

# ESTIMATION OF THE INSTABILITY OF SLOPE SURFACE LAYER BY ELASTIC WAVE ATTENUATION CHANGING WITH SOIL MOISTURE AND DEFORMATION

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**ABSTRACT:** This paper proposes a method to estimate the instability of the slope surface layer by elastic wave attenuation which changes with soil moisture and deformation. The objective of this study is to investigate the effect of soil moisture and deformation on wave attenuation of soil. Two experiments were conducted, the first one was a laboratory experiment using a multi-layer shear model, and the second one was an on-site monitoring wave attenuation with soil moisture. In laboratory experiments, wave attenuation at various soil moisture and deformation were measured. The relationships between wave attenuation and soil moisture were found to have hysteresis, that is, difference paths were observed in rain and drain process. The attenuation of wave energy increased about 20%~40% when the VWC grew up near saturation. With increasing the displacement, the wave attenuation also increased, and the wave energy ratio dropped by 40% during a 3 mm of displacement. The results of on-site monitoring showed that wave attenuation decreased with the increasing soil moisture in the rain events and increased during the drain stages. Since most of the rain-induced landslides start failure in nearly saturated conditions, and the elastic wave attenuation in soil can indicate the status of saturation, monitoring elastic wave in the surface layer of slope can detect its instabilities.

*Keywords: Landslide, Early warning, Wave propagation, Attenuation*

## 1. INTRODUCTION

Rainfall-induced landslide occurred commonly in mountainous areas and caused severe human and infrastructure damages[1],[2],[3],[4]. Most of the Rainfall-induced landslide occur at shallow depths, generally less than 3 m[5][6]. In Japan the average depth is 1.2m, 90% is under 2.5m, 500,000 potentially dangerous slopes exist[7][8].

Early warning system can help people safely escape from the dangerous area. It is an economic and effective method to prevent and mitigate rainfall-induced landslide. Rainfall threshold has been used to predict the slope failure[9][10]. The current early warning systems are mainly focused on monitoring the slope's movements by MEMS (Micro Electro Mechanical Systems) tilt sensors or inclinometers and soil moisture by volumetric water content sensors[11],[12]. To cover a wide area of potential danger slope, a large number of tilt sensors would be required[13]. An alternative method to predict slope failure method applied elastic wave propagation in soil has been proposed, which can detect the soil moisture and deformation of a wide area slope. Irfan and Uchimura found that the velocities of both of shear wave(S-wave) and compression wave(P-wave) velocities decreased with increasing degree of saturation by laboratory triaxial tests[14],[15],[16]. In a series model tests, elastic wave velocity has been observed that it

responded sensitively to soil moisture content and deformation [17],[18],[19],[20]. Thus, many studies were conducted focusing on the velocities of elastic wave, however, precise measurement of travel time is needed to measure the wave velocities.

In this paper, a method using wave attenuation is presented to monitor slope deformations and soil moisture variations. It is an application of geometric spreading, which is as the wave moves away from the source, the area that the wave energy covers becomes larger and thus wave intensity decreases, and wave energy loss due to inelastic material behavior or internal friction during wave propagation [21]. Laboratory experiments using Multi-layer shear model were conducted, wave attenuation affected by shear forces and corresponding with deformations on every layer, and the soil moistures in wet and dry processes have been investigated. To understand the behavior of elastic wave propagation in slope surface layer, an elastic wave monitoring system including one exciter and several revivers have been developed and installed in a nature unstable slope. Wave attenuation and soil moisture were analyzed. The results show that wave attenuation behaviors with soil moisture on-site is similar to laboratory experiments.

## 2. METHODOLOGY OF MODEL TEST

The material used in this study is comprised of Silica sand No4, No5, No7 and No8 mixed with ratio of 1:1:3:1 to be near the particle size distribution of soils of the typical natural slopes. It had a dry density around 1.481 g/cm<sup>3</sup>. It's minimum and maximum dry density were found out to be 1.308 g/cm<sup>3</sup> and 1.707 g/cm<sup>3</sup>. The relative density was 50% and Volume Water Content was 7.4% at the initial state.

