Braking effect (velocity-strengthening) of Kaolinite under intermediate slip velocities

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Introduction

According to the rock mechanics theory, friction prevents the sliding mass from moving. Furthermore, the velocity is affected by the friction strength. A lot of research concentrate on the frictional resistance of the interfaces decreasing while the sliding rates increase. Velocity-strengthening friction has been less noticed, despite its importance for various aspects of frictional phenomena, such as the propagation speed of interfacial rupture fronts and the amount of stored energy released by them. A series of experiments are carried out under intermediate slip velocities (10^{-7} to 1 m/s) on a sample via low to high-velocity rotary shear apparatus with the normal stress of 1 MPa. This thesis conducts two different conditions for shear samples: constant velocity and velocity-step. This study shows that the velocity-step sample steady-state friction coefficient is lower than constant velocity. Comparing this thesis's results with the previous studies, the steady-state friction coefficient and the standard deviation are relatively large. This study builds velocity-dependent friction law from the results of the steady-state friction coefficient and velocity of (Ferri et al., 2011) and pure Kaolinite. With the combination of the law and the friction coefficient only going up without decreasing even the moving mass stops, this study analyzes the process slide of creeping landslides on the stability of infinite slopes with parallel seepage. Although the friction strength of true landslide material (Ferri et al., 2011) and pure Kaolinite is different, the effect of the height of water table above failure surface (h_w) on results is similar. The investigation results showed that h_w significantly impacts acceleration, velocity, and displacement. If $h_w > h_{w-critical}$, the slope will keep sliding without stopping so that keeps the groundwater table always below $h_{w-critical}$. This thesis considers two cases: 1) If the same law, the maximum acceleration and velocity increase, especially with the displacement of the sliding mass significantly rising; 2) if the same h_w: a) the maximum acceleration, velocity, and displacement are larger from Law 1 to Law 4 for true landslide material (Ferri et al., 2011) and from Law 5 to Law 8 for pure Kaolinite, and b) the faster the time duration to reach the peak of the groundwater table rises, the higher the maximum velocity, the accumulated displacement is smaller. It is possible to use the Newmark method to determine the relationship between hw and friction coefficient under various circumstances, such as slope geometry and materials. Applying the landslide warning threshold to evaluate slope instability.

Methodology

The rotary-shear low- to high-velocity frictional testing

A low to high velocity rotary shear apparatus (Fig. 1) was used to measure the apparent friction coefficient of kaolinite clay under a normal stress of 1 MPa and slip rate ranged from 10^{-7} to 1 m/s.

Figure 1. Low to high-veloci rotary shear apparatus installed in National Central University, Taiwan.

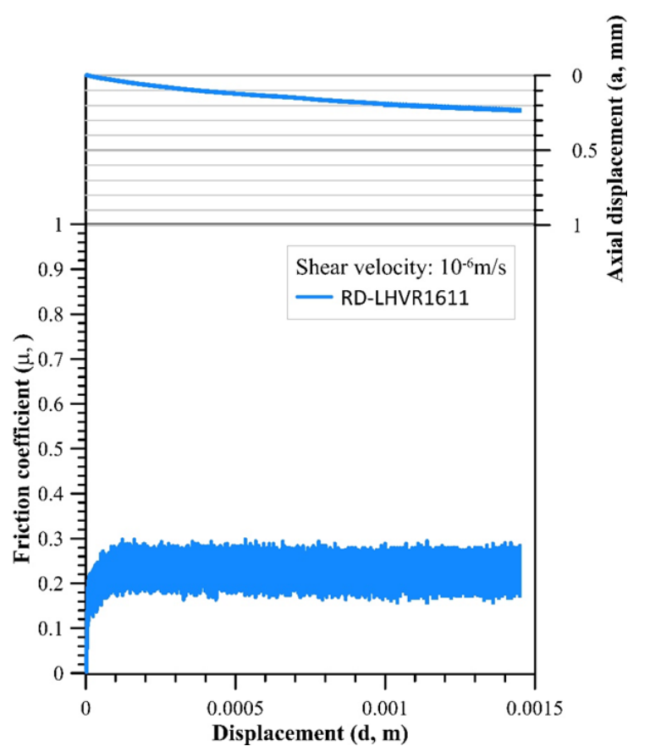


Figure 2. Constant velocity ($v = 10^{-6}$ m/s)

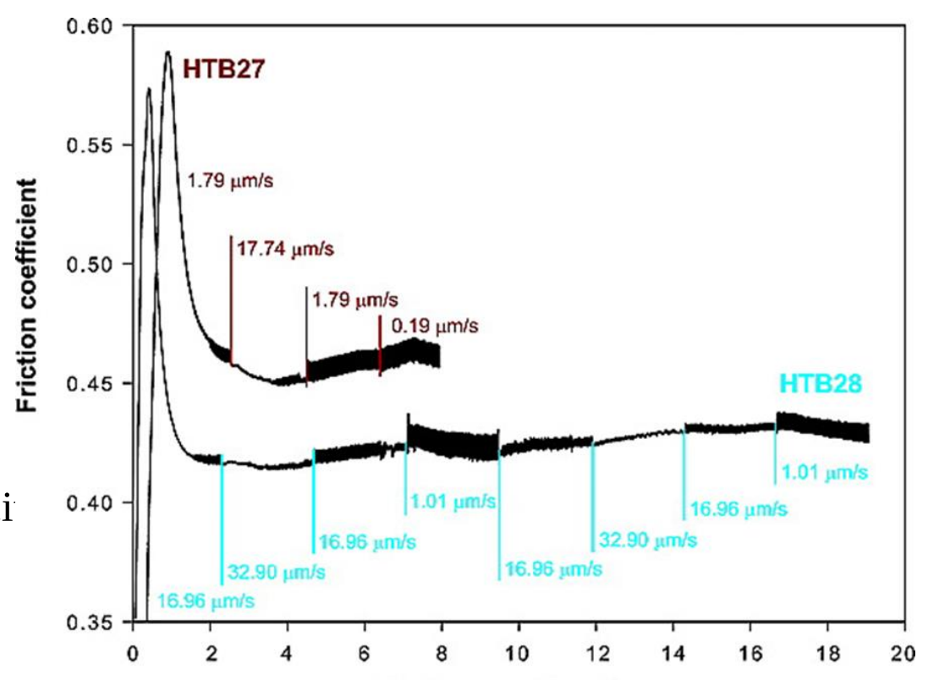


Figure 3. Velocity-step (Ferri et al., 2011)

