Behavior of Wave Velocities During Rainfall-induced Landslides and their Application for Landslide Prediction

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ABSTRACT: In this paper, the authors have proposed a method for the prediction of landslide movement by using elastic wave velocity in soil. Two series of triaxial tests were conducted on unsaturated sand specimens. First set of experiments investigated the behavior of elastic wave velocities with varying soil moisture. While the second series, conducted under constant shear stress water injection conditions, explored the behavior of wave velocities during rain-induced landslides. Wave velocities were found to be a function of soil saturation state and decreased gradually with increasing moisture. In water infiltration experiments, a gradual decrease in wave velocities was followed by a rapid decrease once the failure was initiated. Time of failure initiation and post-failure strain rate could distinctly be identified by observing wave velocities. Based on these observations, ideas for the prediction of landslides using elastic wave propagation in soil are presented. Expected technological and conceptual constraints in the field application of these ideas are also pointed out in this paper.

1 INTRODUCTION

Landslides pose a serious threat to sustainable human development. A novel concept of landslide prediction by monitoring elastic wave velocity changes in soil is presented in this paper. Elastic wave velocities (compression wave velocity (*Vp*) and shear wave velocity (*Vs*)) vary with soil moisture as well as yielding. Two series of triaxial experiments were conducted to elucidate these effects. The first test series called, Isotropically Consolidated Constant Water Content tests (*ICCW*) explored the effects of soil moisture on elastic wave propagation. The second experimental series named Constant Shear Stress Water Injection tests (*CSWI*) evaluated the response of wave velocities during actual rainfall-induced landslide conditions.

2 EXPERIMENTAL PROCEDURES

All the experiments were conducted on cylindrical triaxial specimens (height = 150 mm, diameter = 75 mm) formed by wet tamping Edosaki sand (Gs = 2.639, e_{min} = 0.647, e_{max} = 1.160, fines = 9%) to a predefined density. Disk type piezoelectric transducers (Irfan & Uchimura, 2013), which are capable of measuring both shear (*S*-wave) and compression wave (*P*-wave) velocities were used for elastic wave velocity determination. Transmitter disk transducer, sealed to the pedestal, was excited by a single cycle of 10 kHz or 15 kHz sinusoidal wave for the generation of *P*-wave or *S*-wave respectively. The wave propagated through the soil specimen and was received at the top cap by receiver disk transducer. Time of flight of waves (t) was determined by analyzing the received signals. By knowing the wave travel distance to be equivalent to specimen height (H), elastic wave velocities were calculated as Vp (or Vs) = H/t.

2.1 *Isotropically Consolidated Constant Water Content (ICCW) Tests*

In *ICCW* tests placement moisture content was controlled to prepare specimens with different initial saturation ratios. From an initial isotropic confining pressure of 15 kPa, isotropic confining pressure on each specimen was first increased to 300 kPa, and then brought down to 5 kPa (in steps). Elastic wave velocities were determined at various stress levels along this stress path. Void ratio significantly affects wave velocities(Hardin & Richart, 1963). Since change in void ratio during unloading path is small, so wave velocity results only during unloading path were considered for this paper.

2.2 *Constant Shear Water Injection (CSWI) Tests*

In *CSWI* tests, specimens were prepared at an initial saturation ratio of 30% and an all round confining pressure of 25 kPa. Axial stress was then gradually increased to 85 kPa ($K=\sigma_1/\sigma_3=3.4$) which represented field consolidation state corresponding to slope inclination of about 33°. Water was then

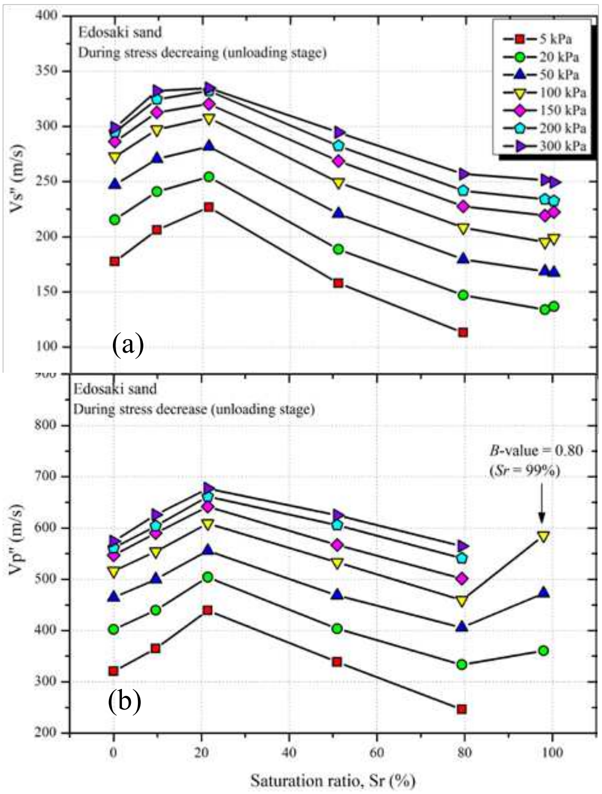

Fig. 1 Variation of (a) *S*-wave velocity; (b) *P*-wave velocity with soil saturation.

injected through a ceramic disk fitted in specimen's base pedestal. Wave velocities were determined at regular intervals. Saturation ratios of specimens were computed by monitoring the amount of injected and drained water.