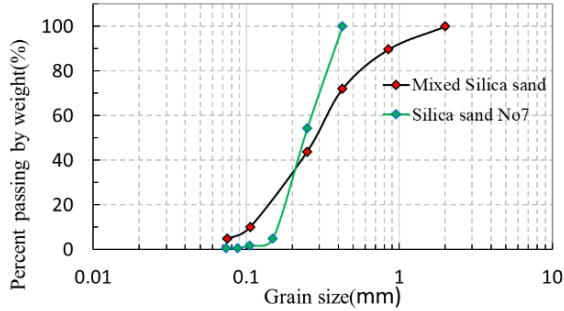


Fig. 1 Grain size accumulation curve

The Multi-layer shear model is shown in Figure 4. It is a model including 20 layers with a total height of 1m to simulate a part of slope surface layer. Every layer has a height of 0.05m, length of 0.6m and width of 0.54m. Shear force is applied on every interface between the layers by air cylinders to simulate the shear force corresponding to the slope angle. Displacement meters are also set at every layer. Rainfall intensity of 60mm/h is given with a nozzle controlled by constant water pressure. Rainwater infiltrates into the top layer of model and drains out from the bottom. Elastic wave is generated by exciter (Figure 2) and detected by receivers (Figure 3). Exciters, receivers and soil

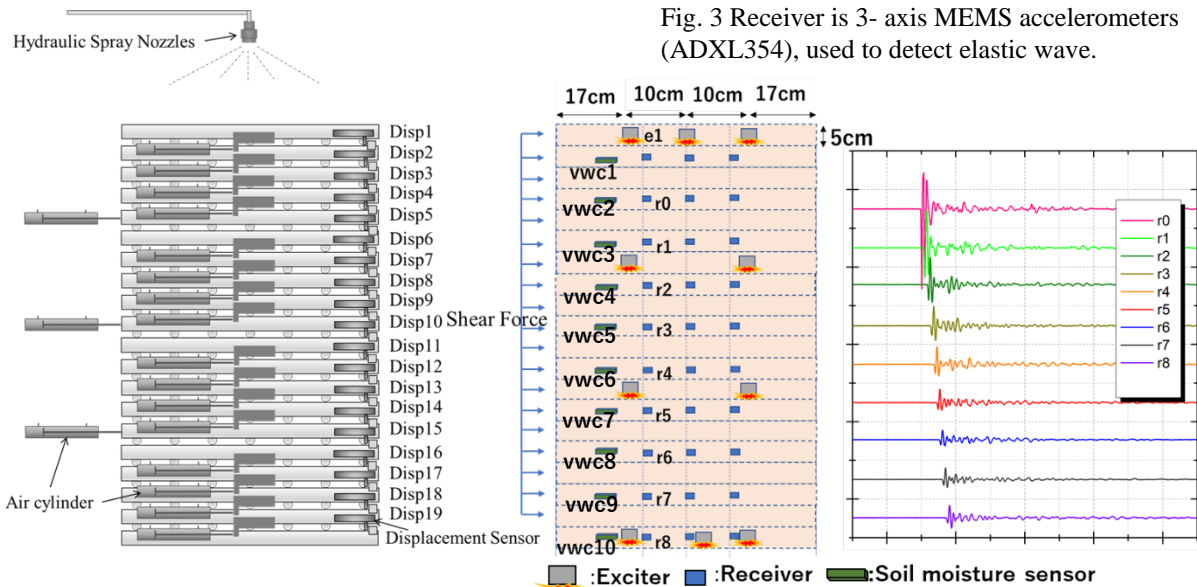


Fig. 4 Multi-layer shear model (left); Sensors layout in soil (middle); Waveform of One pulse wave which generated by exciter e1 and detected by receivers r0~r8 (right).

moisture sensors are set in the model.