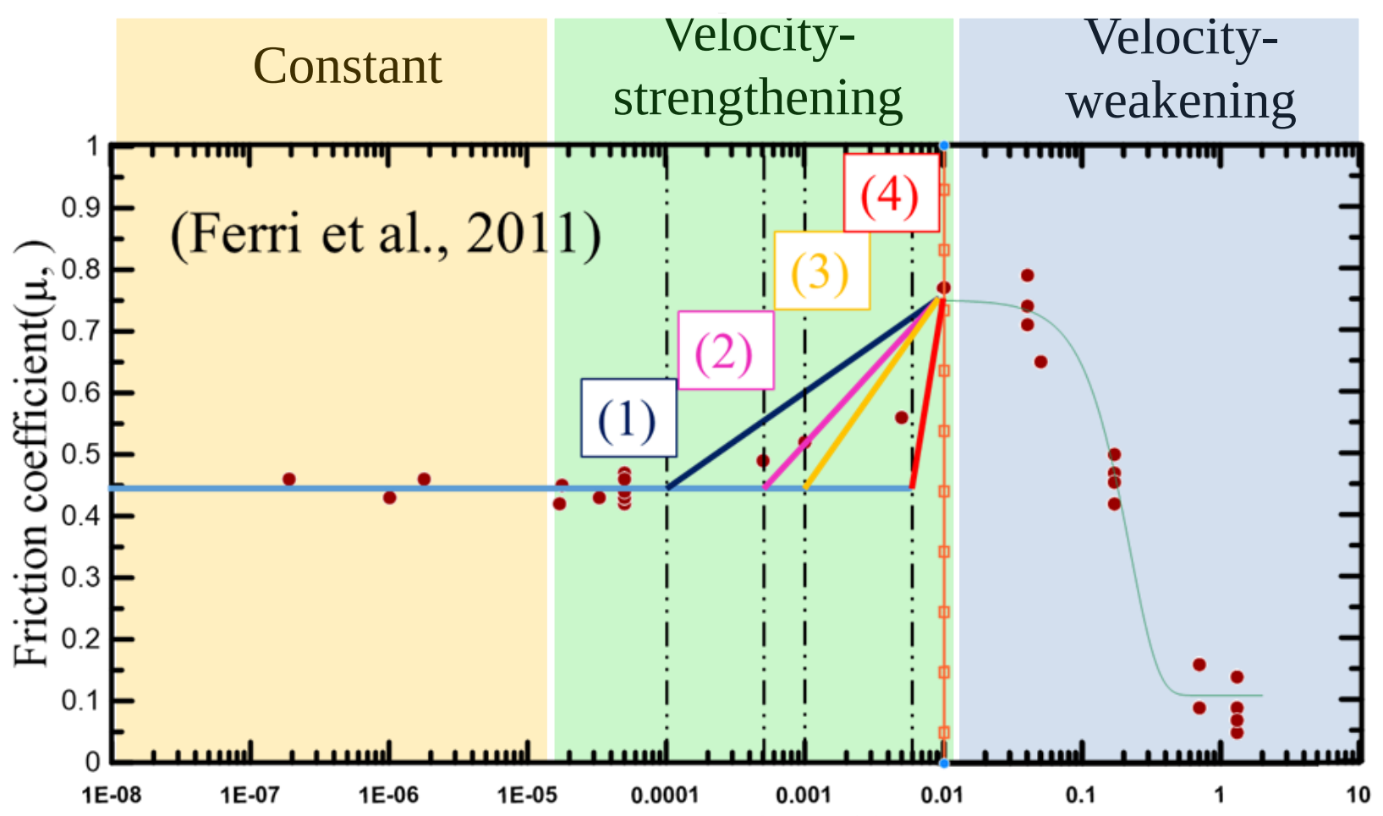


Figure 4. The steady-state apparent friction coefficients under different slip rates for true landslide material Ferri et al.,2011

The velocity-dependent friction Law 1

$$\mu(v)\begin{cases} = 0.44, & v < 0.0001\ \text{m/s} \\ = 0.0656 \times \ln(v) + 1.0477, & 0.0001 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 2

$$\mu(v)\begin{cases} = 0.44, & v < 0.0005\ \text{m/s} \\ = 0.1127 \times \ln(v) + 1.3099, & 0.0005 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 3

$$\mu(v)\begin{cases} = 0.44, & v < 0.001\ \text{m/s} \\ = 0.1362 \times \ln(v) + 1.3827, & 0.001 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 4

$$\mu(v)\begin{cases} = 0.44, & v < 0.0001\ \text{m/s} \\ = 0.457 \times \ln(v) + 2.8632, & 0.0001 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-weakening equation:

$$\mu(v) = 0.11 + (0.75 - 0.11)\exp(-v^{2.13}/0.04),\ v > 0.01\ \text{m/s}$$

Infinite Slopes in Soils with Parallel Seepage

a: the slice of width (m)
h: height soil (m)
h_w: height watertable above failure surface (m)
C : cohesion soil ($\frac{kN}{m^2}$)
γ_w: unit weight water ($\frac{kN}{m^3}$)
γ_{sub}: unit weight soil ($\frac{kN}{m^3}$)
i: slope angle
θ_s : saturated water content (V-%)

Weight of moist soil:

$$W_m = \gamma_s . h + \underbrace{\boxed{\theta_s \gamma_w h_w}}_{\text{Weight of water}} - \underbrace{\boxed{\gamma_w h_w}}_{\text{Buoyancy}} = \gamma_s h + (\theta_s - 1)\gamma_w h_w \sim \left[\frac{kN}{m^3}.m = \frac{kN}{m^2} = Pa\right]$$

Normal force:

$$N = W_m . \cos i \sim [Pa]$$

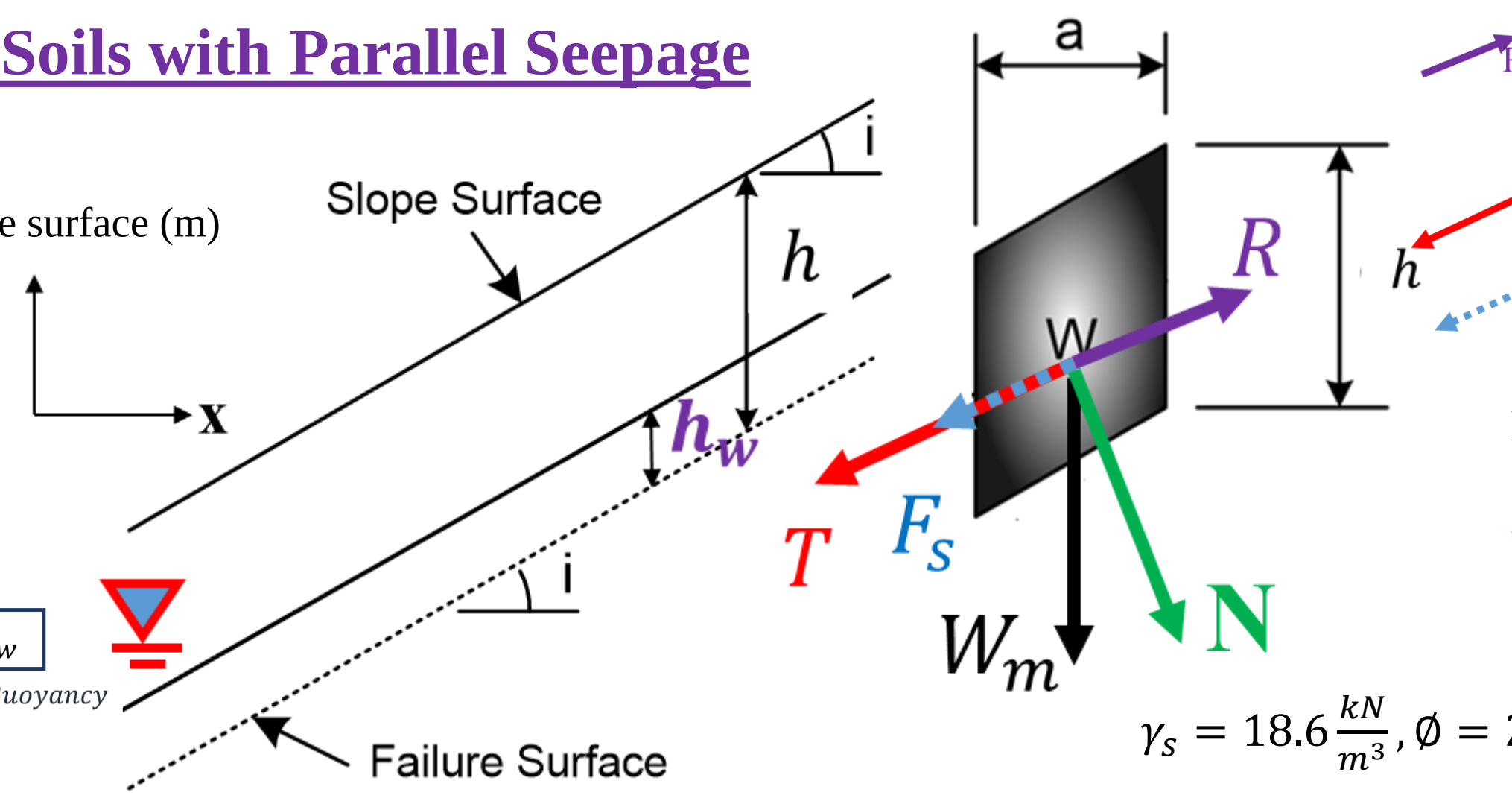


Figure 5. Infinite Slopes in Soils with Parallel Seepage

Resistance force

$$R = N\tan\varphi + \frac{c}{\cos i} = W_m . \cos i . \tan\varphi + \frac{c}{\cos i} \sim [Pa]$$