3 RESULTS AND DISCUSSIONS

3.1 *ICCW Tests*

Fig. 1 summarizes the results of *ICCW* tests. In order to draw a better comparison among various specimens, wave velocities were normalized corresponding to void ratio, e_o=0.673, and dry density, $(\rho_d)_o$=1.578 g/cm^3 by using expression defined by(Hardin & Richart, 1963) given as;

$$G = A \cdot f(e) \cdot (\sigma'_m)^n$$

where, $f(e) = (2.17 - e)^2 / (1 + e)$

and, A and n are fitting parameters, and σ_m*'* is mean effective stress acting on soil. Also from elastic continuum mechanics;

$$V_S = \sqrt{G/\rho} \quad ; \quad V_P = \sqrt{M/\rho}$$

Both *P*-wave and *S*-wave velocities for dry soil are low and they increase to a peak value at around 20% saturation ratio. Increasing saturation beyond this decreases wave velocities. However, for saturated specimens *P*-wave velocity approaches sonic wave velocity in water (~1800 m/s which lie outside the scale of graph in Fig. 1b); as *P*-wave propagates through the pore fluid instead of soil skeleton. Such behavior can be useful for predicting saturation state ofa slope subjected to rainfall.

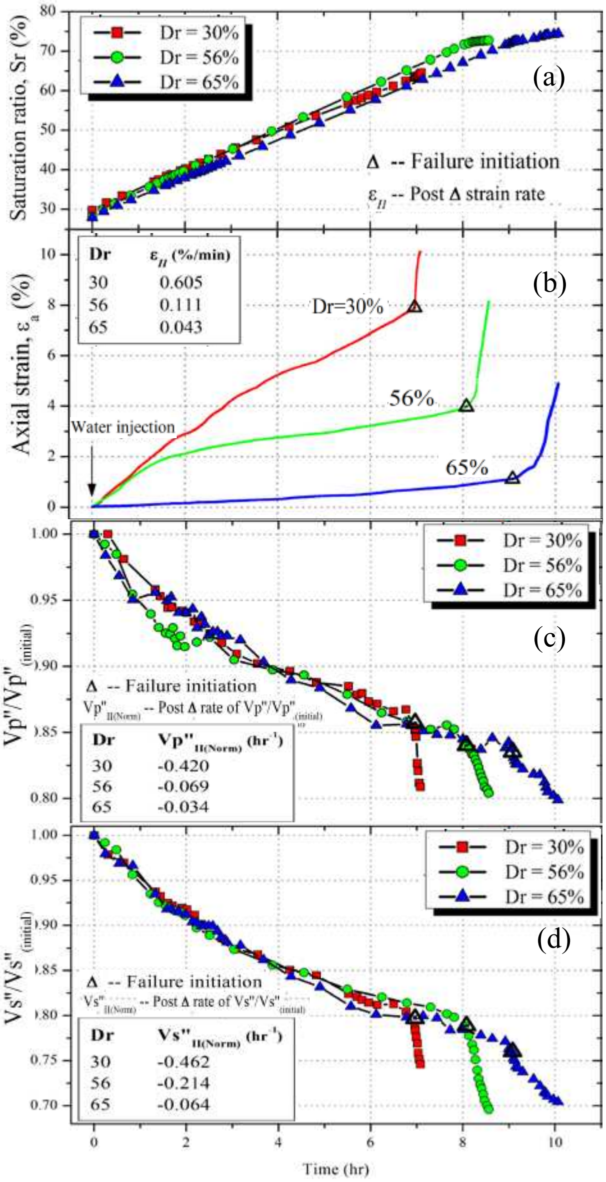

Fig. 2 *CSWI* tests; Variation of (a) saturation; (b) deformation; (c) normalized compression wave velocity, and (d) normalized shear wave velocity, with time