The elastic wave attenuation is defined by the wave energy ratio, calculated by

$$\text{Energy ratio} = E_n / E_0 (n=1, 2, 3, \dots) \quad (1)$$

where  $E_0$  is energy of the receiver near the exciter ( $r_0$  in figure 4),  $E_n$  is others receiver' energy which far away from exciter ( $r_1 \sim r_8$ ). Energy is defined as

$$E = \sum_{f=1}^{f=3000} \left( \frac{1}{2} \right) * 4\pi^2 \rho (f * A_f)^2 \quad (2)$$

where  $\rho$  is the density of material,  $f$  is frequency,  $A_f$  is the wave amplitude. Frequency is resolved from 1~3000Hz by FFT (Fast Fourier Transformation).

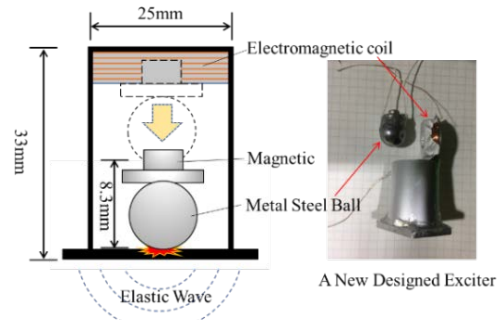


Fig. 2 Exciter used to generate pulse elastic wave. The mass of metal steel ball is 16.95g, the free drop height is 8.3mm.

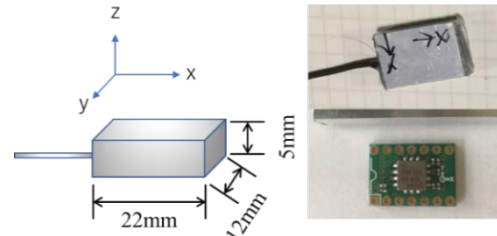


Fig. 3 Receiver is 3-axis MEMS accelerometers (ADXL354), used to detect elastic wave.

### 3. TEST CONDITIONS

Table 1 Test conditions

Test Case	Moisture Control	Slope Angle	Shear Displacement
1	Rain/Drain	0	0
2-1	Rain/Drain	27	0
2-2	Rain/Drain	29	0
2-3	Rain/Drain	31	0
3	Constant	33	50 mm

Three test cases were conducted with the conditions in Table 1. In Test Case 1, slope angle was zero, it means no shear force put on any layer of the model. Rainfall was applied for 4 hours until VWC (Volume Water Content) became stable, then rainfall was stopped, and water was drained out by gravity about 20hours (Figure 5a). In Test Case 2, the slope angle was set to be 27, 29, and 31-degree. Displacement was not found changing during the artificial rainfall(24hours) and drain(24hours) events. In Test Case 3, the slope angle was set to 33-degree (Figure 7). No rain was applied but the displacement continuously increased until failure.

### 4. RESULTS

Figure 5a shows the changes of wave energy ratio with VWC during the rainfall and drain event in the time series observed in Test Case1. It took 4 hours

