<Topic>

About Prediction of Collapse Generated Locations Using Groundwater Aeration Sounds

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1. Overview

In the past, it has been described that rainwater descends and infiltrates through soil layers, and when it reaches to impermeable bedrock a saturation zone forms on the bedrock. As this saturation zone expands this causes a collapse (e.g Okimura et al. 1985, Sanmori et al. 1995). According to this view, it is considered that collapses happen in the leg of the slope where the saturation zone expands or a valley where groundwater concentrates. In addition, it is considered that collapses do not occur on a slope which has ridge type topography. However, in actual shallow landslides, as shown in Picture-1, there are some which occur around catchment boundaries where there is almost no catchment area and there are some which occur on ridge type slopes. On the other hand, when thinking about the timing of rainfall and collapses, it is known that collapses occur near the peak of rainfall intensity. However, it has been pointed out that the times of estimated collapses, calculated numerically using a catchment model which assumes the soil layer is uniform, lag behind the actual times of occurrences of collapse (Hiramatsu et al. 1990). Furthermore, it is empirically known that even if permeability and water retentivity are strictly measured, the results of infiltration analysis do not match the observable data at the local site. These reasons seem to show that non-uniformity in underground and the rainfall infiltration process originating from that are not considered as important (Ex. Tada et al 2002, Tsutsumi et al. 2005).

Picture-1 Example of Shallow Landslide Occurred at Mountain Region

In order to predict locations generating collapses, it can be understood from seeing the following 2 pictures that non-uniformity should be taken into consideration. For example, in collapse areas springs, shown as in Picture-2, are often confirmed (e.g. Kawaguchi et al. 1951). In addition, as shown in Picture-3, we observed piping holes, from which water flowed on the scarp of the collapse, even though there is no spring (e.g. Ota et al. 1981). Meanwhile, blow-offs, stoppages, and turbidity of springs are known as precursory phenomenons of collapse. In this way, since long ago it has been thought that there is a close relationship between water paths and collapse phenomenon. However, since there is no method to efficiently detect distribution of water paths at local sites, there are a great many factors which are unclear about the causal correlation between water paths and collapses.

Therefore, this article introduces the groundwater aeration sound survey which is a simple method to investigate water paths in mountain regions. In addition, we studied the relationships between the positions of collapses and water paths to discover if non-uniform elements such as water paths can be appropriately evaluated and it is possible to improve the accuracy of predicting the positions where collapses will occur. It seems unfamiliar to talk about the sounds of flowing groundwater, but Pond,S. F. (1971)used a stethoscope to reveal the networks of underground pipes in the catchment basin as shown in Figure-1. Also, in Japan too, Japanese woodblock prints *ukiyo-e*, depicted scenes in which welldiggers in the Edo period put their ear on the ground to determine the position wells by using the sounds of flowing groundwater. Actually, even without special equipment, if you put your ear directly on the bedrock seen around the locations where collapses occurred, you can hear slight sounds of flowing groundwater. Meanwhile in the field of trekking, it is said that if you stick a trekking pole into the ground you can locate drinking water at on a mountain summit by just relying the groundwater sounds which echo within the pipe of the trekking pole. This method applies this knowledge to groundwater surveys on mountainous slopes.

Picture-2 Spring Which Can Be Seen at Collapse Area (provided by Forestry Research Center Tottori prefecture Kan Koyama)

Picture-3 Piping Hole Seen in the Collapse Area

2. Properties of Groundwater Aeration Sounds and the Survey

2.1 Measuring Device and Measuring Method

In this article, sounds which are generated by water flow which flows through the water path are described as groundwater aeration sounds. Groundwater aeration sounds include not only sounds produced from water flow but also include other slight noises (wind noise, vibration noise of wind, friction sounds of earth and gravel, etc.). However, by devising measurements to eliminate the noise, you can hear groundwater aeration sounds. From this