Shear force:

$$T = W_m . \sin i \sim [Pa]$$

Seepage force:

$$F_s = \gamma_w h_w \sin i \sim [Pa]$$

Driving force:

$$D = T + F_s = W_m . \sin i + \gamma_w h_w \sin i \sim [Pa]$$

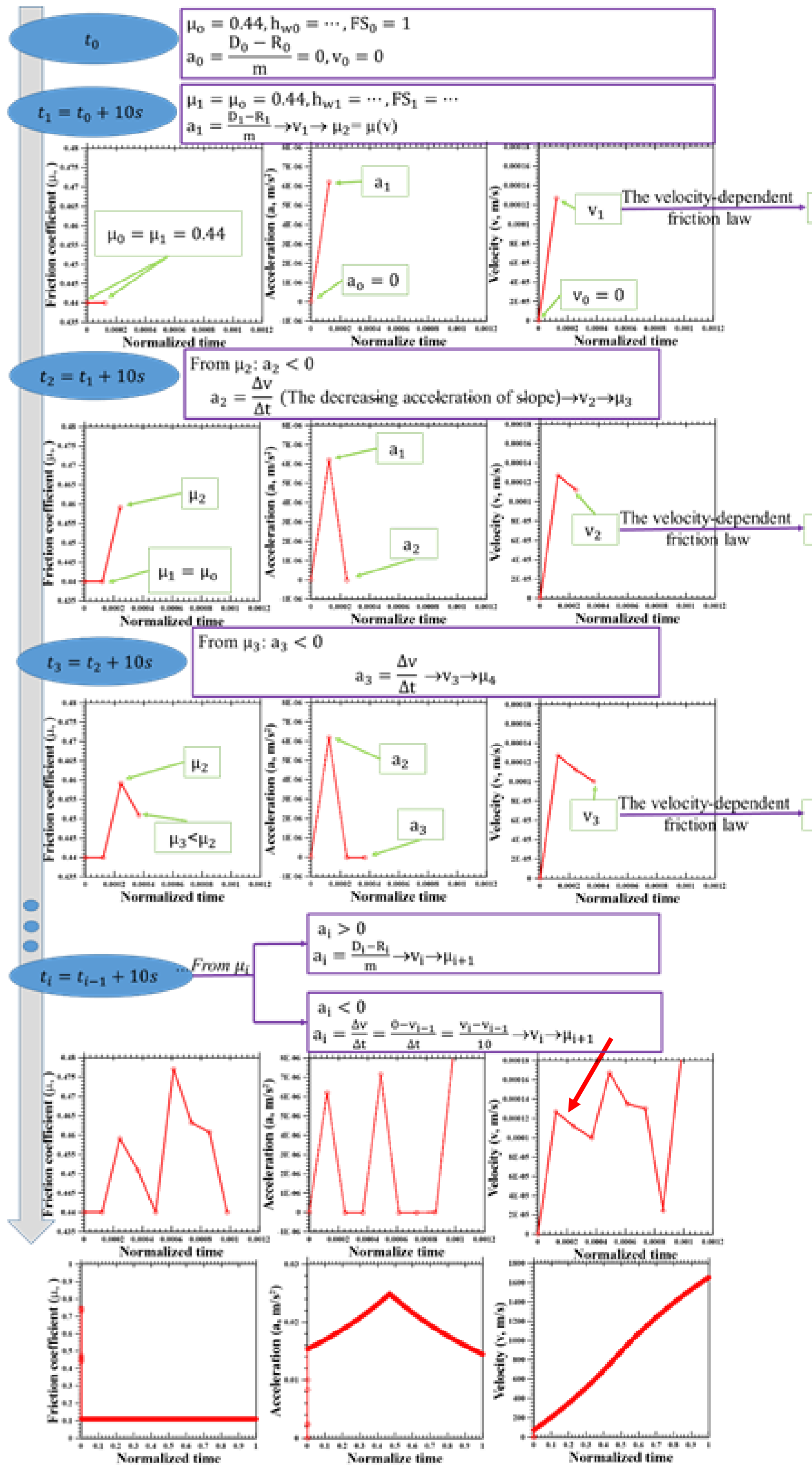
Acceleration (Newton's 2nd law):

$$a = \frac{F}{Weight} = \frac{D - R}{Weight}$$

$\gamma_s = 18.6\frac{kN}{m^3}, \emptyset = 24^0, C' = 0, \theta_s = 39\%, \gamma_w = 9.81\frac{kN}{m^3}$ and

$i = 23^o$ for Ferri's sample, $i = 11^o$ for pure Kaolinite

Approach 1: The friction coefficient increased with increasing velocity will drop back to original static friction coefficient



t_0: $\mu_0 = 0.44, h_{w0} = \cdots, FS_0 = 1$; $a_0 = \frac{D_0 - R_0}{m} = 0, v_0 = 0$

$t_1 = t_0 + 10s$: $\mu_1 = \mu_0 = 0.44, h_{w1} = \cdots, FS_1 = \cdots$; $a_1 = \frac{D_1 - R_1}{m} \rightarrow v_1 \rightarrow \mu_2 = \mu(v)$

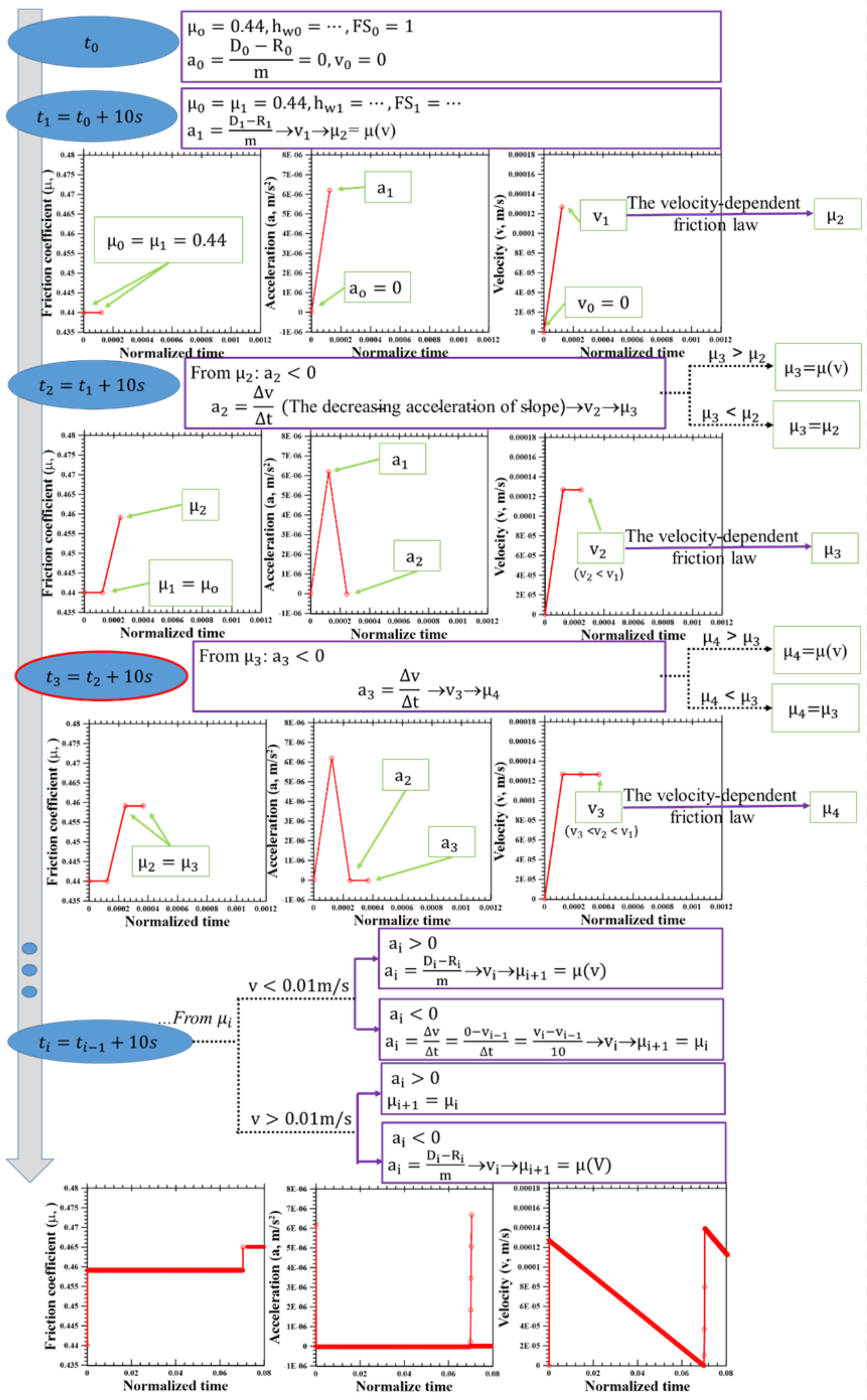
$t_2 = t_1 + 10s$: From μ_2: $a_2 < 0$; $a_2 = \frac{\Delta v}{\Delta t}$ (The decreasing acceleration of slope)$\rightarrow v_2 \rightarrow \mu_3$