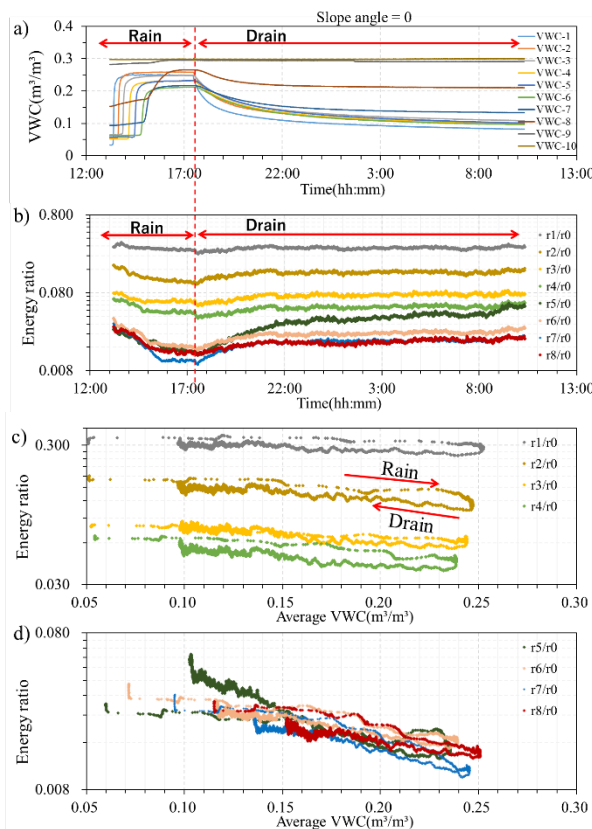


Fig. 5 Energy ratio changes with VWC (slope angle = 0)

rainfall to make the VWC be stable, and more than 20 hours to drain the water out. The deeper from the surface, the higher moisture was observed. Figure 5b shows energy ratio changes in the time series. With soil moisture increased in the rainfall event, the energy ratio decreased. During the drain stage, energy ratio increased. Figure 5c and 5d show the energy ratio at every receiver against the VWC averaged between the nearer and farther receivers. The energy ratio reduced 20%~50% when the VWC grew up from 0.1 to 0.25 m³/m³.

Effects of soil moisture on the wave energy ratio could be explained by matric suction. When the soil moisture becomes higher, the matric suction decreases, and the weaker of force between soil partials results in lower of wave energy propagation. There is hysteresis in the path of energy ratio and VWC between rainfall and drain event. This may be related to the hysteresis observed in the relationship between soil moisture and matric suction.

The response of energy ratio at different shear force corresponding to slope angle during rainfall and drain event is shown in Figure 6, which is the results of the Test Case 2. The stronger shear force applied, the lower energy ratio is observed. Wave energy ratio reduced 20%~40% when shear force increases from 27 to 31degrees. For example, in Figure 6a, at the 0.1 m³/m³ of VWC, when shear force was set to 27-degrees, 29-degrees and 31-degrees, the energy ratio decreased from 0.18, 0.14, and 0.11, wave energy ratio reduced from 22% to 38%.

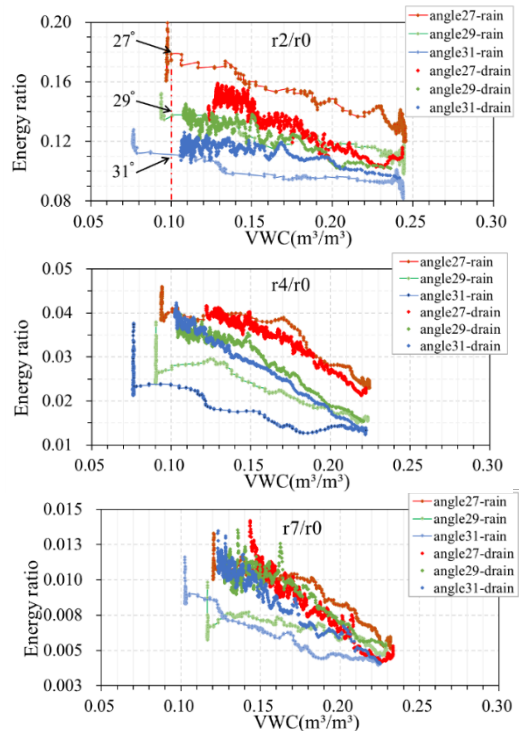


Fig.6 Energy ratio changes with VWC (slope angle = 27, 29,31)

