Effects of soil moisture and shear deformation on elastic wave velocities in shallow slope

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ABSTRACT

A method is proposed that the changes of elastic wave velocities are a function of normal stress, soil moisture, shear stress and shear displacement, can be expressed as \( \Delta V = a \ast (\Delta \sigma) \tau + b \ast \Delta \text{VWC} + c \ast \Delta \tau + d \ast \Delta x \), Where \( \sigma \) is normal stress, VWC is volumetric water content, \( \tau \) is shear stress, \( x \) is the shear displacement. This study aims at investigating the elastic wave propagation in soil, to find out the method using the changes of elastic waves in the slope surface layer and applied to an early warning system. A series of experiments were conducted, the first one was a laboratory experiment using multi-layer shear model to determine the coefficient of normal stress, soil moisture content, the shear stress, and the displacement. The elastic wave velocities calculated by the coefficient and the input soil moisture and shear stress were compared to the measured velocities, the results show they were the similar trend. The second one was elastic wave monitoring on-site. The results of on-site also showed that the elastic wave velocities changes with the soil moisture. It is similar to the result of laboratory experiment. Monitoring elastic wave in the surface layer of slope can detect its instabilities. Slope failure may be predicted based on the historical record of elastic wave propagation in soil.

Keywords: slope failure; early warning; compression wave velocity; shear deformation; multi-layer shear model, elastic wave monitoring on-site

1 INTRODUCTION

Rainfall-induced slope failures occur in many countries like China (Brand, 1981), Japan (Uchimura et al., 2015), USA (Baum and Godt, 2010), and Italy (Peruccacci et al., 2017), cause severe human and infrastructural damage. Most of the previous slope failures have occurred at shallow depths, generally less than 3 m, and the average thickness of the failed surface layer was 1.2 m. A great number of slopes are still under dangerous conditions (Uchimura et al., 2015).

Physical countermeasures such as retaining walls (Conte et al., 2017), ground anchors (Hutchinson, 1984) and dewater systems (Conte and Troncone, 2018) are common to mitigate damage caused by rainfall-induced slope failures. However, they are not economically feasible for the amount of potentially unstable slope. Therefore, early warning systems are an alternative soft countermeasure that can provide an efficient and economical way to reduce the damage of slope failures.

The current early warning systems are mainly focused on monitoring both the soil moisture and the displacement by soil moisture sensors and tilt sensors (Uchimura et al., 2010). These methods have recently been used because they are simple and easy to install in the slope surface layer. However, they can only sense the local area surrounding the position of the sensor. To cover a wide area of the unstable slope, many sensors are required (Wang et al., 2018).

In recent years elastic wave propagation in soil as a non-destructive monitoring technique has received considerable attention. Many researchers had developed the application of elastic wave propagation in soil, for example, shear waves were measured in laboratory specimens by means of piezoelectric transducers (Brignoli et al., 1996), and recently, both shear wave (S-wave) and compression wave (P-wave) velocities were designed to measure the unsaturated soil (Irfan and Uchimura, 2016). It was found that both P-wave and S-wave velocities decreased by nearly half when soil saturation was increased from 20% to 80% in laboratory triaxial experiments (Irfan et al., 2017). A series of model experiments found that elastic wave velocities continuously decreased in response to moisture content and deformation (Chen et al., 2017).

In this paper, a method of evaluating slope shear deformation and soil moisture by elastic wave velocities is presented. The changes of elastic wave velocities can be expressed by a function of normal stress, soil moisture, shear stress and shear displacement. A full-scale multi-layer shear model was used to simulate the process of slope failure and observe the wave propagation. An exciter has been developed that can automatically
generate clear and powerful elastic wave signals. To investigate the behavior of elastic wave propagation in slope surface layer, an elastic wave monitoring system including one exciter and several receivers have been developed and installed in nature unstable slope. The relationship of elastic wave velocities and soil moisture were confirmed.

2 APPARATUS AND DEVICES

The exciter shown in Figure 1 is used to generate pulse elastic waves. It has a height of 33 mm, and a diameter of 25 mm. It has a steel ball inside that weighs 16.95 g. It can be pulled up by an electromagnet and then freefalls from a height of 8.3 mm when the electromagnet is released. The receiver shown in Figure 2 is used to sense the pulse elastic waves. It has a height of 5 mm, length of 22 mm, and a width of 12 mm. It has a MEMS sensor inside, named ADXL354 (Analog Devices), which is a high sensitivity, ultralow noise density, low drift 3-axis accelerometer.

