A laboratory study on groundwater quality and mass movement occurrence

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Abstract In this study, soil samples collected from the sides of two streams with high debris flow potential at Shenmu and Fengchiou village in Nantou County, Taiwan, were used for seepage tank tests in the laboratory. While the tests were being conducted, observations were made to investigate the relationships among displacement of the slope, quality of the seepage water and occurrence of mass movement. The results showed that according to the change rate, displacement could be divided into two stages, namely, the initial failure displacement stage and primary failure displacement stage. While the displacement of the slope was in primary failure displacement stages, the probability of slope failure became much higher. Before general slope failure, electrical conductivity (EC) and sulfate ion (SO_4^{2-}) concentration of the seepage water increased significantly. The time when EC of the seepage water started to increase rapidly was much earlier than that when displacement of the slope started to increase significantly. Therefore, from the hazard mitigation view, there will be a longer time for response if EC of the seepage water was monitored.

Keywords Debris flow · Mass movement · Displacement · Electrical conductivity · Sulfate ion

Introduction

Taiwan is a small island with high and steep mountains, short and rushing streams, and vulnerable geologic conditions. During typhoon and rainy seasons, mass movements such as landslides and debris flow occur quite often in slopeland area, and result in great loss of human lives, property and public facilities (Chang and Chien 2007). For instance, Toraji Typhoon on 30 July 2001 caused the greatest casualties and property loss in the past two decades and triggered a most disastrous and unforgettable debris flow (Fan et al. 2003). This kind of natural hazard occurs rather frequently in Taiwan.

Landslides occurring in a watershed upstream of the stream with high potential of debris flow may not only cause immediate hazard but also provide the materials for the debris flow. In traditional methods of slope stability analysis (including total stress and effective stress methods), such as Culmann's method, Taylor's method, circular failure surfaces method, ordinary method of slices, Bishop's simplified method of slices, Spencer's and Janbu's method of slices, the slope is considered to be under a condition of plane strain (Lambe and Whitman 1979; Das 1998) and progressive failure is not considered. In other words, it is assumed during the failure of the slope, the stresses distributed on the failure surface reach critical shear strength at the same time. To simplify the analysis, in different methods, different assumptions were made on the side forces of the slices, force equilibrium of the slices, friction of the slices and so forth to reduce the redundancies. As for calculating the safety factor, it is obtained from the value of the resisting force on the potential failure surface divided by that of the driving force. To reduce the redundancy, the safety factors of all slices are assumed to be equal, i.e., all the slices will either not fail or fail at the same time.

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In reality, the above-mentioned assumptions may not be correct. Usually, local failure occurs initially and then gradually with the development of the failure surface, general slope failure occurs. Until now, most of the data observed in the field are physical properties such as groundwater level, pressure, displacement and the data observed by inclinometer, extensometer and strain gage etc. Using these observation methods, it is difficult to predict the slope hazards timely and effectively. Until now, few studies have been related to chemistry methods. These studies are described as follows. Aoki (1998) conducted long-term groundwater monitoring at the Mushi landslide area in Niigata, Japan. He found that at a certain time before the landslide occurs, the deep groundwater level will rise and the concentration of hydrogen carbonate ions (HCO_3^{3-}), chloride ions (Cl^-) and sodium ions (Na^+) will change, resulting in an increase in electrical conductivity (EC). Ibe and Ebe (2000) collected water and soil samples at different sections and depths from Cross River in Nigeria after debris flow occurred. Then they conducted a series of environmental chemistry experiments, and found out that the concentrations of magnesium ions (Mg^{2+}) and sulfate ions (SO_4^{2-}) increased downstream. Results of soil analysis also showed the presence of potassium ion (K^+), magnesium ion (Mg^{2+}), calcium ion (Ca^{2+}), and chloride ion (Cl^-).

Based on the studies noted above, it was hypothesized that soil deformation triggered by rainfall and/or a rise of groundwater caused the change in groundwater quality downstream from slope failures. Therefore, in this study, a series of laboratory experiments were conducted to investigate relationships among ion concentration, electrical conductivity of seepage water and mass movement occurrence. There are quite a few efforts needed to be made to achieve the final goal that monitoring of groundwater quality can be used for predicting the occurrence of mass movement, yet it is expected that the findings in this study are a small step toward this goal.