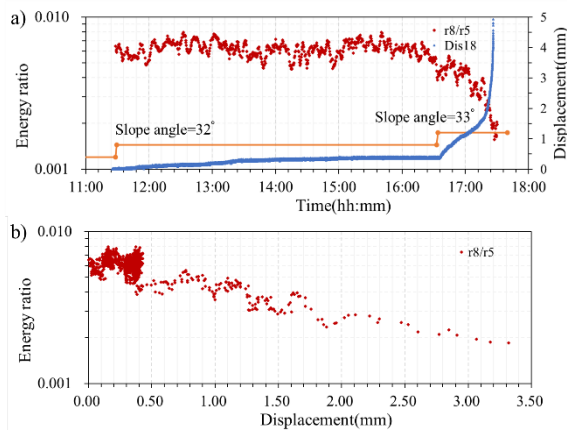


Fig.7 Elastic wave energy ratio changes with displacement

Figure 7a shows the response of wave energy ratio and displacement during shearing in the Test Case 3. VWC did not change in this test. After the shear force was set corresponding to the slope angle of 33-degree, the displacement started with an average 0.3cm/h of moving speed, then accelerated and finally failed, which observed at the displacement sensor No18, so energy ratio of r8/r5 was analyzed. With the increasing displacement, the wave energy ratio also decreased rapidly. Figure 7b shows the wave attenuation against the displacement. Wave energy ratio dropped by 50% during a 3 mm of displacement.

## 5. ELASTIC WAVE MONITORING ON-SITE

To investigate the behavior of elastic wave propagation in natural slope surface layer, elastic wave monitoring has been conducted at a slope located at Aso-shi, Kumamoto, Japan. This slope was suffered from the 2016 Kumamoto Earthquakes and some big cracks appeared on the slope surface. It is a typically unstable slope.

Figure 8 shows elastic wave monitoring devices. It has a fully automatic to generate elastic wave by exciter, measure the wave signal by receivers. It includes a controller and data collection device, an exciter, 4 receivers, and a VWC sensor. Exciter is made with a Solenoid Electromagnet, which is controlled by the controller, it can generate pulse elastic wave per 10 minutes. Receivers are 3- axis MEMS accelerometers, ADXL354, a production of Analog Devices. The controller and data collection device control the timing of exciter, handle the wave data received by the receiver with a 7kHz of sampling rate, and store wave data into SD card. The VWC sensor is a soil moisture sensor EC-5 to measure the volume water content in the soil. The power is supplied by the arrangement of lead-acid battery, which is charged by a solar panel (Figure 9),

to be continually running for a long term.

Figure 9 shows the elastic wave monitoring system installed on an unstable slope. Dotted line in the photo shows the survey line of elastic wave. Sensors and exciter were set in the underground. The exciter and VWC sensor were installed at a depth of 0.2 m. The receiver (CH1) was set at a horizontal distance of 0.01 m and a depth of 0.1 m from the exciter. Receiver (CH3) has a horizontal distance of 0.2 m from the exciter and a depth of 0.1 m; receiver (CH5) has a horizontal distance of 0.2 m from the exciter, a depth of 0.4 m; receiver (CH6) was installed at a depth of 0.1 m at a horizontal distance of 1.5 m from the exciter.

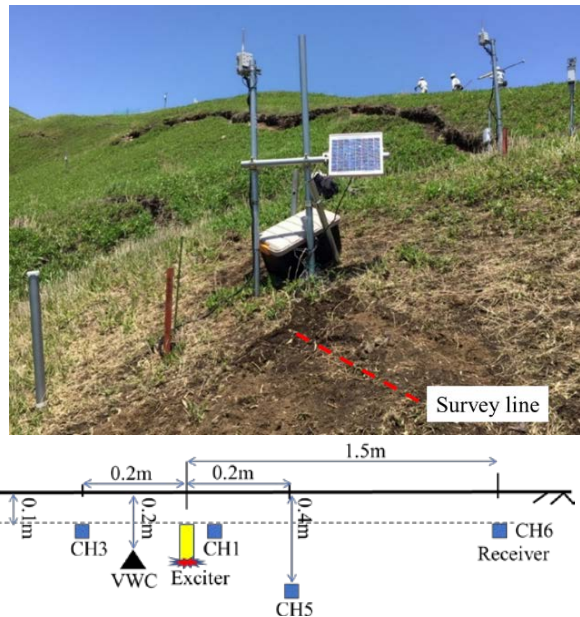


Fig. 9 Elastic wave monitoring system installed on an unstable natural slope. Dotted line shows the survey line of elastic wave. The layout of sensors and exciter underground.