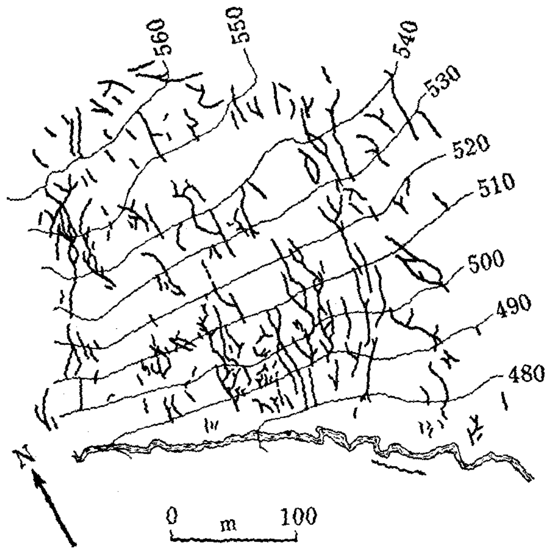
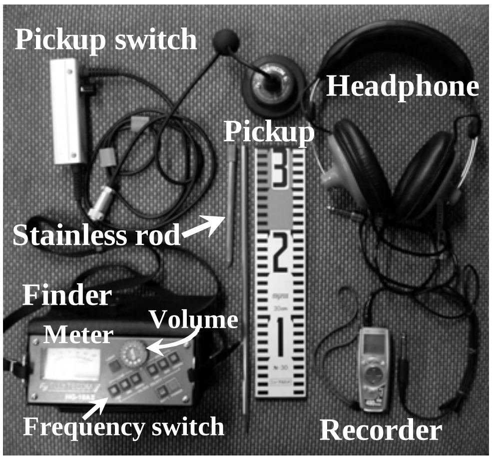


Figure-1 Networks of Underground Pipes Which Were Surveyed Using A Stethoscope
(cited from Pond, S. F..(1983))

point an outline of the mechanism of the measuring device is explained.
The groundwater aeration sound measuring device is shown on Picture-4 and the measurement scene is shown on Picture-5. The groundwater aeration sound measuring device consists of 1) sensor, 2) finder, 3) headphones, 4) recorder. The functions of each part are as follows.
1) Sensor: In order to avoid picking up noise such as wind, a stainless bar of φ0.8×10 cm, shown in Picture-4, is installed on a sensor and this is inserted into the ground to capture the groundwater aeration sounds.
2) Finder: The finder consists of an amplifier circuit which amplifies the groundwater aeration sounds captured by the sensor, a filter circuit to eliminate noises such as wind, and a level meter which displays the sound pressure of groundwater aeration sounds. The filter circuit can pick out only the sounds of specific frequency bands among the groundwater aeration sounds caught by the sensor and can easily deal with the noises which are generated at local sites. In addition, the strength of sounds can be understood visually using the level meter.



Picture-4 Groundwater Aeration Sound Measuring Device


Picture-5 Showing Groundwater Aeration Sounds Being Measured

3) Headphone: It outputs in real time the groundwater aeration sounds caught by the sensor, at the amplification factors and frequency bands as set in the finder.
4) Recorder: A voice recorder which is sold in the general market is connected parallel to the headphones to record groundwater aeration sounds.
The groundwater aeration sound measuring device is not only very light weight with a total weight of 900 g but also the recorder at its largest size is a compact 17.5×7.0×10.5 cm, which can be used easily for surveys in mountain regions.

2.2 Properties of Groundwater Aeration Sounds
2.2.1 Sound Wave Generated from Groundwater Flow
Sounds generated from groundwater flow are aeration sounds such as “*Korokoro*” (trickle), "*Bokoboko*"(burble), and “*Gou*” (gurgle). We carried out the following experiments in order to investigate the mechanism of the generation of groundwater aeration sounds. We introduced water stained by

fluorescent dye to a white sand layer and videotaped the saturation process of the sand layer from the side of the water tank. In addition, at the same time, we installed a water-resistant microphone on the surface of the sand to pick up groundwater aeration sounds. Following these experiments, as a result of aligning the video images and the timing of the output of groundwater aeration sounds, the following generation mechanism of groundwater aeration sounds was revealed.