The multi-layer shear model is shown in Figure 3. It includes 20 layers with a total height of 1 m, where each layer is an independent frame with a height of 0.05 m, length of 0.6 m and width of 0.54 m. Each frame is equipped with wheels and is movable under the horizontal shear force. Shear force is applied on every frame by an air cylinder to simulate the shear force corresponding to the slope angle. Displacement meters are also placed at every layer. Dis1~Dis19 are the displacement meters used to record the shear displacement. A total of 10 exciters and 30 receivers are set in the specified position in the soil. E1~E10 are the exciters used to generate elastic waves; CH01~CH30 are the receivers used to sense the elastic waves.

Rainfall intensity is constant 60mm/h. Rainwater infiltrates into the top layer and then into sublayer, and finally drains from the bottom of the model. The soil moisture sensor (ECH2O EC-5 (METER Group, Inc.)) determines the volumetric water content of the soil. Ten soil moisture sensors were set up in the soil, with a vertical interval of 100 mm, to measure the soil moisture distribution with depth.

\[
V_i = \frac{D_i}{t_{i1}} = \frac{d_i}{t_{i+1} - t_i}
\]

where \(V_i\) is the wave velocity, \(D_i\) is the distance, \(t\) is the first travel time of the wave signal, \(i\) is the number of the receiver.

When the rainwater infiltrates into the slope, the soil moisture content of the upper layer increases and makes the normal stress near the sliding surface increase, resulting in an increase of the shear stress. The rainwater continues to infiltrate the area of sliding surface, a
gradual increase in softening of the soil upon water infiltration may be wreaked the soil strength, leading the deformation and cracks appears, and then drive the slope move. The soil moisture, normal stress, shear stress, shear deformation are the main parameter of the status of an unstable slope or slope failure. These parameters can be evaluated by elastic wave velocities. The change of velocity is presented as the following formula

\[ \Delta V = \left(F(\sigma, VWC, \tau, x)\right) \]
\[ = g(\sigma) + f(VWC) + h(\tau) + k(x) \]
\[ = a \cdot (\Delta \sigma)^m + b \cdot \Delta VWC + c \cdot \Delta \tau + d \cdot \Delta x \quad (2) \]

Where \( \sigma \) is normal stress, VWC is volumetric water content, \( \tau \) is shear stress, \( x \) is the shear displacement, coefficient \( a, m, b, c, \) and \( d \) are constants, and they are determined from experiments.

4 TEST MATERIAL AND TEST PROCEDURE

4.1 Test material

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/cm³. It’s minimum and maximum dry density were found out to be 1.308 g/cm³ and 1.707 g/cm³ (Figure 4). The relative density was 50% and Volumetric Water Content was 7.4% at the initial state. A nature soil showed Figure 4 is sampled from a slope in Aso-shi, Kumamoto.

Fig. 4. Grain size accumulation curve of the material.

4.2 Test procedure

A series of test cases were conducted to simulate the rainfall-induced slope failure. The changes in soil moisture, shear stress and shear displacement, which were the main factors that affect slope stability, were investigated by these test cases. In these experiments, elastic wave velocities were used to determine the soil moisture, shear stress, and shear displacement, in order to study their behaviors in the process of slope failure. The overall test program was divided into seven series of test cases, and the conditions of every test case are summarized in Table 1 and Figure 5.

In the test case 1, the maximum wave velocities observed in several different survey lines, are named with Vp(initial), which was used as a comparison standard value to express the change ratio of velocities by the following test.

Table 1. Test cases and conditions.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Soil moisture</th>
<th>Shear Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>(Slope Angle)</td>
</tr>
<tr>
<td>1-1</td>
<td>Rainfall (21 h)</td>
<td>0°</td>
</tr>
<tr>
<td>1-2</td>
<td>Drain (46 h)</td>
<td>0°</td>
</tr>
<tr>
<td>2-1</td>
<td>Rainfall (24 h)</td>
<td>24°</td>
</tr>
<tr>
<td>2-2</td>
<td>Drain (288 h)</td>
<td>0°</td>
</tr>
<tr>
<td>3-1</td>
<td>Rainfall (4 h)</td>
<td>0°</td>
</tr>
<tr>
<td>3-2</td>
<td>Drain (19 h)</td>
<td>0°</td>
</tr>
<tr>
<td>4-1</td>
<td>Rainfall (24 h)</td>
<td>27°</td>
</tr>
<tr>
<td>4-2</td>
<td>Drain (28 h)</td>
<td>27°</td>
</tr>
<tr>
<td>5-1</td>
<td>Rainfall (22 h)</td>
<td>29°</td>
</tr>
<tr>
<td>5-2</td>
<td>Drain (70 h)</td>
<td>29°</td>
</tr>
<tr>
<td>6-1</td>
<td>Rainfall (23 h)</td>
<td>31°</td>
</tr>
<tr>
<td>6-2</td>
<td>Drain (41 h)</td>
<td>31°</td>
</tr>
<tr>
<td>7</td>
<td>Constant</td>
<td>32°, 33°</td>
</tr>
</tbody>
</table>