Research method

Electrical conductivity (EC) of seepage water is a combined index of seepage water quality. Therefore, in this study, a series of indoor seepage tank tests were conducted to simulate slope failures because of rises in the groundwater level. During the tests, slope displacements, EC and ion concentrations of seepage water were monitored.

Soil test for samples

Soil samples for the indoor seepage tank tests of this study were collected from the sides of two streams with high

debris flow potential at Shenmu village and Fengchiou village in Sinyi Township, Nantou County, Taiwan, where debris flows occur frequently. Among 199 debris flow potential streams in Nantou County, the streams of Shenmu village and Fengchiou village were numbered “Nantou 037” and “Nantou 029”, respectively, by the Soil and Water Conservation Bureau in Taiwan, as shown in Fig. 1. The basic physical properties of the soil samples were determined using ASTM standards (Table 1; Fig. 2). The tests of specific gravity, liquid limit and plastic limit were performed twice, whereas the sieve and hydrometer analyses for determining particle size distributions were performed only once.

Description of the tank for tests

The dimension of the seepage tank used in this study was $100 \times 30 \times 30$ cm as shown in Fig. 3. There were three observation holes inside the tank, and one outside.

Using the holes, the variation of EC of water in and out of the tank was monitored. EC meter No. 1 was placed at the water source to record the variation of EC near the water inlet and excess water outlet. Excess water outlet was used to maintain the water level. EC meter No. 2 was placed inside the soil sample and about 30 cm from the filter and inlet. It was used to record the variation of EC upstream of the soil slope. A 1 in. hole was made 15 cm from the opening of the seepage tank and EC meter No. 3 was put there to record the variation of EC downstream of the soil slope. EC meter No. 4 was placed at the tank outlet to record the EC of seepage water coming out of the sample. A data logger was used to record data from different EC meters. Apart from these, to observe the soil sample failure, horizontal and vertical displacement meters were placed at the soil slope to monitor soil displacement. Further, a 1 in. hole was made near the opening of the tank

Fig. 1 The location of the test sample collection sites (Sinyi Township of Nantou County in Taiwan)

on the other side of EC meter No. 3 and a valve was installed to collect water samples for testing.

Sample preparation

To make the physical properties of the test samples similar to their in-situ counterparts, the scalp-and-replace method (Houston and Walsh 1993; Lin 1986; Chen et al. 1995) was used to modify the particle size distribution curves of the soil samples. The plus 1.5 in. (38.1 mm) material was removed before compaction and replaced with an equal weight of No. 4 to 1.5 in. (38.1 mm) material. Sometimes,

Table 1 Basic physical properties of soil samples from Shenmu village and Fengchiou village

Parameters	Sample location	
	Shenmu village	Fengchiou village
Specific gravity (G_s) ^a	2.71	2.65
Void ratio (e) ^b	0.59	0.54
D_{10} (mm)	0.06	0.07
D_{30} (mm)	4.76	4.24
D_{60} (mm)	34.90	20.70
C_u	581.67	295.71
C_z	10.82	12.41
Liquid limit (LL, %)	37	28
Plastic limit (PL, %)	29	22
Plastic index (PI, %)	8	6
USCS classification	GM	GM–GC

^a The specific gravity is defined as $G_s = \rho_s / \rho_w = \gamma_s / \gamma_w$, therefore, it is dimensionless

^b The void ratio is the field value

this method is referred to as the procedure for replacement of oversized aggregate. In Taiwan, this method has been named the “equal weight replacement” method, and the “modified weight replacement” method because of different translations from Chinese to English.

According to ASTM (2003, D2850; 2004a, D3080; 2004b, D4767), the largest particle size should be smaller than one-sixth the specimen diameter or thickness. Therefore, 1.5 in., which is smaller than one-sixth the smallest dimension (namely 30 cm, approximately 12 in.) of the tank, was selected as the maximum particle size. The maximum particle sizes of the soil samples collected from Shenmu and Fengchiou, in Nantou, were much greater than 1.5 in. (as can be seen in Fig. 2); therefore, the scalp and replace method (or the equal weight replacement method) was used to adjust the curves as shown in Fig. 4.

