surrogate datasets were formed by randomizing the Fourier surrogates of the original data, and then by computing the inverse transform to obtain randomized time series.

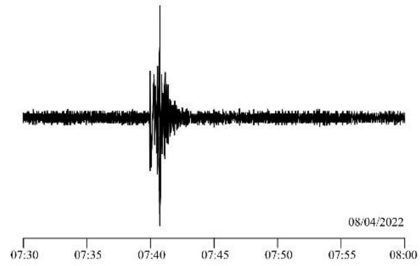


**Fig. 7.** Ambiental noise before and after the small seismic event on 08/04/2022 recorded at ETNA accelerograph station at location of Zavoj dam.

The results of the analysis indicated that background noise belongs to the linear stationary stochastic process with Gaussian inputs, since zeroth-order prediction error $\varepsilon_0$ is within $\varepsilon$ for all the tested surrogates (Fig. 8).

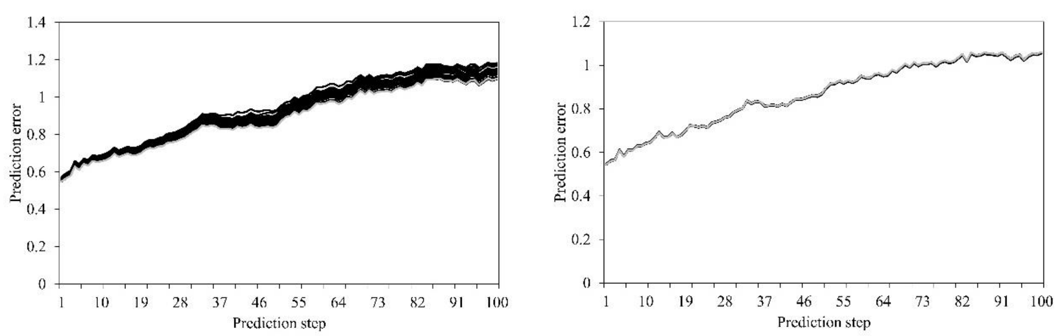


**Fig. 8.** Results of surrogate data testing that background noise belongs to the linear stationary stochastic process with Gaussian inputs: temporal distribution of the zeroth-order prediction error for the original dataset (gray) and for the surrogate datasets (black). It is clear that $\varepsilon_0$ is well within $\varepsilon$ for all the tested surrogates.

The analysis of the influence of background random noise on dynamics of landslide model (4) is conducted numerically, using 4th order Runge-Kutta numerical method, under the effect of the introduced time delay $\tau$ and spring stiffness k. Results of the conducted analysis indicate the occurrence of the direct supercritical Hopf bifurcation, with the increase of time delay and/or spring stiffness (Fig. 9). Particularly, the observed dynamical system goes from equilibrium state to regular periodic oscillations, which are considered as the unstable dynamical regime.

Regarding the effect of noise, there is a positive effect of background random noise on the landslide stability. This effect could be clearly seen both for the low and high values of time delay and spring stiffness, as shown in Fig. 9. Such effect for high values of time delay and relatively low values of spring stiffness is shown in Fig. 10(a). Such conditions are expected in strongly weathered rock masses, with the loose connections between the actually moving parts of the unstable slope, where higher values of delayed displacements are expected. On the other and, effect of noise for low values of time delay and high values of spring stiffness is shown in Fig. 10(b). Such regime corresponds to the slope built of rock mass which is just slightly weathered and with low deformability, where low values of delayed displacements are expected. One could see that increase of D for constant k and $\tau$ leads to stabilization of landslide dynamics.

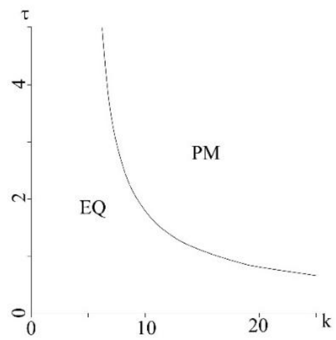


**Fig. 9.** Bifurcation diagrams τ-k for model (4). While τ and k are varied, other parameters are being held constant: ε=10-4, p=1, $V_0$=0.2, a=4.8, b=-7.2, c=3.2, initial conditions: $m_x$=0.001, $m_y$=0.0001; $s_x$=$s_y$=0.05, D=0.0001.

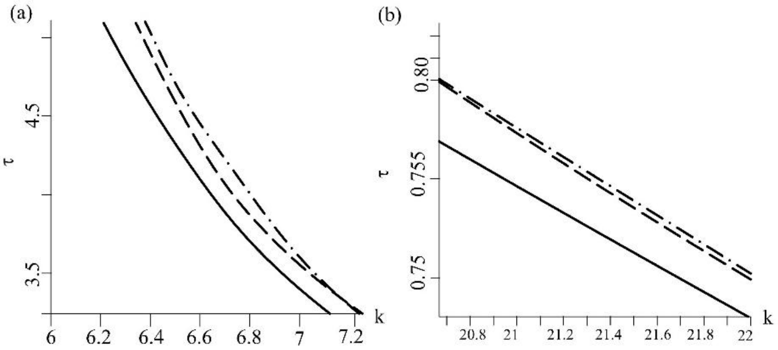


**Fig. 10.** Effect of noise intensity on dynamics of the observed system (4): (a) for high values of time delay τ and low values of spring stiffness k, (b) for low values of time delay τ and high values of spring stiffness k. Constant values of other parameters are the same as for Fig. 9. Continuous curve stands for D=$10^{-4}$, dashed curve for D=$10^{-3}$ and dashed-dot curve for $10^{-2}$.