5 RESULTS AND DISCUSSIONS

5.1 Normal stress and elastic wave velocities

Wave velocity propagation in soil depends on the state and history of the effective stresses, void ratio, degree of saturation, and type of particles. Based on early studies, the relationship of wave velocity and effective stress for granular geomaterials is expressed as a power function having two parameters: a coefficient and an exponent. The velocity-stress power relationship for granular media under isotropic loading is expressed as (B. O. Hardin & Richart, 1963; B. O. Hardin, 1978);

\[ Vp = a(\sigma)^m/2 \quad (3) \]

Where Vp is compression wave velocity, \( \sigma \) represents...
effective isotropic stress (the unit is 1kPa), a and m are material constants associated with the type of grains, void ratio, the nature of contacts and the stability of soil skeleton. Parameters a and m are determined by experiment. It can be determined from Figure 6.

In the initial status, the soil moisture in the model was constant, no shear strength was applied at any layer. Thus, the effect of soil moisture, shear stress and displacement can be ignored. The wave velocity was found larger at the bottom than at the top. It was the effect of the weight of the specimen, in other words, the normal stress was different from the depth. The more depth the higher stress. The relationship of normal stress and elastic wave velocities is expressed as

\[ V_p = 157.36 \sigma^{0.432/2} \]  

(4)

In the formula (3), the coefficient a is 157.36, the exponent m is 0.432.

5.2 Soil moisture and elastic wave velocities

In test case 3, no shear strength was applied to any layer. Soil moisture in the model changed by the rainfall event. The effect of shear stress and displacement can be ignored. The wave velocity between ch9 and ch2 is investigated because it is near the top, small effect of the normal stress. Figure 7 shows the effects of soil moisture on elastic wave velocities at the ch9-ch2. The wave velocity increased at the beginning of the rainfall, this is the effect of the increase of normal stress at upper layer. When the water went through the vertical survey ch9-ch2, the wave velocity was found decreasing with the increasing of the VWC. The relationship of VWC and elastic wave velocities is expressed as

\[ V_p = b \cdot VWC + V0 \]  

(5)

where the coefficient b is -80.101.

Figure 8 shows the response of elastic wave velocities at different VWC values during the rain and drain events. The wave velocity ratio reduced by 0.1~0.2 when the VWC increased from 0.1 to 0.27 m$^3$/m$^3$.
5.3 The effects of shear stress on wave velocities

To understand the effect of loading and unloading shear force on elastic wave velocities, the survey line between ch12 and ch13 was analyzed. The test cases of 2, 4, 5, and 6 in Table 1 were included. The results are shown in Figure 9. When loading the shear stress corresponds to a 24-degrees slope angle, the \( Vp/Vp(\text{initial}) \) ratio dropped from 0.85 to 0.65, where the VWC = 0.19. On the contrary, when unloading the shear stress from 24-degrees to 0-degree, the wave velocities ratio increased from 0.6 to 0.8, where the VWC = 0.28.

![Fig. 9. Wave velocities ratio changes with the slope angle at the survey line between receivers ch12 and ch13.](image)

Figure 10 shows the wave velocity ratio against the shear stress at every layer with the different soil moisture content. This shows that the closer to the bottom, the lower the wave velocities. The wave velocity ratio reduced by 0.2~0.3 at the middle layer and about 0.5 near the bottom where the shear stress is highest. The relationship between the wave velocity ratio and the shear stress is near-linear, it is expressed as

\[
Vp/V0 = c \times \tau + 1.1176
\]

where the coefficient \( c \) is \(-0.0943\).

![Fig. 10. The response of wave velocities at different levels of shear stress during rain events](image)

5.4 Shear distance and elastic wave velocities

Test case 7 was used to investigate the effect of shear displacement on elastic wave velocities before slope failure. Soil moisture content did not change during this test. In the Figure 11, when the shear force corresponding to a slope angle of 32-degrees was set, a very small displacement appeared but stopped moving after 2 h. When the shear force corresponding to a slope angle of 33-degrees was set, the slope started moving with an average speed of 3 mm/h, then accelerated and finally failed. The model showed that with increased displacement, the wave velocities decreased rapidly. The relationship of shear displacement and elastic wave velocities is expressed as

\[
Vp = d \times x + V0
\]

where the coefficient \( d \) is -8.9939.