$t_3 = t_2 + 10s$: From μ_3: $a_3 < 0$; $a_3 = \frac{\Delta v}{\Delta t} \rightarrow v_3 \rightarrow \mu_4$

$t_i = t_{i-1} + 10s$ …From μ_i:

- $a_i > 0$: $a_i = \frac{D_i - R_i}{m} \rightarrow v_i \rightarrow \mu_{i+1}$
- $a_i < 0$: $a_i = \frac{\Delta v}{\Delta t} = \frac{0 - v_{i-1}}{\Delta t} = \frac{v_i - v_{i-1}}{10} \rightarrow v_i \rightarrow \mu_{i+1}$

Approach 2: The friction coefficient will only go up without decreasing even the moving mass stopped



t_0: $\mu_0 = 0.44, h_{w0} = \cdots, FS_0 = 1$; $a_0 = \frac{D_0 - R_0}{m} = 0, v_0 = 0$

$t_1 = t_0 + 10s$: $\mu_0 = \mu_1 = 0.44, h_{w1} = \cdots, FS_1 = \cdots$; $a_1 = \frac{D_1 - R_1}{m} \rightarrow v_1 \rightarrow \mu_2 = \mu(v)$

$t_2 = t_1 + 10s$: From μ_2: $a_2 < 0$; $a_2 = \frac{\Delta v}{\Delta t}$ (The decreasing acceleration of slope)$\rightarrow v_2 \rightarrow \mu_3$

- $\mu_3 > \mu_2$: $\mu_3 = \mu(v)$
- $\mu_3 < \mu_2$: $\mu_3 = \mu_2$

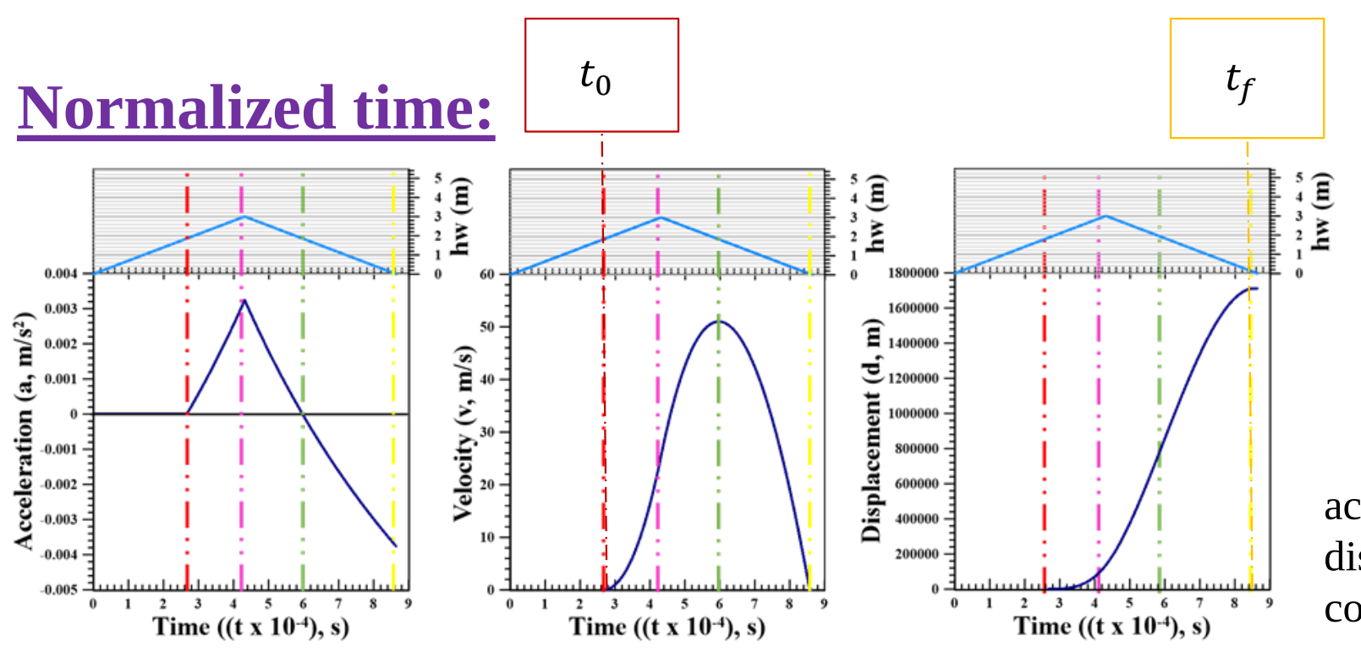
$t_3 = t_2 + 10s$: From μ_3: $a_3 < 0$; $a_3 = \frac{\Delta v}{\Delta t} \rightarrow v_3 \rightarrow \mu_4$

- $\mu_4 > \mu_3$: $\mu_4 = \mu(v)$
- $\mu_4 < \mu_3$: $\mu_4 = \mu_3$

$t_i = t_{i-1} + 10s$ …From μ_i:

- $v < 0.01$m/s:
  - $a_i > 0$: $a_i = \frac{D_i - R_i}{m} \rightarrow v_i \rightarrow \mu_{i+1} = \mu(v)$
  - $a_i < 0$: $a_i = \frac{\Delta v}{\Delta t} = \frac{0 - v_{i-1}}{\Delta t} = \frac{v_i - v_{i-1}}{10} \rightarrow v_i \rightarrow \mu_{i+1} = \mu_i$
- $v > 0.01$m/s:
  - $a_i > 0$: $\mu_{i+1} = \mu_i$
  - $a_i < 0$: $a_i = \frac{D_i - R_i}{m} \rightarrow v_i \rightarrow \mu_{i+1} = \mu(V)$

Normalized time:



$$\frac{t - t_0}{t_f - t_0}$$

Figure62. The acceleration, velocity and displacement at friction coefficient is contant (0.44)

