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DEVELOPMENT OF "LUMPED MASS DAMPER MODEL" TO PREDICT FAILURE TIME AND VELOCITY OF LANDSLIDE

Summary:

The authors developed a simulation model using viscous damping to predict the moving velocity of landslide before it reaches a strain limit and named this model „Lumped mass damper model". Even if LMDM is very simple model based on the motion equation incorporating viscous damping, it is clarified that the analysis of landslide behavior using this LMDM is suitable method to predict the velocity and further displacement of landslides induced by not only increasing groundwater level but also by terrain modification. Furthermore, LMDM is newly improved using tank model for prediction of landslide displacement corresponding to rainfall. As a result of a lot of case studies on landslide displacement using LMDM analyses, it is found that the results of LMDM analyses are closely related to observation data of displacement up to a certain time, however they deviate after this time point. These deviation points might represent the limit strains. In order to solve this probelm of deviation, the authors modified LMDM with introduction of reduction functions on ***φ*** *and* ***Cd*** *parameters. There is a possibility to predict not only moving velocity of landslide but also failure time of landslide using analysis results by this modified LMDM.*

Key words:

Lumped mass damper model, Moving velocity, Displacement, Damper, Mass system model, Reduction function

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1. INTRODUCTION

The authors proposed a lumped mass system model with damper in order to predict moving velocity of landslide mass before reaching the strain limit [4]. This model was first briefly introduced in the GEO-EXPO 2016 in Banja Luka [8]. The analytical result using this technique to the Kostanjek landslide in Croatia shows that this mass system model is able to reproduce the variations of landslide velocity in response to the variation of groundwater level. Additional analytical result using same model on other type of landslide was reported in comparison with the analytical result on Kostanjek landslide in the 4th World Landslide Forum in Ljubljana [6]. Namely the analytical result on Takino landslide in Japan shows that this model is useful to predict the landslide velocity also for a landslide induced by the surcharge load of an embankment at the head part of a landslide area. Afterwards the authors carried out various case analyses using this model concerning 16 landslides including the Vajont landslide [5]. The targetted 16 landslides can be basically classified into two categories, although each individaul landslide has different characteristics in dimension, in topography, in triggering factor and so on. One category is a remainig type landslide: The displacement of this landslide type does not exceed the strain limit and the sliding soil mass remains on the slope. For example the Kostanjek landslide belongs to this category. Another category is a complete failure type landslide: The displacement of this landslide type exceeds the strain limit and the sliding soil mass falls down completely. For example the Vajont landslide belongs to this category. It is clarified that actually monitored values of displacement show good coincidence with calculated values by the lumped mass damper model concerning the remaining type landslide. However, it is also clarified that actually monitored values show divergence from claculated values with the same model concerning the complete failure type landslide.In order to solve the problem of such divergence, the authors introduced some modification into the lumped mass damper model.

From the view point of risk evaluation and further risk management, it is very important to predict not only landslidde velocity but also final failure time of landslide. The Saito model (1987) and Fukuzono model (1990) are well known models for predicting the final slope failure stages of landslide displacement from the collected data on earlier displacement velocity. Although these models provide very useful results for the time of the final stage of slope failure after the tertiary creep stage, they do not consider the mechanicl and physical state of landslide bodies. The effects of increasing forces induced by such phenomena as rainfall, embankment and excavating are not considered in the analyses using such models. Therefore, the authors proposed a simulation model, which is a mass system model incorporating with viscous damping, on the basis of the motion equation. This model was named „lumped mass damper model". In this paper, first the concept of the model is described. Subsequently, analytical results on Kostanjek landslide as a remainig type landslide and also on Oikubo landslide as a copmplete failure type landslide are described. Modifictaion of the model is introduced based on the analytical result on Oikubolandslide as a complete failure type landslide. Finally model characteristics especially physical meaning of ϕ and Cd reductions are discussed.