The average dry unit weights and moisture contents of Shenmu village and Fengchiou village in-situ were determined to be 16.63 kN/m³ and 15.6%, and 16.71 kN/m³ and 12.1%, respectively. The method used in this study to determine the field density is similar to that of Bertram (1973). However, the diameters of the holes were 1 m instead of 6 ft. For each test in the laboratory, the weight of dry soil and water were calculated according to the dry unit weight and moisture content in-situ, the modified particle size distribution curve and the sample volume in the seepage tank. The dry soil and water for each corresponding layer and batch were then weighed, well mixed, covered and kept undisturbed for at least 24 h to allow the soil to have evenly distributed moisture content. The moisture contents of the soil samples were controlled as close as that in the field, i.e. only 1% of error was allowed. Compared with the most common individual moisture specification in

Fig. 2 Particle-size distribution curves for test samples collected from Shenmu village and Fengchiou village

Fig. 3 Diagram of seepage tank **Fig. 4** The modified particle distribution curves by using the scalp-and-replace method for the soil samples from Shenmu village and Fengchiou village

the United States, which was $OMC \pm 2\%$ (Parsons et al. 2001); the controlled range of moisture content seems reasonable. When everything was ready, the sample was put into the tank in five layers and compacted for each layer. After the first two layers (with a total height of 10 cm) were

prepared, a metal slab 40 cm from the opening of the tank was installed to make a 75° slope. Then, the rest of the three layers (with a total height of 20 cm) were put in and compacted to ensure that the dry unit weight and the moisture content were close to those in the field.

Results and discussion

Slope failure in the seepage tank was triggered by a groundwater rise. The slope angle was 75° . Displacements of the slope and variation of EC were monitored and recorded. Aside from these, water samples were collected from the valves for water quality analysis.

Variation of seepage water level

While the seepage tank experiments were being conducted, the water levels at the source as well as at different observation holes (the height from the bottom of the tank to the water level) were measured and recorded. The results were analyzed as follows.

The water head measurements consisted of two parts, namely, the water head at the source and that observed in the holes. Initially, a water head of 10 cm was maintained at the source and in the observation holes. Then, the water head at the source was increased by 0.5 cm every 10 min. The head increase controlled at this rate was mainly to ensure that it was slow enough to allow the experiments to be successfully conducted and observed. The water heads at the source and in the observation holes were recorded every 10 min. From the test results, it was found that the average water heads at the source and in the observation hole for No.3 EC sensor, and the average total failure time were 21.78 cm, 21.70 cm and 235.5 min, respectively, for Shengmu village (2 sets of data in total); and 21.42 cm, 21.23 cm and 228.3 min, respectively, for Fengchiou village (three sets of data in total).

Displacement analysis

To investigate the soil mass displacement situation while the seepage water rose and the soil mass failed, vertical and horizontal displacement meters were installed at the outlet to record the data. From five sets data of the test results, it could be observed (see Figs. 5, 6), from the start of slope displacement till general slope failure, displacement versus time curve could be divided into two parts, namely, initial failure displacement zone and primary failure displacement zone. In this curve, it could be seen that in the beginning, displacement increased slowly with time, however, after a certain time, displacement increased rapidly and resulted in general slope failure. Therefore, the displacement versus time curve was divided into two stages for further discussion as follows. (Note: In the following, horizontal displacement was used for discussion.)

1. Initial failure displacement stage: it was defined as the time from when slope displacement starts to occur till the time when displacement increased significantly.

The stage represents a sign that the slope might fall into an unstable situation after a certain time.

2. Primary failure displacement stage: in this stage, displacement increased significantly, subsequently resulting in general slope failure. Therefore, this stage was the most important part during mass movement monitoring.

In this study, the start time of the initial failure displacement stage was defined as the starting time of slope displacement (t_{di}); the time when general slope failure occurred was defined as the general slope failure time (t_{df}), while the time separating the two stages (t_{pi}) was defined as either the end of initial failure displacement or the start of primary failure displacement. As shown in Fig. 5, the results of the third set of tests of Fengchiou were used for description. In this figure, t_{pi} was the corresponding time where the slope steepness changed significantly (i.e. the maximum curvature). In this study, the difference between t_{df} and t_{pi} was defined as Δt_d (i.e., $\Delta t_d = t_{df} - t_{pi}$). In other words, from the displacement observation view, Δt_d was the time needed for primary failure.