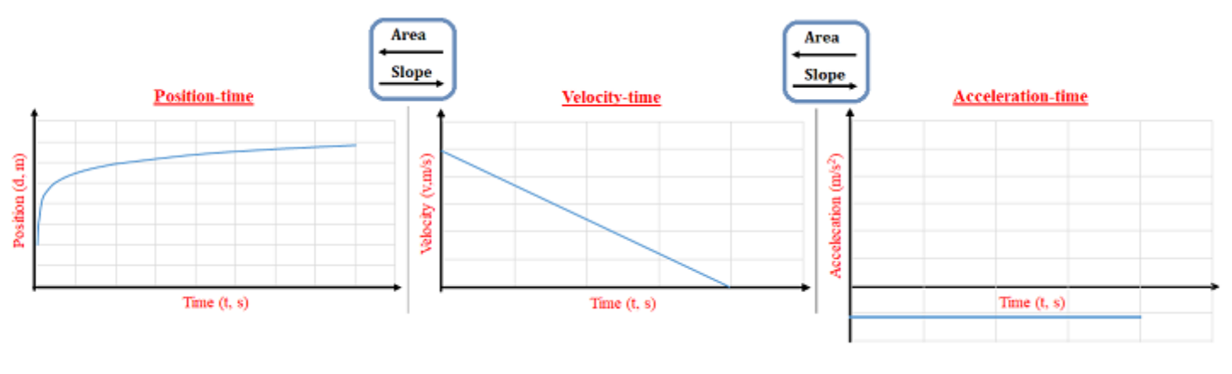


Figure 7. The decreasing acceleration of slope

Results

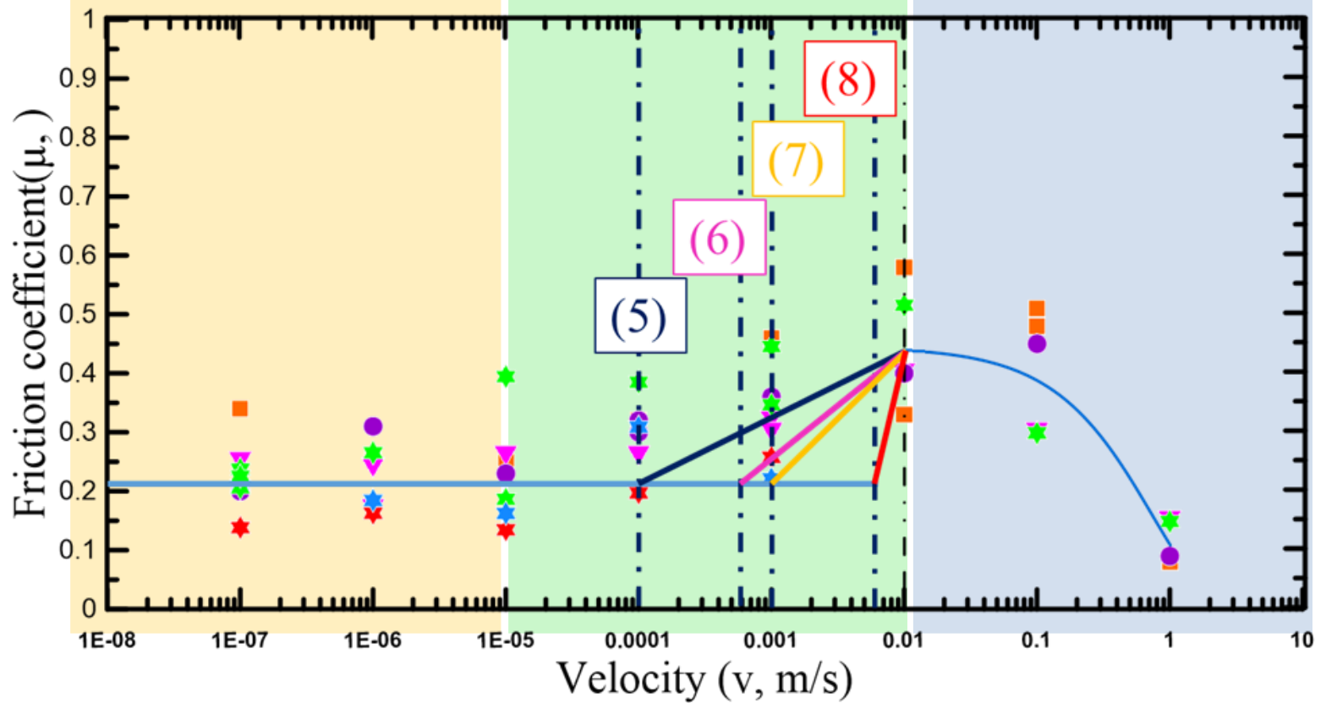


Figure 8. The steady-state apparent friction coefficients under different slip rates for pure Kaolinite

The velocity-dependent friction Law 5

$$\mu(v)\begin{cases} = 0.205, & v < 0.0001\ \text{m/s} \\ = 0.0518 \times \ln(v) + 0.683, & 0.0001 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 6

$$\mu(v)\begin{cases} = 0.205, & v < 0.0005\ \text{m/s} \\ = 0.0783 \times \ln(v) + 0.8024, & 0.0005 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 7

$$\mu(v)\begin{cases} = 0.205, & v < 0.001\ \text{m/s} \\ = 0.1056 \times \ln(v) + 0.9314, & 0.001 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-dependent friction Law 8

$$\mu(v)\begin{cases} = 0.205, & v < 0.005\ \text{m/s} \\ = 0.339 \times \ln(v) + 2.0021, & 0.005 < v < 0.01\ \text{m/s} \end{cases}$$

The velocity-weakening equation:

$$\mu(v) = 0.11 + (0.446 - 0.11)\exp(-v^{1.504}/0.2593),\ v > 0.01\ \text{m/s}$$

The true landslide material Ferri et al., 2011

This study

Critical groundwater table ($h_{w-critical}$)

Law	$h_{w-critical}(m)$
1	4.903
2	4.952
3	4.978
4	4.999

Table 2. Critical value of h_w in each law of Ferri's sample

If the water level h_w exceeds the $h_{w\text{-critical}}$ ($h_w > h_{w\text{-critical}}$), the slope will keep sliding without stopping (velocity-weakening). This is the case this thesis does not want to explore. This study only cares about the slowly creeping debris slide that keeps the groundwater table consistently below the $h_{w-critical}$.

Law	$h_{w-max}(m)$
5	4.708
6	4.709
7	4.709
8	4.710

Table 2. Critical value of h_w in each law of pure Kaolinite

The variation of velocity-dependent friction law.