2. MODEL COMPOSITION

This model can be incorporated into simple slope stability analysis such as Fellenius method. The viscous damping is introduced to express a damping force, which acts in the opposite direction to the motion of the landslide, according to the landslide velocity. In the slope stability analysis, resistant force (***R***) and driving force (***D***) are calculated for each individual slice and summed for all slices. The safety factor (***Fs***) of the slope stability is indicated as '$Fs = R/D$'. Downward force (***F***) is defined as difference between driving force and resistance force namely as $F = D - R$. Damper (***k***) is introduced to express damping force which effects along the sliding surface in the opposite direction to downward force (***F***) as shown in Figure 1. Damping force is proportional to to the velocity (***v***). Damper (***k***) is defined as product of coefficient of viscous resistance (***Cd***) and area of sliding surface of landslide mass (***A***). Namely $k = A \cdot Cd$.

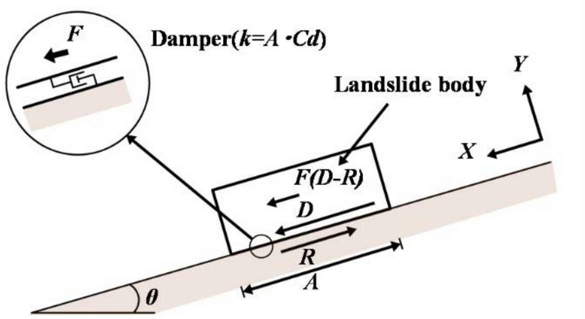

Figure 1. Kinematic diagram on landslide body with damper (Hamasaki et al, 2016) [4]

2.1. Model formula

The equation of motion to describe the motion of landslide body is formulated as shown in equation (1), considering the force components acting the landslide body on the slope shown in Figure 1:

$$m\alpha = F - kv \tag{1}$$

Where,

m: Mass of the landslide body

α : Moving acceleration of the landslide

F : Downward force [$F = D - R$, $F > 0$] ($D = mg\sin\theta$, $R = (mg\cos\theta - u)\tan\varphi' + c'A$)

k : Coefficient of Viscous resistance [$k = A\mathrm{Cd}$]

v : Moving velocity of the landslide

Dividing equation (1) by m, leads to the following formula:

$$\frac{dv}{dt} = \frac{F}{m} - \frac{k}{m} \cdot v \tag{2}$$

Where,

t : Time

dv/dt : Acceleration of the landslide [= α]

Using the method of separation of variables in equartion (2), and integrating both sides of the equation with respect to time, the lanslide velocity is indicated by the following equation:

$$v = \frac{F}{k}(1 - e^{\frac{-k}{m}t}) \tag{3}$$

Since $k = A \cdot Cd$, equation (3) is transformed to the following eqaution:

$$v = \frac{F}{A \cdot Cd}(1 - e^{\frac{-A \cdot Cd}{m}t}) \tag{4}$$

Moreover, in a very short time ($t < 10^{-5}$ second by calculation) , the term ($e^{\frac{-A \cdot Cd}{m}t}$) will converge to 'zero'. Hence, the velocity of landslide is given approximately as:

$$v \approx \frac{F}{A \cdot Cd} \tag{5}$$

Equation (5) means that when ***A·Cd*** is constant, the landslide velocity increases or decreases in direct ratio to the downward force (Hamasaki et al., 2016)

2.2. Damper characteristics

Damper characteristics are depending on velocity of landslide movement. Figure 2 shows the schematic diagram of creep for the relationship between downward force (***F***) and displacement (***X***) of the landslide. Here, the velocity (***v***) varies in proportion to the downward force, F, as indicated in equation (5). Based on this model, when F is less than zero, the velocity of landslide is zero, hence the displacement ***X*** does not increase. However, when ***F*** is greater than zero, the displacement ***X*** begins to increase. During the duration of increasing ***v*** and ***F***, the acceleration (***α***) is greater than zero. At the same time, the displacement ***X*** increases, as in tertiary stage. On the other hand , during a reduction of ***F*** (>0), the landslide slows at the same time. However, the ***X*** contnues to increase while the rate of increase of ***X*** is reduced, as in primary creep. Moreover, when the value of ***F*** continues at constant value greater than zero, the velocity ***v*** also remains constant. Therefore, the acceleration is zero and the velocity remains constant as in secondary creep.