From the five sets of test data of Shenmu and Fengchiou (see Fig. 6; Table 2), it could be found that the average values of t_{di} , t_{pi} and t_{df} for the two sets of test of Shenmu were 157.0, 207.0 and 235.5 min, respectively; those for the three sets of test of Fengchiou 142.7, 214.3 and 228.3 min, respectively. As for the average time needed for primary failure (Δt_d), for two sets of the tests of Shenmu and three sets of the tests of Fengchiou, they were 28.5 and 14.0 min, respectively.

Electrical conductivity (EC) analysis

Electrical conductivity was monitored from the start of the test till the end of general slope failure. It could be seen in Fig. 6, for the five sets of tests, the initial values were slightly different and at the beginning the EC values

Fig. 5 Points of times defined for displacement–time curve and EC–time curve

Fig. 6 Displacement and EC versus time curves of the five sets of tests of Shenmu and Fengchiou

Table 2 Results of time and EC value of NO.3 EC meter for the five tests of Shenmu and Fengchiou

Test results	Location				
	Shenmu 1	Shenmu 2	Fengchiou 1	Fengchiou 2	Fengchiou 3
t_{di} (the starting time of slope displacement; min)	155	159	181	72	175
t_{df} (general slope failure time, i.e., the ending time of displacement monitoring; min)	240	231	226	230	229
t_{ei} (the EC starting time of slope failure; min)	196	184	184	181	191
t_{pi} (the starting time of primary failure displacement; min)	212	202	217	216	210
t_{ef} (the ending time of EC monitoring; $t_{ef} = t_{df}$, min)	240	231	226	230	229
Δt_d (the time needed for primary failure from displacement analysis; $\Delta t_d = t_{df} - t_{pi}$, min)	28	29	9	14	19
Δt_e (the time needed for slope failure from EC analysis; $\Delta t_e = t_{ef} - t_{ei}$, min)	44	47	42	49	38
EC_i (the EC value corresponding to t_{ei} ; $\mu s/cm$)	65	71	97	95	97
EC_f (the EC value corresponding to t_{ef} ; $\mu s/cm$)	105	109	131	141	139
ΔEC (the increment of EC value in the time period of Δt_e ; $\mu s/cm$)	40	38	34	46	38
% ΔEC (the increase rate of EC in the time period of Δt_e ; %)	62	54	35	48	39

fluctuated and after a certain time they became more smooth. The EC values of No. 1 and No. 2 EC meters upstream of the potential failure surface did not change

significantly. However, the EC values of No. 3 EC meter downstream of the potential failure surface increased significantly from t_{pi} to the end of general slope failure.

In this study, the time when EC value started to increase significantly (the maximum curvature) was defined as the EC starting time of slope failure (t_{ei}). The EC value corresponding to t_{ei} was the EC starting value of slope failure (EC_i). The ending time of EC monitoring (t_{ef}) was equal to general slope failure time (t_{df}), i.e., $t_{ef} = t_{df}$. The EC value corresponding to t_{ef} was EC_f as shown in Fig. 5. In this study, the time difference between t_{ei} and t_{ef} was defined as Δt_e . In other words, from the EC observation view, Δt_e was the time needed for slope failure. In the time period of Δt_e , the increment of EC value was ΔEC , and $\Delta EC = EC_f - EC_i$.

As shown in Fig. 6 and Table 2, for two sets of the tests of Shenmu, the average values of Δt_e , ΔEC and the increase rate of EC during the time period of Δt_e ($\% \Delta EC$) were 45.5 min, 39.0 $\mu S/cm$ and 58.0%, respectively; for the three sets of the tests of Fengchiou, they were 43.0 min, 39.3 $\mu S/cm$ and 40.7%, respectively.