## 3. Conclusions

The effect of delayed displacement and random background noise is examined in the present paper. Displacement delay is assumed following the initial suggestion made by Davis [4]. New models for landslide dynamics are proposed and investigated. The influence of time delay is examined in the suggested two-block model, with the assumed rate-dependent friction law. Impact of noise, on the other hand, is analyzed in a model of n globally coupled blocks. Background noise is introduced in the model as random, considering the results of ambiental noise testing recorded before and after the small seismic event on 08/04/2022 at ETNA accelerograph station installed at the location of Zavoj dam (landslide prone area). Surrogate data testing indicates that recorded time series belong to the linear stationary stochastic process with Gaussian inputs.

Modelling of landslide dynamics is conducted under the following assumptions: (a) friction law is rate dependent; (b) time delay exists in displacement of neighboring blocks; (c) there is a permanent effect of background seismic noise. Both models exhibit small constant displacements in equilibrium state, which is considered to correspond to the continuous movements of creep landslides. Examples of recorded superficial displacements of geodetic benches and movements along the depth in the installed inclinometer at the location of "Plavinac" landslide (Smederevo, Serbia) are presented.

Dynamics of the two-block model is represented through a system of deterministic delay differential equations, which is solved numerically. On the other hand, dynamics of n all-to-all coupled blocks is assumed to be governed by a set of stochastic delay differential equations, which are solved firstly by applying the mean-field approximation and, then, by analysis the approximated deterministic system. One can easily show that both the stochastic and deterministic system exhibit qualitatively the same dynamics before and after the bifurcation point.

The results obtained indicate that in the model of two coupled blocks sliding on an inclined slope, increase of time delay for certain friction conditions between the upper and lower part of the slope does not have effect on stability of landslide dynamics. It seems that in such setup friction plays a crucial role, and it suppresses the destabilizing effect of time delay, leading the dynamics of the observed delay model to equilibrium state for the constant value of the introduced time delay. On the other hand, fine analysis of the effect of the random background noise indicates the stabilizing effect of noise, i.e. the increase of noise intensity leads to stabilization of landslide dynamics.

Considering the significant effect of noise on landslide dynamics, further analysis should explore the possible occurrence of more bifurcation curves (more complex behavior). Also, further analysis in this direction could include possible significant effect of the artificially generated colored noise on the landslide dynamics. Regarding the effect of time delay, one could examine the possible effect of time delay in the velocities of the neighboring blocks.

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# 9th International Congress of the Serbian Society of Mechanics, July 5-7, 2023, Vrnjačka Banja, Serbia

## Invitation and Venue

It is our great pleasure to invite you to the **9th International Congress of the Serbian Society of Mechanics**. The Congress will be held in Vrnjačka Banja, Serbia, on July 5-7, 2023. Vrnjačka Banja is a municipality located in the Raška District, Central Serbia, well-known for its hot springs. Vrnjačka Banja is also the most celebrated and most popular spa town of Serbia and, at same time, a very attractive international recreation center.

## Objectives

**9th International Congress of the Serbian Society of Mechanics** aims to bring together leading academic scientists, researchers and research scholars to exchange and share experiences and research results on various aspects of Theoretical and Applied Mechanics. It will bring an interdisciplinary platform for researchers, practitioners and educators to present and discuss the most recent innovations, theories, algorithms, as well as practical challenges encountered and solutions adopted in the fields of Classical Mechanics, Solid and Fluid Mechanics, Computational Mechanics, Biomechanics, Applied Mathematics and Physics, Structural Mechanics and Engineering.

## Congress Venue

The **9th International Congress of the Serbian Society of Mechanics** will be held at the **Hotel Vrnjačke Terme (https://vrnjacketerme.rs/)**, Vrnjačka Banja.

Accommodation at the hotel can be booked by e-mail **prodaja@vrnjacketerme.rs (mailto:prodaja@vrnjacketerme.rs)** with an e-mail subject – *ICSSM 2023 Congress* (in order to get a special discount for accommodation as a conference participant).

## Important Dates:

- Tentative: **Manuscript Submission** **20th April, 2023**
- Tentative: **Manuscript Notification** **15th May, 2023**
- Tentative: **Registration Fee** **15th June, 2023**



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## Plenary Speakers:

1. **Assoc. Prof. Dr Miha Brojan** – *University of Ljubljana, Slovenia*

   Title: **From symmetry breaking to functionality: Examples from nonlinear mechanics of beams, plates and shells**
2. **Prof. Dr. Dimitri V. Georgievskii** – *Institute of Mechanics, Lomonosov Moscow State University, Russia*

   Title: **Elements of the Theory of Constitutive Relations and Formulations of the Linearized Problems on Stability**
3. **Prof. Dr. Stefano Lenci** – *Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, Ancona, Italy*

   Title: **Nonlinear Wave Propagation in Cables and Beams Resting on a Bilinear Foundation**
4. **Prof. Dr. Parviz Moin** – *Center for Turbulence Research, Stanford University, California, USA*

   Title: **Large Eddy Simulation at Affordable Cost: Application to a Full Aircraft Configuration**
5. **Prof. Dr Rafal Rusinek** – *Lublin University of Technology, Lublin, Poland*

   Title: **Bio-electro-mechanical System of the Human Middle Ear**