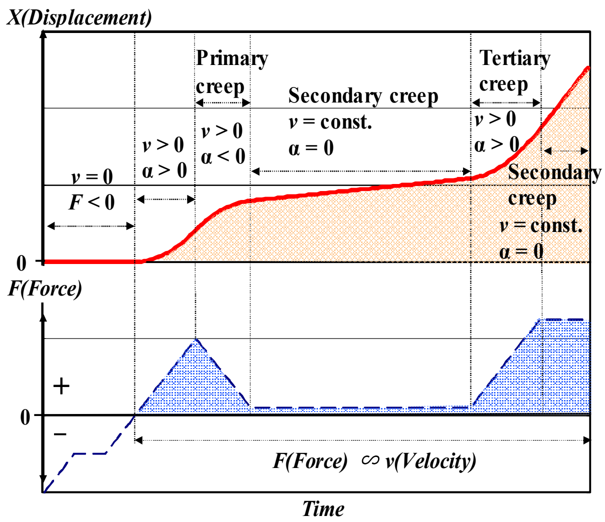

Figure 2. Schematic diagram for relation between Force (F) and Displacement (x) (Hamasaki et al., 2016) [6]

3. ANALYSIS ON THE KOSTANJEK LANDSLIDE

The Kostanjek landslide, located in Zagreb in Croatia, is a large deep-seated translational landslide, with a approximate width of 1000 m, a maximum length of about 1,300 m and a thickness of about 70 m(Figure 3). The geological features affecting the landslide are the distribution of Tripoli mar and the gentle slope of structural bedding planes. Relationship among monitoring data is shown in Figure 4. Using this lumped mass damper model , the variation of landslide velocity in response to the variation of the groundwater level concerning Kostanjek landslide is analysed. In consideration of available data values, a simlified lumped mass damper model as shown in Figure 5 is used for two dimensional slope stability analysis. The moving velocity (***v***) and displacement (***X***) of the Kostanjek landslide are calculated using daily observation results of groundwater level concerning target period. The safety factor (***Fs***) of the lanslide is also calculated as ***Fs*** = ***R***/***D***.

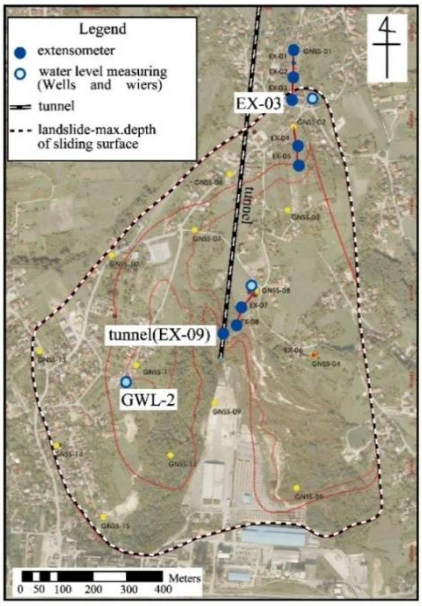

Figure 3. Plan of Kostanjek landslide and location of monitoring equipment (Hamasaki et al, 2016) [4]

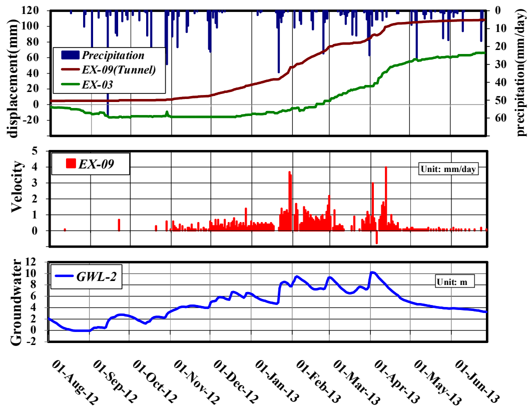

Figure 4. Relationship among monitoring data (daily precipitation, displacement of extensometers EX-09 and EX03, velocity of EX-09, growndwater level in borehole 2)

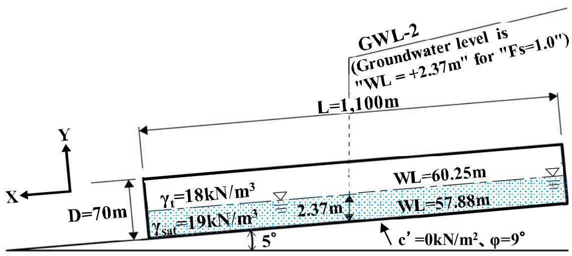

Figure 5. Schematic diagram of simplified landslide mass adapted for Kostanjek landslide (Hamasaki et al, 2016) [4]