Water quality analysis

The seepage water in the soil mass was collected every 30 min during each test for analysis to examine the variation in groundwater quality during slope failure. Water was collected from two different spots, namely, upstream (No. 2 EC meter) and downstream (No. 3 EC meter) of the potential slope failure zone. Eight kinds of chemical tests were performed to determine the concentrations of ions which were likely to change because of soil and rock deformation, according to the studies by Aoki (1998), and Ibe and Ebe (2000). The test items included: hydrogen carbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and tests for metal ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+). From the test results, it could be found:

1. For all five sets of samples, either upstream or downstream of the soil mass, the concentration of chloride (Cl^-) and nitrate (NO_3^-) showed no significant change throughout the tests. The concentrations

- of metal ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+) in the water were less than 10 mg/l with a variation no greater than 3 mg/l. In addition, metal ion concentrations showed no significant changes before or after the slope failed.
2. For the three sets of samples from Fengchiou village, the hydrogen carbonate (HCO_3^-) ion concentrations upstream and downstream of the soil mass ranged from 15 to 30 mg/l, while the concentration of the two sets of samples from Shenmu village varied from 5 to 15 mg/l. Based on this observation, hydrogen carbonate (HCO_3^-) ion concentrations showed no significant changes before or after slope failure.
3. Sulfate ion (SO_4^{2-}) concentrations upstream of the slope failure zone remained roughly unchanged during the tests. However before a soil mass failure, the downstream ion concentrations of the two sets of samples from Shenmu village rose from 11.7 to 21.7 mg/l and 12.2 to 22.4 mg/l, respectively. The downstream ion concentrations of the three sets of samples from Fengchiou village rose from 15.0 to 25.1 mg/l, 14.5 to 23.6 mg/l and 15.0 to 25.5 mg/l, respectively (see Table 3).

After analyzing the ion concentrations of the five tests, it might be concluded as follows.

(1) Before slope failure caused by a rise in groundwater level, downstream sulfate ion (SO_4^{2-}) concentrations tended to increase significantly, whereas upstream sulfate ion concentrations generally remained unchanged. (2) Concentrations of other ions including hydrogen carbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-) and metal ion (Ca^{2+} , Mg^{2+} , Na^+ , K^+) showed no significant changes either upstream or downstream.

Similar to electrical conductivity analysis as previously mentioned, the concentration of sulfate ion (SO_4^{2-}) and displacement versus time curves were analyzed and plotted as shown in Figs. 7 and 8. In this study, the time when sulfate ion (SO_4^{2-}) concentration started to increase significantly (the maximum curvature) was defined as the

Table 3 Analysis of the change in sulfate ion concentration upstream and downstream of the slope failure zone

Time (min)	Upstream SO_4^{2-} concentration (mg/l)					Downstream SO_4^{2-} concentration (mg/l)				
	SM1	SM2	FC1	FC2	FC3	SM1	SM2	FC1	FC2	FC3
30	9.0	9.4	11.7	12.3	11.5	8.8	8.8	13.6	8.3	12.6
60	9.4	9.7	10.8	11.1	11.0	9.2	10.6	13.8	11.7	13.8
90	9.4	9.6	10.2	13.2	11.2	9.0	9.7	13.6	12.3	13.6
120	9.3	9.2	10.8	11.8	10.8	9.4	10.3	14.0	12.8	13.7
150	9.4	9.9	11.0	12.0	11.0	9.6	11.2	13.8	13.0	13.8
180	8.8	9.7	10.6	10.8	11.4	11.4	11.5	13.6	12.6	13.6
210	8.3	9.7	9.9	10.9	11.3	11.7	12.2	15.0	14.5	15.0
240	8.7	9.7	10.4	11.2	11.3	21.7	22.4	25.1	23.6	25.5

sulfate ion starting time of slope failure (t_{si}). The sulfate ion (SO_4^{2-}) concentration corresponding to t_{si} was the sulfate ion starting value of slope failure (S_i); whereas the ending time of sulfate ion monitoring (t_{sf}) was equal to the general slope failure time (t_{df}), i.e., $t_{sf} = t_{df}$. The sulfate ion (SO_4^{2-}) concentration value corresponding t_{df} was S_f as shown in Fig. 7. In this study, the time difference between t_{si} and t_{sf} was defined as Δt_s . In other words, from the sulfate ion concentration observation view, Δt_s was the

time needed for slope failure. In the time period of Δt_s , the increment of SO_4^{2-} concentration was ΔS , and $\Delta S = S_f - S_i$.