Fig.8 Elastic wave monitoring devices, which can automatically generate elastic wave and measure wave signal.



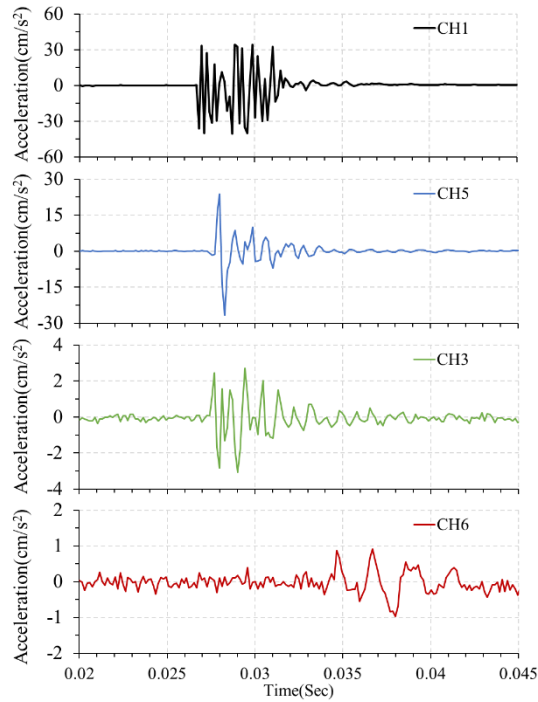


Fig.10 Examples of waveforms of a pulse elastic wave observed by receivers.

Figure10 shows the examples of waveforms of a pulse elastic wave observed by each acceleration sensor. CH1, the nearest with exciter, could detect the strongest signal around  $30 \text{ cm/s}^2$ , whereas CH6, the farthest from the exciter, detected the weakest signal around  $1 \text{ cm/s}^2$ . It indicates that wave amplitudes reduced quickly with distance.

Figure 11 shows VWC and energy ratio plot in time series from 2018/9/24 to 2018/12/20. In the dry process, the energy ratio of the elastic wave tends to increase with the decrease of VWC. On the contrary, in the wet process (rainfall events), the energy ratio of the elastic wave tends to decrease with the increase of VWC.

Figure 12 shows energy ratio response with VWC. Wet process is the cases of rain event, the dry process is a drain event. In CH5/CH1, wave energy ratio dropped down 60% when VWC increased from  $0.39$  to  $0.41 \text{ m}^3/\text{m}^3$ . In CH3/CH1, wave energy ratio dropped down 70% when VWC increased from  $0.39$  to  $0.44 \text{ m}^3/\text{m}^3$ . Whereas CH6, the farthest from the exciter, not clear changes trend. Hysteresis had been observed in CH3/CH1, that is similar to the results in laboratory experiments.