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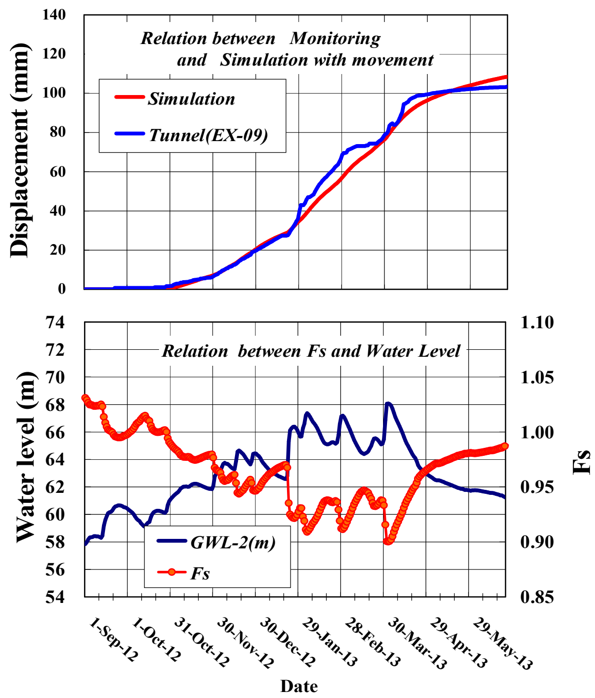

Figure 6. Reproduction of landslide displacement by two dimensional model. Upper diagram shows relationship between calculated and mnitored displacement. Lower diagram shows relationship between safety factor Fs and groundwater level in borehole 2. (Hamasaki et al, 2016) [4]

Calculation results are shwon in Figure 6. Upper diagram shows relationship between actually monitored values by the extensometer in tunnel and calculated values of displacement. Both values show basically good coincidence, although there is still slight difference. Lower diagram shows relationship between safetey factor (***Fs***) and groundwater level. Variation of saftey factor shows very clear inverse correlation with the groundwater level. Furthermore, correlation between monitored values and calculated values of displacement velocity evaluated by 10 days moving average is examined. The correlation coefficient shows high value of 0.88. It is clarified that this lumped mass damper model is effective to reproduce the variation of landslide velocity in reponse to the variation of the groundwater level.

4. ANALYSIS ON THE OIKUBO LANDSLIDE

The Oikubo landslide occurred in 2007 in Miyagi prefecture in northern Japan. After intensive rainfall brought by typhoon, the landslide mass completely slipped dwon. The landslide is medium dimension, with a length of about 300 m, a width of about 250 m and a thickness of about 30 m. The bedrock consits of Miocene to Pliocene alternation of sandstone and claystone or tuff.Since 5 month before the complete failure, one rain gauge and 4 extensometers were installed in this landslide area (Figure 7). Monitoring data of landslide displacement measured by 4 extensometers and rainfall amount are shown in Figure 8. However, groundwater level was not monitored. In consideration of available data values, a simplified lumped mass damper model as shown in Figure 9 is used for two dimensional slope stability analysis. It is necessary to estimate variation of groundwater level using Tank model as shown in Figure 10.

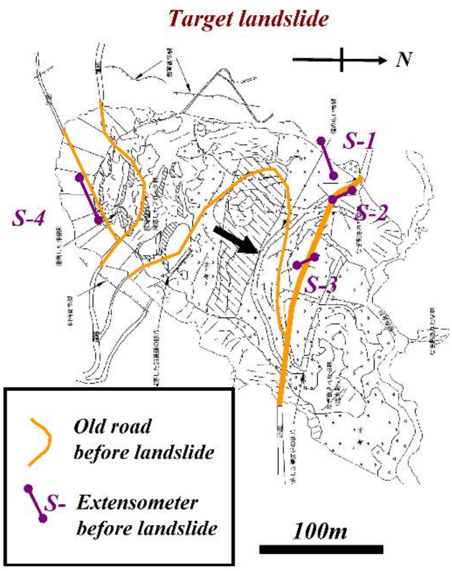

Figure 7. Plan of Oikubo landslide and location ofextensometers (Kato et al, 2007) [5]