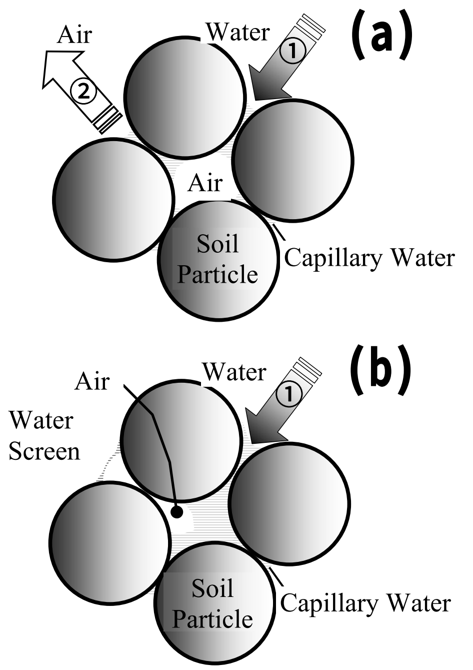


Figure-2 Movements of Water And Air in Sand Layer

Figure-2 represents a schematic depiction of the movements of water and air in the sand layer, which were confirmed by the video images. In a sand layer in an unsaturated condition, there is air and water in the gaps between soil particles, as shown in Figure-2 (a). In an unsaturated condition, capillary water is absorbed in the small gaps between soil particles thus creating a meniscus. Meanwhile, there is air in in the middle of large gaps. As shown in Figure-2 (a), when water intrudes into this part from ① the air between the soil particles is pushed out through ②. However, the escape route of the air is blocked by capillary water which is absorbed between the soil particles, so in order for the water to make its way in, the air must push out the capillary water. At this time, the capillary water which was absorbed between the soil particles is pushed by the air and forms a water screen in the direction of movement shown in Figure-2 (b). Then at the same time as water fills the gaps between soil particles, it breaks up. At the moment of the water screen breaking up, "*Poko*" (plop), the bursting sound of the air bubble occurs. For this sound of air bubbles, there are different pitches of sounds such as "*Koro* (plip)", "*Poko*"(plop), and “*Boko*” (blob). This is because the size of air bubbles varies depending on the size of the gap between the soil particles. A large air bubble generates low sounds and a small bubble generates high pitch sounds. The sounds of flowing groundwater are generated when many of these air bubbles in different sizes burst inside the soil. On the other hand, at locations where a large amount of groundwater flows, the air and water in the soil are actively exchanged. In other words, at locations where the more groundwater flows, many air bubbles burst and the strength of groundwater aeration sounds become loud. By discovering this location of strong sounds, the groundwater aeration sound survey identifies locations where groundwater flows. In addition, even if there is groundwater, if there is no exchange between air and water from the movement of water, there is no sound of water flow generated.

2.2.2 Water Path Locations And Distribution of Groundwater Aeration Sounds

We carried out the following model experiments to study characteristics of distribution of groundwater aeration sounds when there is one water path in a uniform soil layer.

As shown in Figure-3, standard sand was sprinkled with water and flattened with pressure to a length of 5 m, width of 2 m, and depth of 0.7 m. A porous pipe covered by non-woven fabric was installed in the middle of the soil layer at a position of 2.5 m, and was supplied

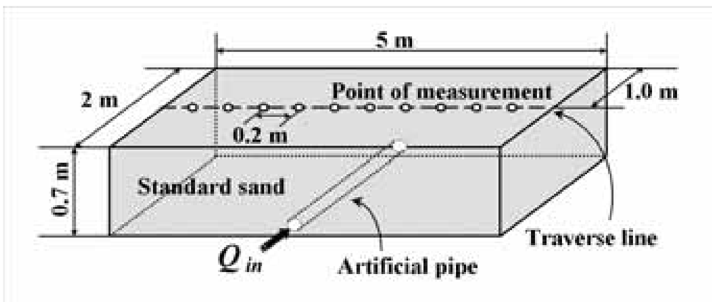


Figure-3 Model Soil Layer

with water from Q_{in} in Figure-3. The experiment conditions were changed for depth and the amount of the flow of water to the water supply porous pipe. In other words, for depth, there are two cases of 35 cm and 62 cm, for amount of the flow, there are six cases of 50, 100, 150, 200, 250, 300 mℓ/sec. In addition, the water supply was set as a steady water supply.