As shown in Fig. 8 and Table 4, for the two tests of Shenmu, the average values of Δt_s , and ΔS and the increase rate of SO_4^{2-} during the time period of Δt_s ($\% \Delta S$) were 25.5 min, 10.1 mg/l and 84.5%, respectively; for the two tests of Fengchiou, they were 18.3 min, 9.9 mg/l and 66.7%, respectively.

Fig. 7 Points of times defined for displacement-time curve and sulfate ion time curve

General discussion

From five sets of results of the seepage tank tests in the laboratory shown in Table 5, general discussion is as follows.

From the slope displacement observation view, from the start of slope displacement till general slope failure, displacement versus time curve could be separated into two parts, namely, the initial failure displacement stage and the primary failure displacement stage. That is to say, when the slope displacement fell into the primary failure displacement stage, the occurrence probability of mass movement notably increases.

Fig. 8 Displacement and sulfate ion versus time curves of the five tests of Shenmu and Fengchiou

Table 4 Results of time and sulfate ion concentration value downstream for the five tests of Shenmu and Fengchiou

Test results	Location				
	Shenmu 1	Shenmu 2	Fengchiou 1	Fengchiou 2	Fengchiou 3
t_{si} (the sulfate ion (SO_4^{2-}) starting time of slope failure; min)	210	210	210	210	210
t_{sf} (the ending time of sulfate ion (SO_4^{2-}) monitoring; $t_{sf} = t_{df}$, min)	240	231	226	230	229
Δt_s (the time needed for slope failure from SO_4^{2-} concentration analysis; $\Delta t_s = t_{sf} - t_{si}$, min)	30	21	16	20	19
S_i (the SO_4^{2-} concentration value corresponding to t_{si} ; mg/l)	11.7	12.2	15.0	14.5	15.0
S_f (the SO_4^{2-} concentration value corresponding to t_{sf} ; mg/l)	21.7	22.4	25.1	23.6	25.5
ΔS (the increment of SO_4^{2-} concentration value in the time period of Δt_s ; mg/l)	10	10.2	10.1	9.1	10.5
% ΔS (the increase rate of SO_4^{2-} concentration value in the time period of Δt_s ; %)	85	84	67	63	70

Table 5 Average values of the tests of Shenmu and Fengchiou

Test results	Location		
	Shenmu (2 sets)	Fengchiou (3 sets)	Average value of the 5 tests
Average Δt_d (average time needed for primary failure from displacement analysis; min)	28.5	14.0	21.3
Average Δt_e (average time needed for slope failure from EC analysis; min)	45.5	43.0	44.3
Average Δt_s (average time needed for slope failure from SO_4^{2-} concentration analysis; min)	25.5	18.3	21.9
Average ΔEC (average increment of EC value in the time period of Δt_e ; $\mu\text{S}/\text{cm}$)	39.0	39.3	39.2
Average % ΔEC (average increase rate of EC in the time period of Δt_e ; %)	58.0	41.0	49.5
Average ΔS (average increment of SO_4^{2-} concentration value in the time period of Δt_s ; mg/l)	10.1	9.9	10.0
Average % ΔS (average increase rate of SO_4^{2-} concentration value in the time period of Δt_s ; %)	85.0	67.0	76.0

From the seepage water quality observation view, before general slope failure, electrical conductivity (EC) and sulfate ion (SO_4^{2-}) concentration of the seepage water showed an increasing tendency. The average increments and increase rates for EC and SO_4^{2-} concentration, namely, ΔEC , % ΔEC , ΔS and % ΔS , were 39.2 $\mu\text{S}/\text{cm}$, 49.5%, 10.0 mg/l and 76.0%, respectively.

From time period observation view, when displacement was used for monitoring slope failure, there were 21.3 min (average Δt_d) for response before mass movement hazards. When the EC and SO_4^{2-} concentration of the seepage water were used for monitoring slope failure, there were 44.3 min (average Δt_e) and 21.9 min (average Δt_s), respectively, for the response time. Therefore, it could be concluded compared with monitoring of displacement when EC of the seepage water was monitored, there were a longer time for response. This might because the EC of the seepage water was more sensitive to the local failure of the slope.