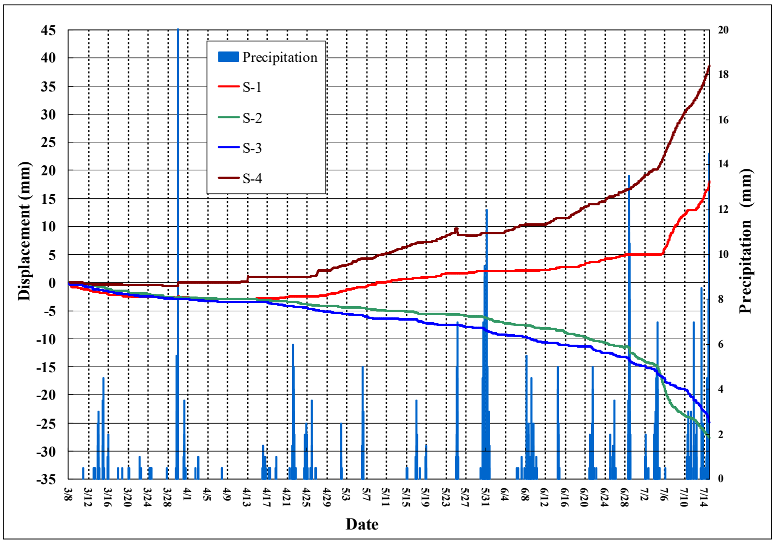

Figure 8. Monitoring data of displacement by 4 extensometers and rainfall amount in Oikubo landslide (Kato et al, 2007) [5]

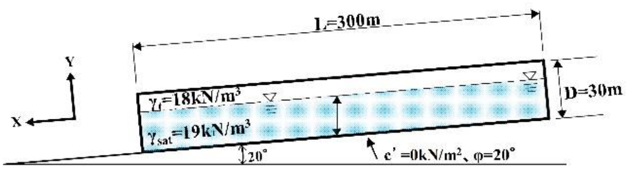

Figure 9. Schematic diagram of simplified landslide massadapted for Oikubo landslide (Ikeda et al, 2016) [1]

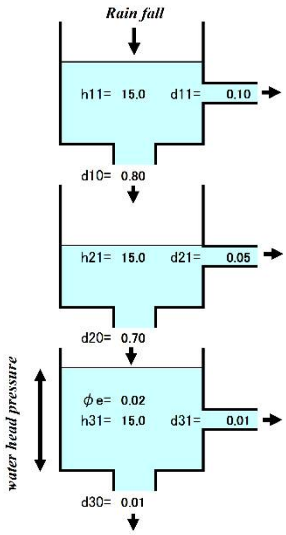

Figure 10. Tank model for target area (Ikeda et al, 2016) [1]

Using the lumped mass damper model, the variation of landslide velocity monitored by extensometer S-3 in response to the variation of the groundwater level calculated by the Tank model is analysed. Where, as an initial ***Cd*** value, ***Cd*** = 0.66 $\times 10^6$ kNsec/m^3 is used. Calculation results are shown in Figure 11. Upper diagram shows relationship between actually monitored values of displacement by the extensometer S-3 and calculated values of displacement. Both values show basically good coincidence until 21st June, however after that they deviate. Namely, the actually monitored values increase more quickly and devaite from the calculated values.

In order to solve above mentioned deviation, the authors introduced a reduction ratio (***dr***) of ϕ and ***Cd***. The reduction ratio (***dr***) varies from 0 to 1 in dependence on the velocity. Concerning ϕ and ***Cd*** respectively, the following reduction functions are introduced.

Pattern 1: $\phi = dr(v) * \phi_0$. ***(6)***

Pattern 2: $Cd = dr(v) * Cd0$. ***(7)***

Where, 24 hours mean velocity is used as moving velocity of the landslide (***v***).

Reduction functions are shown in Figure 12, concerning ϕ in upper diagarm and concerning ***Cd*** in lower diagram. Both reduction ratios on ϕ and ***Cd***are staying 1.0 until v = 0.3 mm/day. After then reduction ratio on ϕ decreases parabolically and reduction ratio on ***Cd*** decreases exponentially.