3.2 *CSWI Tests*

The results of *CSWI* tests for various relative densities are summarized in Fig. 2. The confining pressure (σ_3), principle stress ratio (K), and initial saturation ratio (Sr) were kept constant at 25 kPa, 3.4, and 30% respectively. All the specimens deformed gradually upon water infiltration. However, upon failure initiation (represented by Δ) strain rate (represented by ε_{II}) increased rapidly (Fig. 2b). Loose specimens would possess low initial matric suction which dissipated quickly upon water infiltration, thus initiating failure very quickly. Additionally, high post-failure strain rate (ε_{II}) was observed for loose specimen. This implies that slopes comprising of loose deposits are expected not only to initiate failure quickly but will also slide at a rapid pace after failure initiation. Fig. 2c and 2d show the corresponding response of compression wave (Vp'') and shear wave (Vs'') velocities normalized with their corresponding initial values. Initially with water injection, there was a gradual decrease in both (consistent with *ICCW* tests). However, wave velocities decreased rapidly upon failure initiation, with the post-failure rate of wave velocities (represented by $Vp_{II(Norm)}$, and $Vs_{II(Norm)}$) being consistent with corresponding strain rate (ε_{II}).

4 FIELD APPLICATION IDEAS

Experimental results and discussions presented in preceding sections explain the fundamental mechanism of elastic wave velocity variation in unsaturated soils. This information provides conceptual framework for landslide monitoring using elastic waves. Wave velocities measured on an actual slope surface would decrease gradually during rainfall, but they would decrease sharply upon failure initiation providing us an idea to issue a warning. Additionally in the post-failure initiation stage, rate of slope movement would be proportional to rate of wave velocity decrease. Thus, simply by monitoring the rate of wave velocities, an indication of rate of slope movement can be obtained.

4.1 *Single Exciter with Multiple Receivers*

Two key components controlling the cost of wave velocity based landslide monitoring system are the ‘wave exciter/transmitter’ and ‘receiver’ devices. A variety of receiving devices like electromagnets, piezoelectric ceramics, accelerometers, microphones, geophones, etc. are already available commercially. Many of these receiving devices are available literally at throw away prices e.g., contact microphones can be purchased as low as $1. Compensating for overhead expenditures including modification and upgrading of these sensors, and water proofing, etc, a good quality receiving unit may be prepared for about $10 cost. Development of a cost-efficient wave exciter/transmitter is however going to be a challenging task. Transmitters comprising of piezoelectric or electromagnetic type sensors generally do not have any mechanically moving parts. They typically require less driving voltage and the excitations generated by them are low in amplitude. Such excitations may not be able to be transmitted to receivers, a few meters from the exciter. On the contrary, mechanical exciters (drop hammer, etc) can generate high amplitude excitations which may be received several meters away. However, a continuous source of large driving voltage required by them can be a concern for landslide monitoring in remote areas.

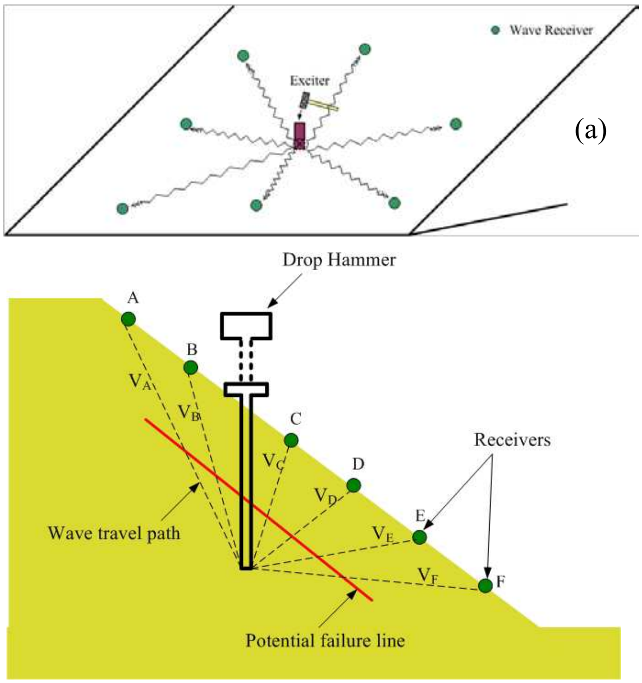

Fig. 3 Single exciter/multiple receiver assembly (a) Plan view; (b) Cross-section showing wave excitation deep into the slope.

In any case, a more cost-efficient approach for landslide monitoring based on elastic waves may be to install several receiving units on the slope surface which are made to receive excitations from a single excitation device. This concept is schematically shown in Fig. 3a. General procedure for landslide monitoring using this approach is outlined in the following points;

- A single exciter is strategically located on the slope surface to transmit waves to several receiving units.
- The exciter is triggered at regular intervals and wave velocity record of each receiver is monitored regularly.
- Each receiver represents a specific section of slope geometry. Variation of wave velocity recorded by each receiver can give an indication of saturation state across the slope surface.
- Sharp decrease in wave velocity recorded by any receiver can not only provide an idea about possible failure initiation but can also indicate its location on the slope surface.