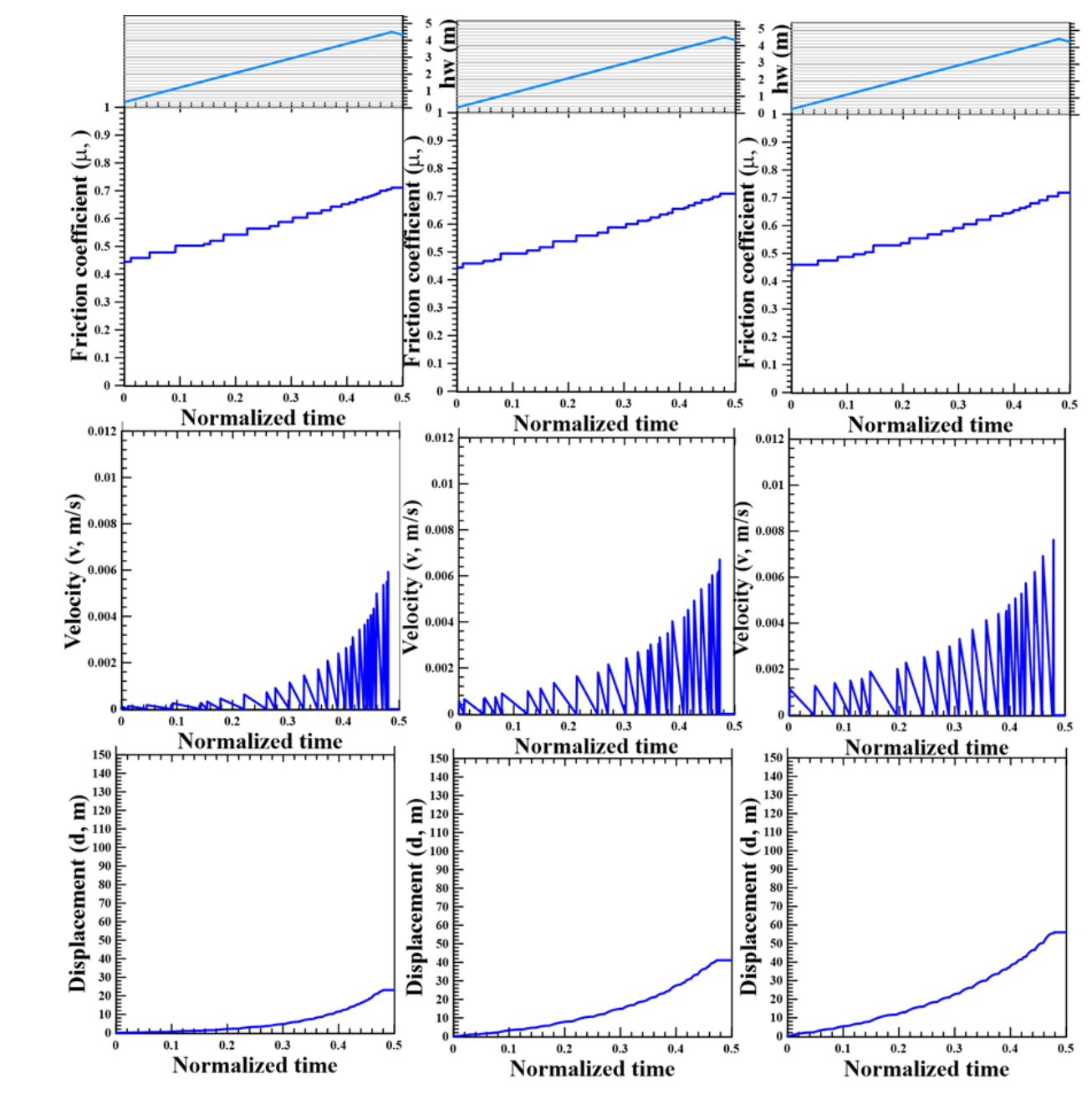


Figure 9. The velocity and displacement– normalized time at $h_{w4} = 0 - 4.5$ m for true sample in velocity-dependent friction from Law 1 to Law 3, respectively

The oscillation of velocity peak is too large in Law 4 and Law 8, so this study doesn't need to consider it

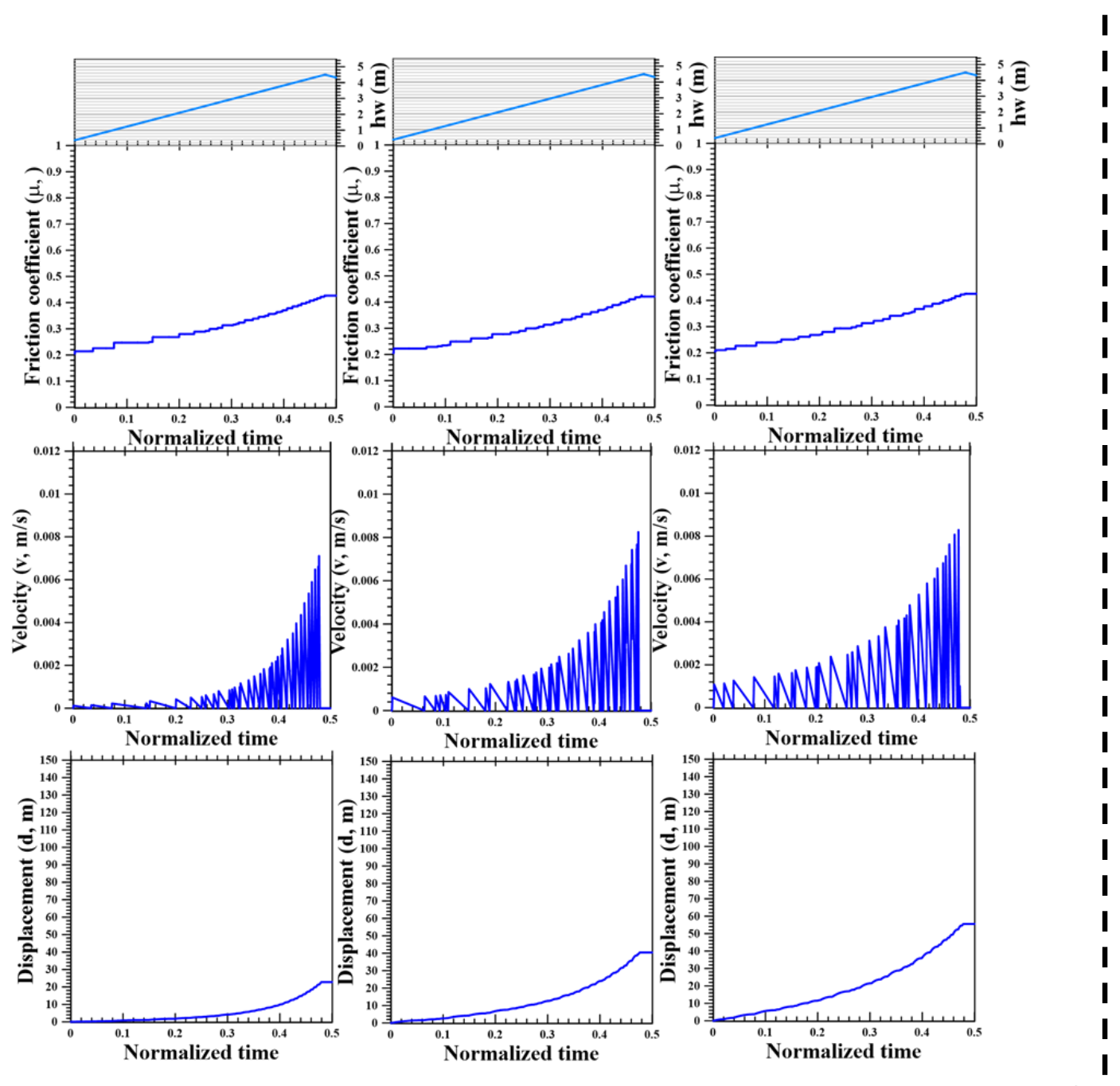


Figure 10. The velocity and displacement– normalized time at $h_{w4} = 0 - 4.5$ m for Kaolinite sample in velocity-dependent friction from Law 5 to Law 7, respectively

The peak groundwater table.

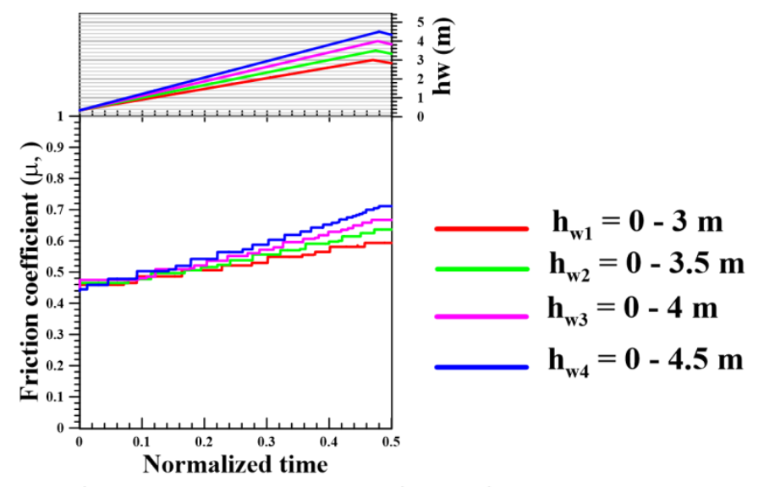


Figure 11. The friction coefficient – normalized time at $h_{w1}, h_{w2}, h_{w3}, h_{w4}$.