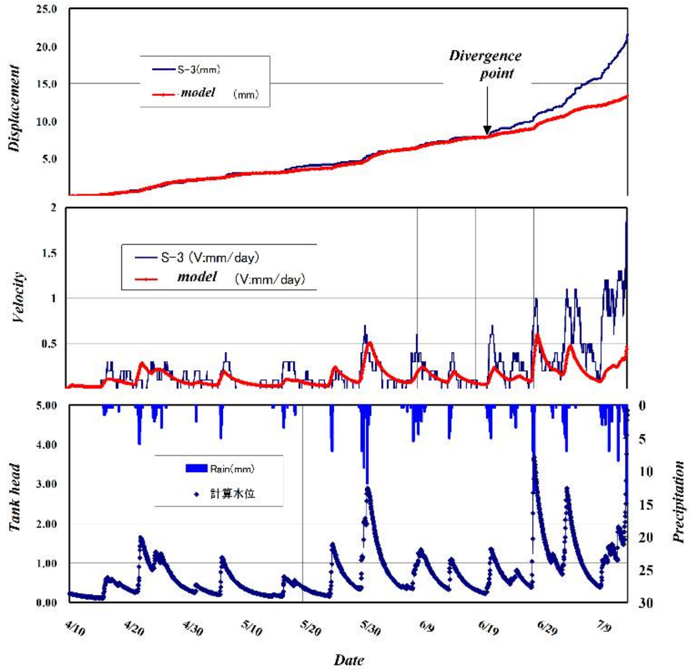

Figure 11. Simulation results using lumped mass damper model on Oikubo landslide (Ikeda et al, 2016) [1]

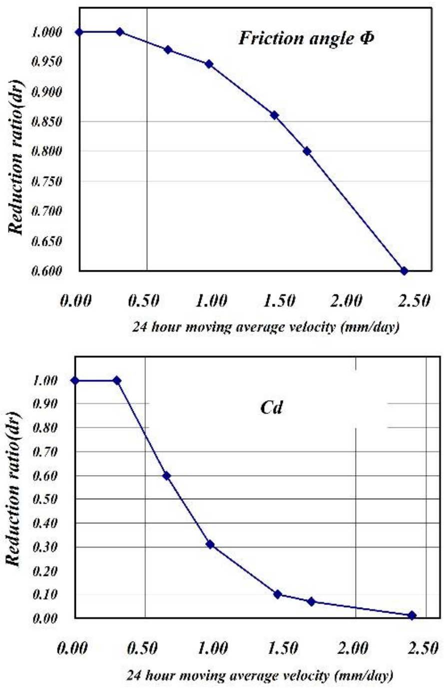

Figure 12. Reduction functions concerning ϕ and Cd

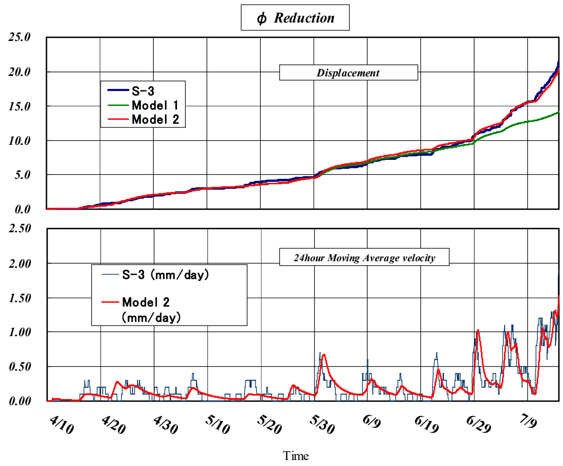

Figure 13. Reproduction of landslide displacement and 24 hours average velocity using φ reduction

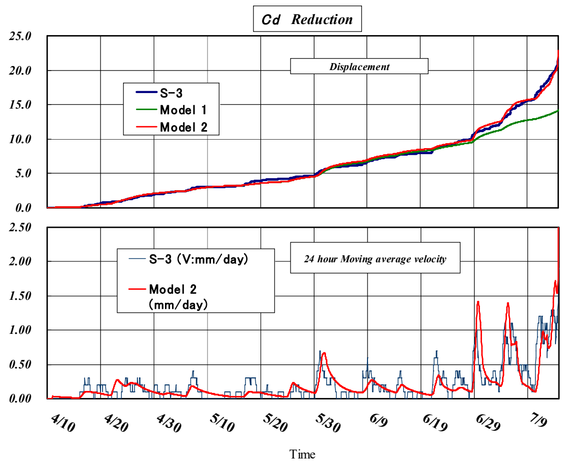

Figure 14. Reproduction of landslide displacement and 24 hours average velocity using Cd reduction