In such an assembly it may still be very difficult to determine the location of potential failure plane. This can be improved by placing the excitation source at a certain depth inside the soil. Excitation source in the form of a hollow cylindrical rod can be pushed into the slope surface by ramming. A drop hammer, as shown in Fig. 3b, can then be used to generate excitations deep into the slope surface. Waves from the point of excitation would travel towards the receivers which can be interpreted to monitor any variations in the travel time. Development of yielding in the failure plane could thus be identified and the location of failure plane development could better be realized.. One possible limitation in this approach may be that, the thickness of failure plane may be too small to cause any variation in wave velocities. However, this phenomenon is yet unexplored and requires further research to confirm the effect of failure plane thickness on wave velocities.

4.2 *Use of Seismic Refraction Method*

The fundamental assumption of this method is that the potential failure plane lies at the interface of two layers. Thus, by monitoring the change in wave velocity of *critically refracted wave*, criteria can be developed for landslide early warning. An exciter and a series of receivers can be aligned on the slope surface. Any wave generated by the exciter would travel in the form of direct wave on slope surface, and as critically refracted wave at the potential failure plane, as shown in Fig. 4a.

Fig. 4b shows response of direct wave and refracted wave at various stages of landslide. V_A represents velocity of direct waves (i.e. travelling on the slope surface), whereas V_{FP} represents the velocity of critically refracted waves which travel along the failure plane. Path '*A*' in the plot, represents the initial conditions before the start of rainfall. During rainfall, soil surface starts getting wet and therefore wave velocity decreases, as indicated by the trend of V_A in path '*B*' (Fig. 4b). However, wave velocity along the potential failure plane, which is a function of wave velocity in the underlying stable layer is not expected to drop. This is indicated by a near-parallel response of V_{FP} during path '*A*' and path '*B*'. However, once the failure is initiated along the failure plane, no change in V_A is expected, however, V_{FP} is expected to decrease due to soil yielding along the slip surface. By following this approach, wave propagation in soil can be utilized to predict the initiation of landslides.

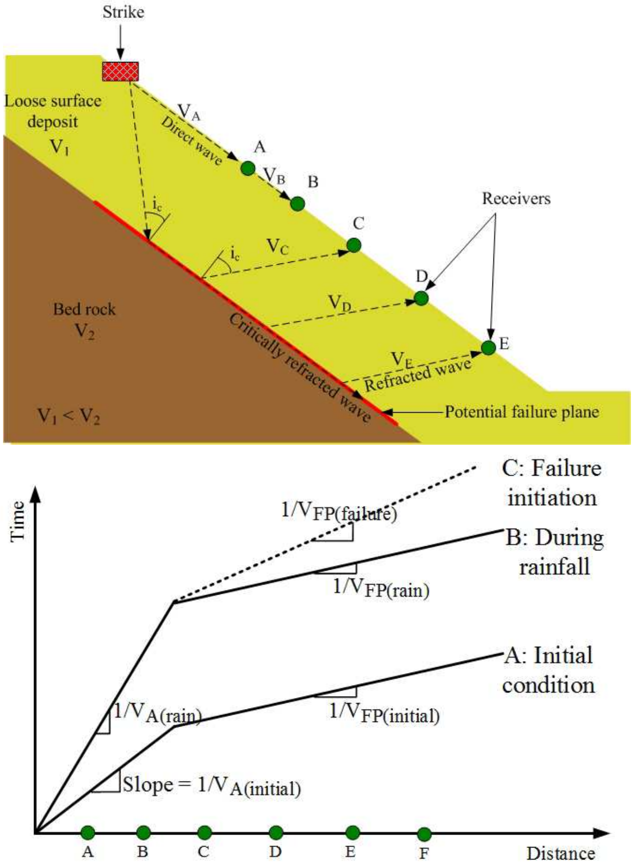

Fig. 4 Schematic illustrations of seismic refraction method for landslide prediction (a) layout of sensors and wave propagation paths (b) Interpretation of test results.

5 CONCLUDING REMARKS

Comprehensive series of triaxial tests were conducted to elucidate the behavior of elastic wave velocities during rainfall-induced slope failures. Shear and compression wave velocities were found to be sensitive to soil moisture. The marked decrease in wave velocities with soil wetting makes it a strong candidate to be used for landslide prediction. Decrease in wave velocities upon soil yielding could not only give us an indication of failure initiation time but it can also provide us an estimate of rate of slope movement. In conclusion, use of elastic wave velocities holds strong potential to be used for landslide early warning.

6 ACKNOWLEDGEMENTS

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