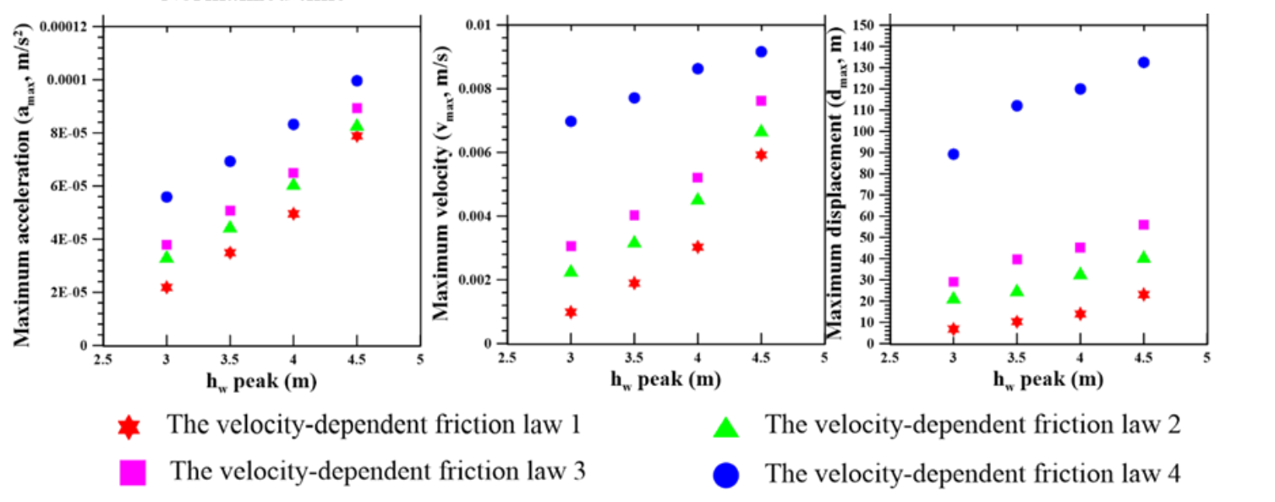


Figure 12. All results of peak acceleation, velocitu, displacement - h_w peak in the velocity-dependent friction law for true landslide material Ferri et al., 2011

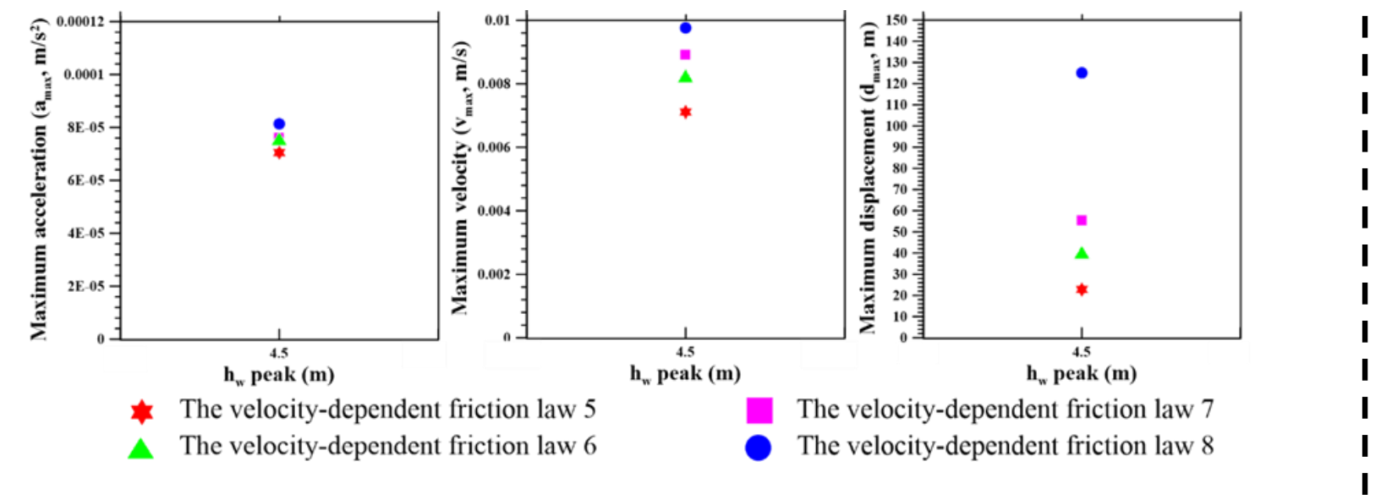


Figure 13. All results of peak acceleation, velocitu, displacement - h_w peak in the velocity-dependent friction law for pure Kaolinite

Groundwater table raising pattern.

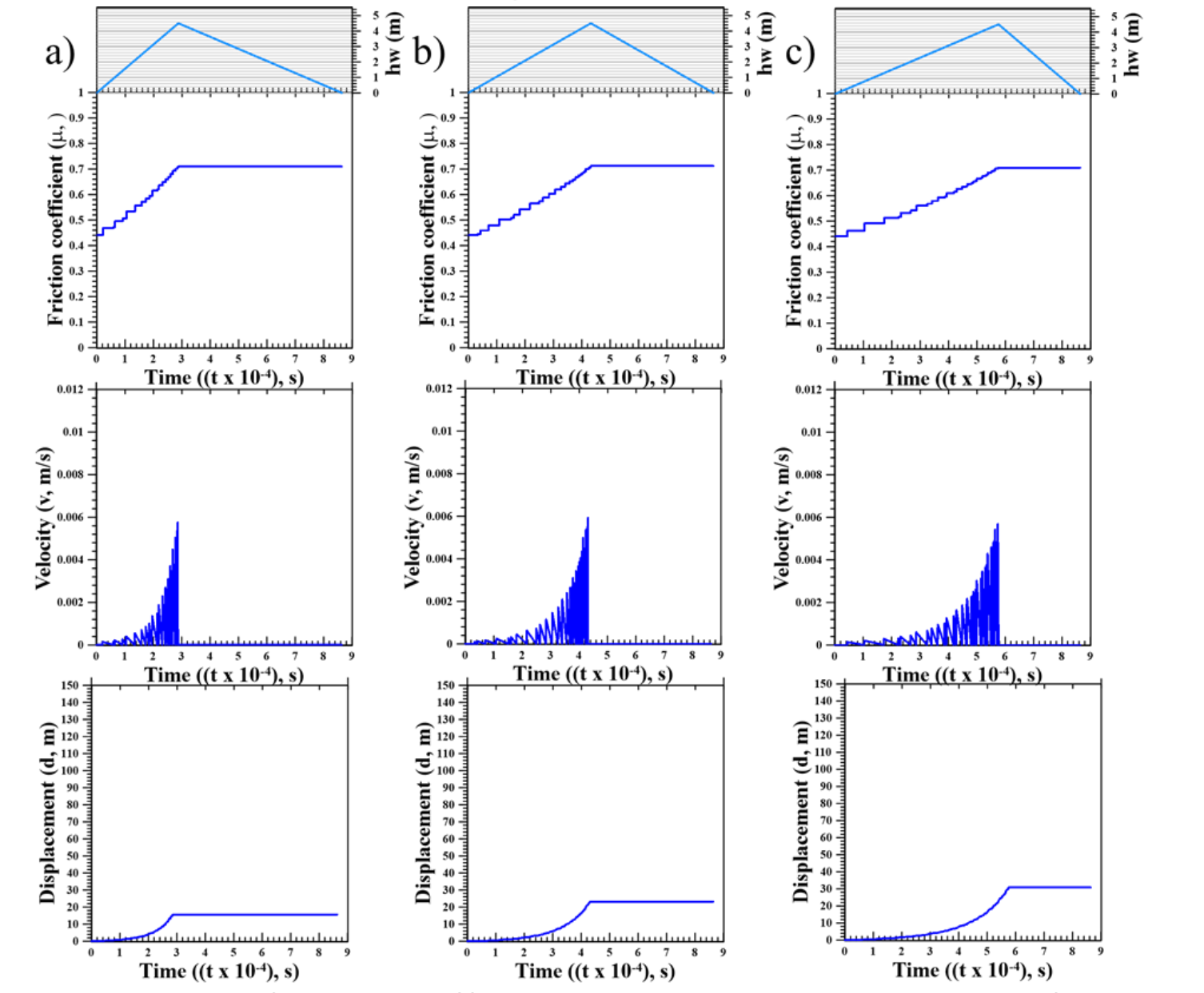


Figure 14. The friction coefficient, velocity, and displacement of true landslide material of (Ferri et al., 2011) in a day (86400 s): a) $t_{1/3}$; b) $t_{1/2}$; c) $t_{2/3}$