Calculation results are shown in Figure 13 on ϕ reduction and in Figure 14 on ***Cd*** reduction. Upper diagrams in Figure 13 and Figure 14 show relationship between actually monitored values by extensometer S-3 and calculated values of displacement. Red line shows calculated values using reduction ratios and green line shows initially calculated values without reduction ratio. Both calculated values of displacement using ϕ reduction and ***Cd*** reduction show good coincidence with actually monitored values until final complete failure stage. Lower diagrams in Figure 13 and Figure 14 show relationship between actually monitored values by extensometer S-3 (blue line) and calculated values (red line) of 24 hours average velocity. Calculated values using ϕ reduction show slightly lower than monitored values and calculated values using ***Cd*** reduction show slightly higher values than monitored values.

5. DISCUSSION

In order to reproduce the displacement of landslide until final complete failure stage, the original „lumped mass damper model“ is modified by introduction of the reduction function on ϕ or the reduction function on ***Cd***. As described in the previous chapter, it is clarified that actual displacement of landslide can be well reproduced by this modifictaion of the LMDM. Howevr, it is necessary to examine the validity of such reduction of ϕ and reduction of ***Cd*** with due consideration of physical meaning of such reductions.

Variation of ϕ reduction (blue line) is shown in Figure 15 corresponding to actually monitored 24 average velocity (red bar). The ϕ value varies from initial 20° to 15° and repeat frequent reduction and recover within this range. In general ϕ value can reduce from peak strength to residual strength at sliding surface of landslide and recover from residual strength to softening strength. However, it is not clarified whether such frequent reduction and recover of ϕ value in a short term can actually occur or not.

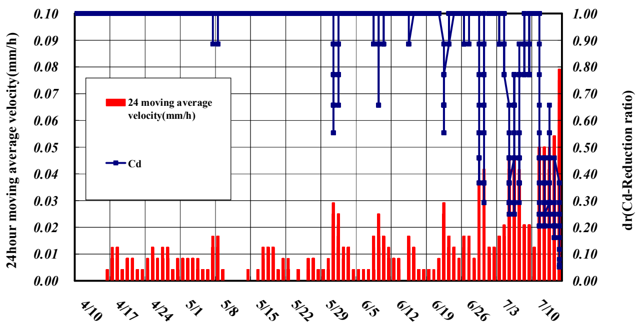

Figure 15. Variation of φreduction corresponding to 24 hours average velocity

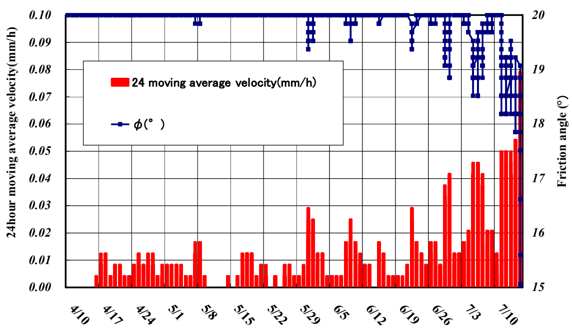

Figure 16. Variation of Cd reduction corresponding to 24 hours average velocity

Variation of ***Cd*** reduction (blue line) is shown in Figure 16 corresponding to actually monitored 24 average velocity (red bar). The Cd value varies from initail 1.0 to less than 0.1 and gradually decreases while repeating recovery. The frictional force (***F***) in viscous flow is expressed by the following equation (Figure 17).

$$F = \eta AU/h \quad (8)$$

Where,
U: Displacement velocity

h: Thickness of displacement layer

η : Viscosity

On the other hand the displacement velocity (***v***) is expressed as ***v*** = ***F***/***ACd*** in the LMDM (equation (5)). As ***U*** = ***v*** and viscosity η is expressed by the product of coeffcient of viscous resistance ***Cd*** and thickness of displacement layer ***h***, equation (8) accords with equations (5). Namely, diplacement of landslide basically shows equivalent behavior to Newtonian flow. On the other hand, Saga et al made clear that the suspension of the

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montmorillonite, which is swelling clay, shows high thixotropy by an experiment and the behavior of thixotropy changes by the density of suspension.From the above-mentioned ground, the authors introduce the following hyptheses. Namely, displacement of lanslide indicates Newtonian flow up to a certain threshold value of velocity and it can be analysed by the original LMDM.If the displacement of landslide exceeds a certain threshold value of velocity, it indicates Non-Newtonian flow and the displacement velocity accelerates according to ***Cd*** reduction. This case should be analysed by the modified LMDM.