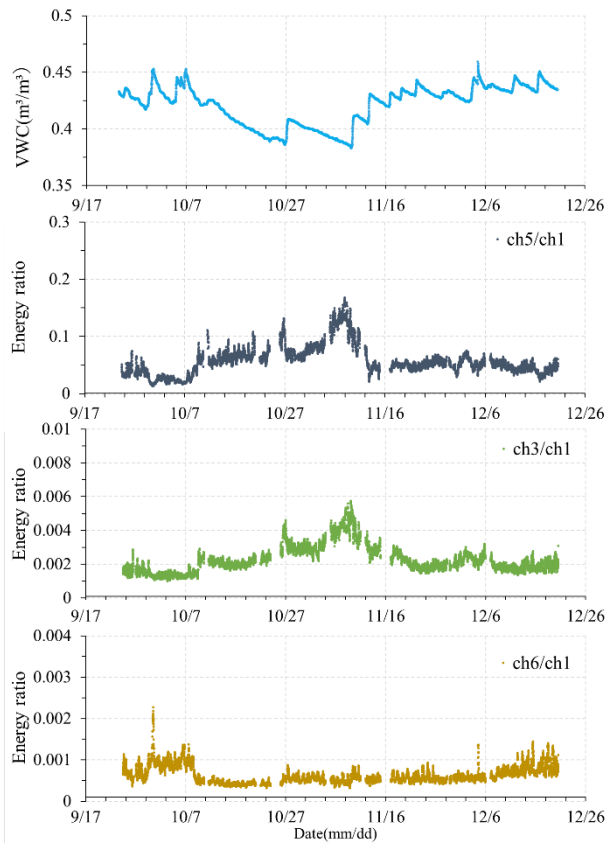


Fig.11 VWC and energy ratio plot in time series. Elastic wave data was collected from 2018/9/24 to 2018/12/20 on-site.

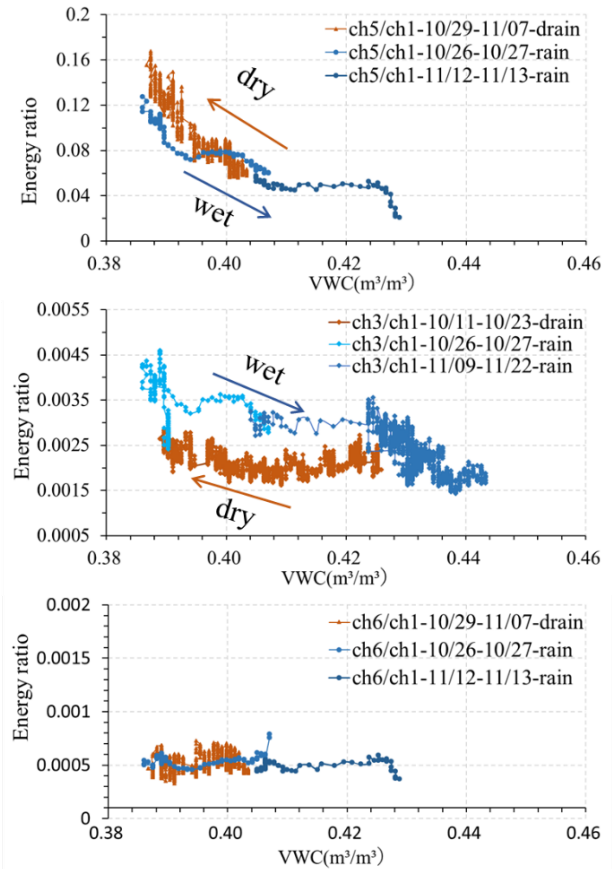


Fig.12 Energy ratio responses with VWC. Wet and dry process are the cases of rain event and drain event.

## 6. CONCLUSION

In this research, a method using elastic wave attenuation to predicts slope failure is presented. Laboratory experiment using multi-layer shear model was conducted to observe the changes of elastic wave propagation in slope surface layer. The results show that the wave attenuation increased with the increasing soil moisture, the wave energy reduced by 20%~50% when the VWC grew up from 0.1 to 0.25 m<sup>3</sup>/m<sup>3</sup>. The stronger shear force applied, the lower energy ratio observed. With increasing the displacement, the wave attenuation also increased.

An elastic wave monitoring system including one exciter and several revivers have been developed and installed in a nature unstable slope. The results show that wave attenuation behaviors with soil moisture on-site is similar to laboratory experiments.

Monitoring wave attenuation in slope surface layer can indicate the status of saturation state and shear deformation. Slope instabilities may be predicted based on its historical record.

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