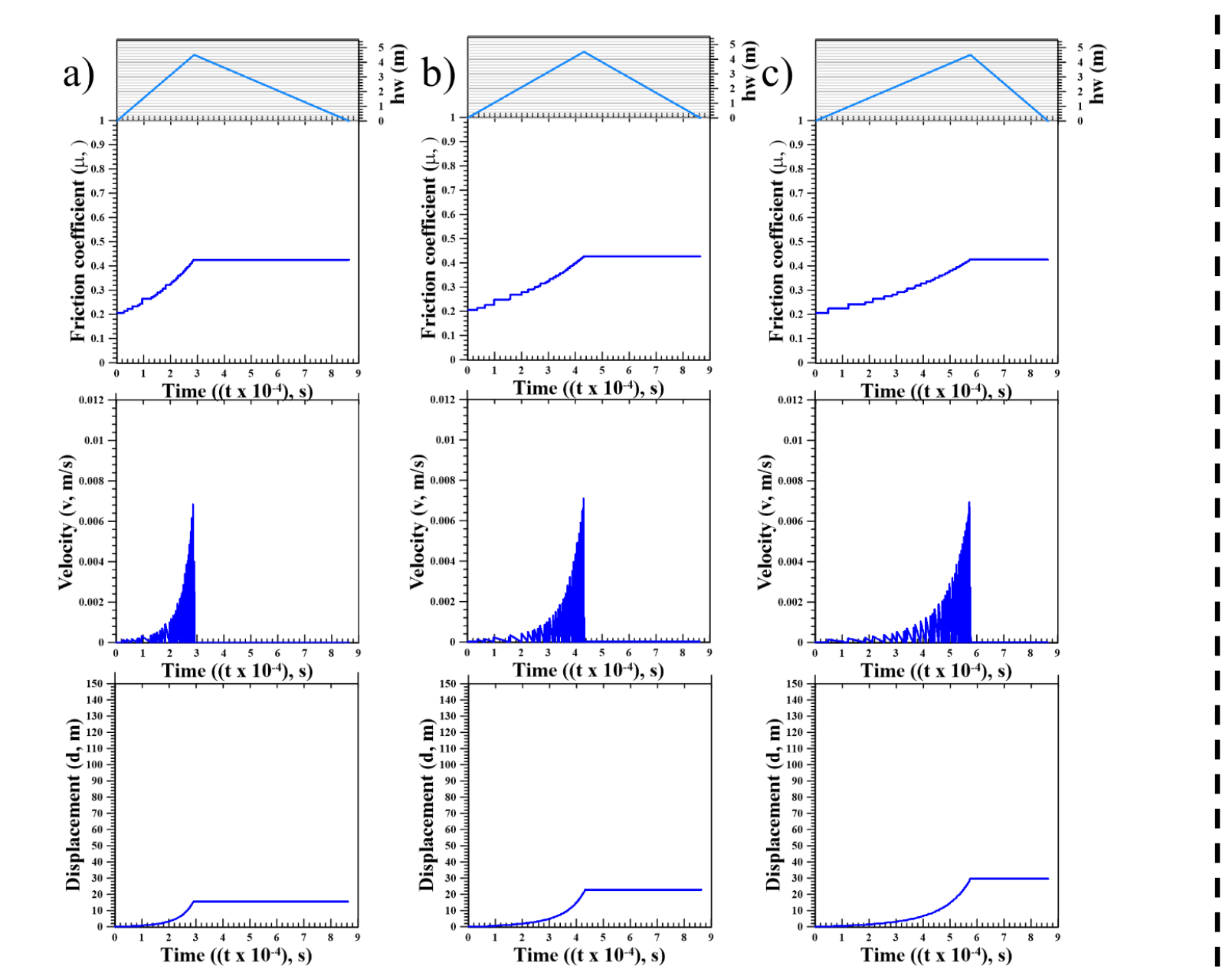


Figure 15. The friction coefficient, velocity, and displacement of true landslide material of (Ferri et al., 2011) in a day (86400 s): a) $t_{1/3}$; b) $t_{1/2}$; c) $t_{2/3}$

Discussion and Conclusion

This study is based on the Newmark displacement method to analyze the moving process of landslides. However, Newmark displacement analysis is restricted in ignoring the consequences of dynamic pore pressure. So the purpose of this study is to analyze the process of sliding mass when it is affected by pore water press. This study consider groundwater table change like rainfall-triggered landslides. Based on the testing results, the following conclusion can be drawn:

1. The steady-state friction coefficient of the velocity-step tests is lower than the constant velocity tests. The sample's friction strength is declining due to the sample's ongoing changes in slip rate.
2. Comparing this study and our previous lab results, the standard deviation of the steady-state friction coefficient is quite significant. Because correction results might be affected by the Teflon sleeve's different points of contact with the rotating holder and the determination of different points to friction coefficient reach steady-state.
3. The steady-state friction coefficient of the Kaolinite sample is lower than the (Ferri et al., 2011) sample. The cause of that phenomenon is that the Vaiont gouges sample was dried in the oven (Ferri et al., 2011), and pure Kaolinite samples in this study were kept saturating or wet. Also, the results of the pure Kaolinite and (Ferri et al., 2011) tests show the same phenomena (velocity-strengthening from 0.0001 m/s to 0.01 m/s and velocity-weakening when v < 0.01 m/s.
4. This thesis searches for various $h_{w-critical}$ with each friction law. However, $h_{w-critical}$ does not increase significantly when this study change law. .$h_{w-critical}$ is higher from Law 1 to 4 for true landslide material (Ferri et al., 2011) and from Law 5 to Law 8 for pure Kaolinite. All of the findings show the same phenomenon: the sliding mass continues to slide and diminish until it stops after reaching the highest speed due to the force of inertia. Creeping transforms to fast sliding when h_w is greater than $h_{w-critical}$ value (velocity-weakening).
5. This thesis considers for effects of h_w on the motion of a landslide by checking the same law. This study shows that the maximum acceleration and velocity rise, especially significantly increasing the displacement of sliding mass. The increasing groundwater table causes this phenomenon.
6. In the same h_w:
   - The peak acceleration and velocity are larger from Law 1 to Law 4 for true landslide material (Ferri et al., 2011) and from Law 5 to Law 8 for pure Kaolinite. They lead to the displacement is also larger.
   - The rainfall changes differently, leading to different groundwater table concentrations (Iverson, 2000). So this study try examining the time duration to reach the peak of the groundwater table affects the displacement mechanism. This thesis found that the shorter the time to the highest amount of water, the faster acceleration and velocity reach their maximum value. However, displacement of sliding mass is accumulated value, so with a long time, the accumulated displacement is higher than others, which does not affect the displacement of the sliding block.
7. The increase in water level greatly affects the rate of landslips (Zhao et al., 2017). The larger h_w, higher displacement is shown. However, displacement of sliding mass does not affect so much the displacement in the time duration to reach the peak of the groundwater table. Applying the Newmark method is possible in establishing the relationship between h_w and friction coefficient with different conditions such as slope geometry and materials. The threshold for the landslide warning and applying it to assess slope instability

References

F. Ferri, G. Di Toro, T. Hirose, R. Han, H. Noda, T. Shimamoto, M.Quaresimin and N. de Rossi, "Low- to high-velocity frictional properties of the clay-rich gouges from the slipping zone of the 1963 Vaiont slide northern Italy", J. Geophys. Res., Vol 116, B09208, doi:10.1029/2011JB008338, 2011.