From observing the whole experimental process and from the slope displacement observation view, it could be

found that general slope failure did not occur while the displacement of slope started to appear. It was more likely that small deformation occurred first in the soil mass of the slope and then through the rise of seepage water level and with the increase of displacement finally resulting in general slope failure. From local failure to general failure of the slope, displacement seepage water quality more or less reflected the information of the slope failure process.

When the traditional slope displacement monitoring method is used in the field, it is rather difficult to predict the location of local failure of the slope. In this study, variation of seepage water quality was used for monitoring mass movement, and from the results, it was found that the response time for mass movement by monitoring EC (Δt_e) was about twice as long as that by monitoring displacement (Δt_d). However, the conclusions as drawn in this study are limited in observing tests in the laboratory; and whether local failure of the slope is the reason why Δt_e is greater Δt_d is not completely understood and therefore, it needs further study.

The observation method of seepage water quality was proposed to analyze and monitor mass movement. The proposed method is rather different from the traditional observation method for monitoring mass movement. However, the situations in the field are much more complicated than those in the laboratory. For instance, in the field, apart from being affected by mass movement, seepage water quality may be influenced by other factors such as point and non-point source pollution. In addition, the direction and the depth of seepage water are difficult to be detected. Before the proposed method is applied in the field, there are still a number of problems needing to be solved. For example, how to avoid the interference to groundwater quality by the external environment, how to orientate the observation holes and the depths to monitor the seepage water quality, whether there is threshold of the change in groundwater quality during the mass movement occurrence, if yes, how much will that be, how to implement the real-time monitoring, and whether the findings in this study are valid for slopes with different soils. Aside from these, the mechanisms of variation of groundwater quality and mass movement need to be further examined in the future.

For groundwater quality monitoring in the field, we selected three observation holes near the outlets of the watersheds of the streams at Shenmu and Fengchiou. Upstream of the holes, there were no residential, agricultural, or recreational activities. At the observation stations, automatic recording rain gages, groundwater level meters, electrical conductivity (EC) sensors, automatic samplers for collecting water samples, data loggers and wireless transmitters were installed for monitoring in the field. Although there were some data, there was no conclusive result.

Conclusions and suggestions

In this study, five sets of seepage tests were conducted in the laboratory. All processes of slope failure, displacements and seepage water quality were observed. From the displacement analysis, it was found that from the start of slope displacement till general slope failure, displacement versus time curve could be divided into two parts, namely, the initial failure displacement stage and primary failure displacement stage. All mass movements occurred in the primary failure displacement stage.

From observing displacement and seepage water quality, it was found that a certain time before general slope failure, displacement, EC and sulfate ion concentration value increased significantly. The time periods are helpful for response of hazard prevention. Among the three noted values, EC increased rapidly in the earliest time. This

might be because EC was more sensitive to the local failure of the slope. In addition, compared with the monitoring method of displacement, the monitoring method of EC in the field is better, because local failure of the slope is difficult to be detected by displacement monitoring. Usually, when the sign of slope failure was detected using displacement monitoring, the displacement had already fallen into the primary failure displacement stage. However, it was possible to detect the occurrence of local slope failure using EC monitoring. Based on the findings in this study, compared with the displacement monitoring, the EC monitoring showed its superiority for monitoring mass movement.

In this study, the observation method of groundwater quality was proposed for monitoring mass movement. However, if the proposed method is to be used in the field, there are still problems that need to be solved. For instance, how to allocate the locations and the depths of the observation holes, how to prevent groundwater quality from interference by the external environment, whether there is threshold of change of groundwater quality while the mass movement occurs, if yes, how much will that be, and whether the findings in this study are valid for the slopes with different soils, and how to conduct the real-time monitoring, etc. Besides, the mechanisms of variation of groundwater quality and mass movement need to be further studied. Forecasting the occurrence of mass movement in the field by monitoring groundwater quality is yet to be further researched. However, it is anticipated that the findings in this study could be a small step toward this final goal.

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