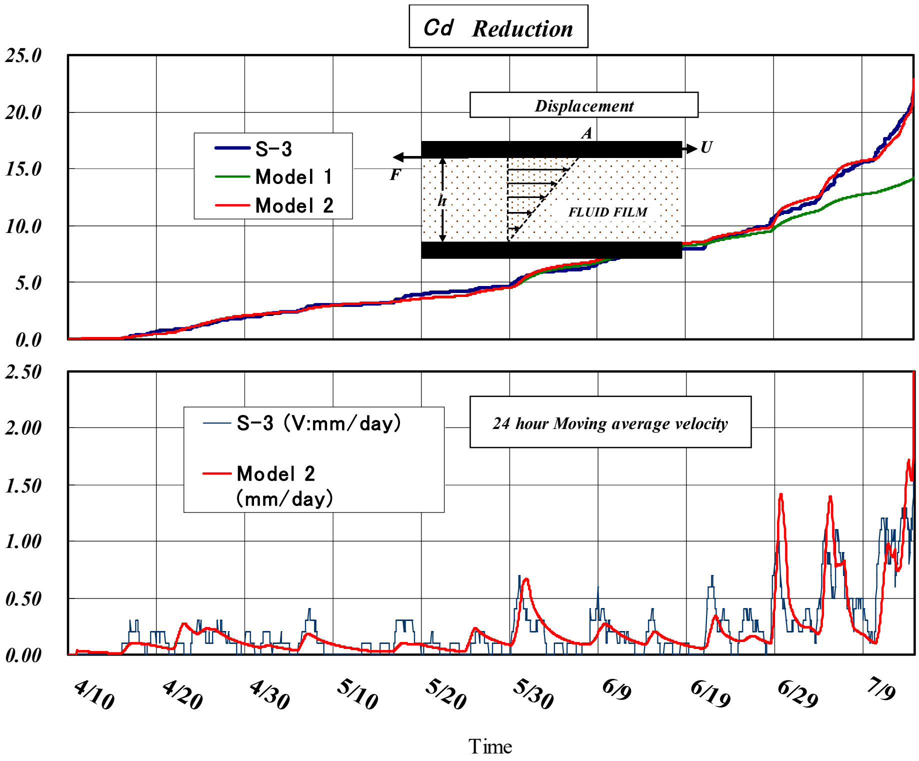

Figure 17. Schematic diagram of viscous flow (Soda, 1971) [11]

6. CONCLUDING REMARKS

The authors developed „Lumped mass damper model" (LMDM) with consideration of physical property of landslide in order to reproduce moving velocity and displacement of landslide. The original version of LMDM with constant ϕ and ***Cd*** parameters can effectively reproduce displacement of remaining type landslide, which dose not exceed thestrain limit. The calculation results of displacement values of complete failure type landslide, which exceeds the strain limit and falls down completely, shows divergence from the actually monitored values of displacement, if displacement velocity exceeds a certain threshold value. In order to solve this problem of divergence, the authors modified the orginal LMDM with introduction of reduction functions on ϕ and Cd parameters. The modified version of LMDM with variable ϕ or ***Cd*** parameters can effectively reproduce displacement of complete failure type landslide until final failure stage.Therefore, the modified LMDM is useful to predict final failure time of complete failure type landslide. After consideration of physical meaning of ϕ reduction and ***Cd*** reduction, the authors think that ***Cd*** reduction is based on thixotropy in Non-Newtonian flow and ***Cd*** reduction has higher plausibility than ϕ reduction.However, further detailed examination on physical property of ***Cd*** reduction should be carried out. The authors intend to make more case studies and also experimental studies on physcial property of the damper effect.

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