![Fig. 11. The effects of shear distance on elastic wave velocities.](image)

5.5 Verification

Based on the results of experiments, the coefficient \( a, m, b, c \) and \( d \) in the formula (2) are determined. So, the elastic wave velocities can be calculated by the coefficient and the input soil moisture and shear stresses. Figure 12 shows the comparison of measured velocities and the velocities calculated by the coefficient and the input soil moisture and shear stresses through the whole test procedure. The results show they are a similar trend. The most effective of wave velocities is the shear stress, about 50% decrease near the bottom where the shear stress is highest. Figure 13 shows the comparison of measured velocities and the velocities calculated by the coefficient and the input soil moisture and shear stresses.
between ch12-ch13 in the test case 4-1. The shape is near the same, but the scale is different.

![Diagram of measured and calculated velocities](image1)

Fig. 12. The comparison of measured velocities and the velocities calculated by the coefficient and the input soil moisture and shear stresses through the whole test procedure.

![Diagram of measured and calculated velocities](image2)

Fig. 13. The measured velocities and the calculated velocities between ch12-ch13 in the test case 4-1.

### 6. ELASTIC WAVE MONITORING ON-SITE

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. The behavior of elastic wave propagation in the natural slope surface layer has been investigated.

![Elastic wave monitoring devices](image3)

Fig. 14. Elastic wave monitoring devices.

Figure 14 shows the elastic wave monitoring devices. It includes an exciter, several receivers, a controller and a data collection device. Exciter is made with a Solenoid Electromagnet, which is controlled by the controller, it can automatically 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 100kHz of sampling rate, and store wave data into SD card. The soil moisture sensor is EC-5 to measure the volume water content in the soil. The pressure sensor is LPS33HW (STMicroelectronics). 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 15 shows the elastic wave monitoring system installed on an unstable slope. The dotted line in the photo shows the Y survey line of the elastic wave. Sensors and exciter were set in the underground. The exciter was installed at a depth of 0.5 m. The receiver (A1) was set near the exciter. At the vertical survey line, Receiver A2 and A3 were set at the depth of 1m and 1.5m. At a horizontal survey line, Receiver A4 and A5 were set at a distance of 0.3 m and 0.6m. Receiver (CH6) has a horizontal distance of 0.6 m from the exciter and a depth of 1 m; A tilt sensor was set near the exciter with a distance of 1m, use to measure the deformation of the slope, angle X was the direction of the slope. The soil moisture sensors were placed at different depth from 0.2m to 0.8m underground. One of the pressure sensors was set up in the box on the ground and the other one was set at a depth of 0.4m underground, the pressure and temperature data were collected for the pressure sensors. A rain gauge was also set on this slope to collect the precipitation.
Fig. 15. Elastic wave monitoring system installed on an unstable natural slope. The dotted line shows the Y survey line of elastic wave. The layout of sensors and exciter underground.

Fig. 16. a) daily precipitation, b) volume matrix water content in the soil, c) pressure and temperature in air and underground.

Figure 16 a) shows daily precipitation from 5/15 to 6/30. Several rainfall events over 20mm recorded. The volume matrix water content increased quickly with the rainfall event, and slowly decreased during the dry period, shown in Figure 16 b). The pressure is higher than the pressure in the air. The temperature difference in the air between day and night is intense, while the temperature underground is stable, shown Figure 16 c).

Figure 17 shows the changes of the tilt sensor. The tilt angle X was found that it started to move with a very slow rate (1 degree/20 day) after heavy rainfall, whereas the tilt angle Y had no changes. Figures 18 and 19 show the effects of soil moisture on elastic wave velocities.

Since the deformation is very small, the results of on-site showed that the elastic wave velocities mainly change with the soil moisture. It is similar to the result of the laboratory experiment.
7 CONCLUSIONS

A method is proposed that the changes of elastic wave velocities are a function of normal stress, soil moisture, shear stress and shear displacement. Laboratory experiments using a multi-layer shear model simulating shallow slope failure were conducted and got the coefficient. The elastic wave velocities calculated by the coefficient and the input soil moisture and shear stresses, was compared to the measured velocities, it showed they were the similar trend. The results can be concluded as follows:

1. Wave velocities increased with increasing normal stress.
2. Wave velocities decreased with increasing soil moisture in the rain event and increased during the drain stage. The wave velocity ratio reduced by 0.1–0.2 when the volume of water content increased from 0.1 to 0.27 m³/m³.
3. The stronger the shear force applied, the lower the velocities observed. A drop-in wave velocity of 0.2–0.3 was observed at the middle layer, and near 0.5 at the bottom layer.
4. Increasing the displacement caused the wave velocities to also increase. The wave velocity ratio dropped by 0.2 after 3 mm of displacement.

An elastic wave monitoring system including one exciter and several receivers have been developed and installed in nature unstable slope. The relationship of elastic wave velocities and soil moisture were confirmed.

It is similar to the result of the laboratory experiment.

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