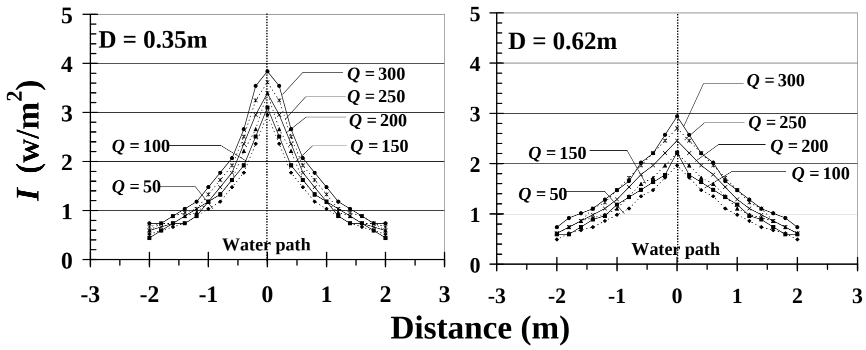


Figure-4 Results of Groundwater Aeration Sound Measurements for Each Depth

As shown in Figure-3, a measurement line on the ground surface in the middle of soil layer was set, and measurement of groundwater aeration sounds was carried out at 2 m to the left and right from directly above the porous pipe. The measuring interval was set at 0.2 m. After inserting stainless rods attached to a sensor into the ground at each survey point, we carefully observed the relationship between the variation of groundwater aeration sounds which can be heard from the headphones and the variation of indicated values of the level meter and measured the peak value of groundwater aeration sound 10 times. After that we determined the average value of these values as the groundwater aeration sound levels. In addition, as a result of the preparatory experiments, groundwater aeration sounds were able to be captured well between 100 and 600 Hz. In this experiment, for the groundwater aeration sounds, we took this frequency band as measuring values.

Figure-4 shows the groundwater aeration sound levels I (W/m^2) measured at each survey point by the porous pipes at each depth. In addition, Q in the figure represents the amount of flow (mℓ/sec). Also, the position of porous pipes is shown as 0 m in the figure. The following points can be understood from the figures.

1) The groundwater aeration sound levels measured at the ground surface are loudest at the position of 0m directly above the porous pipe, and the further from the sound source of the porous pipe the more the sound pressure is diminished.
2) When the depths of the porous pipes are equal, the gradient of the distributed wave form of the groundwater aeration sounds are similar, and the greater the amount of flow the louder the groundwater aeration sound levels at each survey point.
3) When the amount of the flow in the porous pipes is equal, the shallower the sound pressure in the vicinity of porous pipe as the sound source is larger. In addition, compared to the case in which the gradients of distributed wave form are steep, we saw that the shallower the pipe, the steeper the gradient.

From these results mentioned above, we obtained the following understanding:

1) The groundwater aeration sounds are loudest directly above the water path and the further from the water path, the weaker the sound.
2) If the water paths are at an equal depth, the larger the amount of flow, larger the peak of groundwater aeration sound level.
3) If the amounts of water flow in the water path are equal, the shallower the water path, the larger the peak of groundwater aeration sound level.
4) The strength of groundwater aeration sounds transmitted to the ground surface is determined by the relationship between the amount of flow and the depth of the water path.

It is considered that the groundwater aeration sounds are characterized by diminishing due to the distance of the groundwater aeration sounds. From now on, by developing a theory based on a formula based on diminishing sounds due to distance, there is a likelihood that it will be possible to identify the depth of sound sources.

2.3 Application of Groundwater Aeration Sound Survey to Local Sites

2.3.1 Outline of Investigation

It was discovered that when there is only one water path in a uniform soil layer, a water path exists directly below the position where groundwater aeration sounds are the strongest. However, it was not certain whether similar results can be obtained in non-uniform natural ground. Therefore, in order to study whether groundwater aeration sounds are the loudest directly above water paths no matter the different geological conditions and density of the ground, we carried out the groundwater aeration sound surveys at locations where geological conditions differ: Hiruzen highland in Okayama prefecture, Misasa-cho in Tottori prefecture, Mount Rokkosan in Kobe City, Hyogo prefecture, and Hiru valley located in Kamitakara village in Gifu prefecture (Figure-5). The summary of each investigated site is as follows:

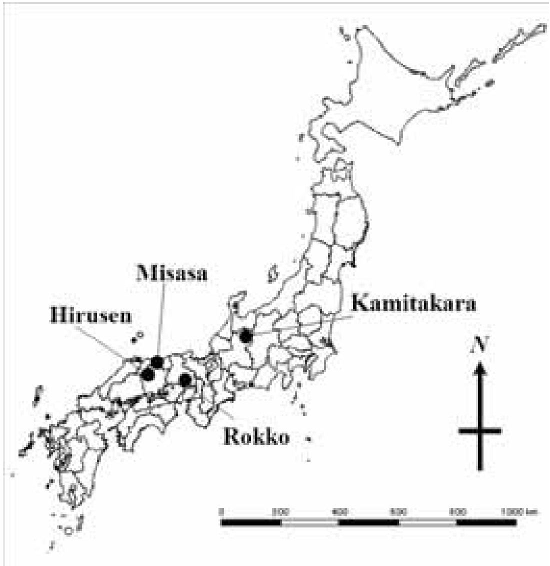
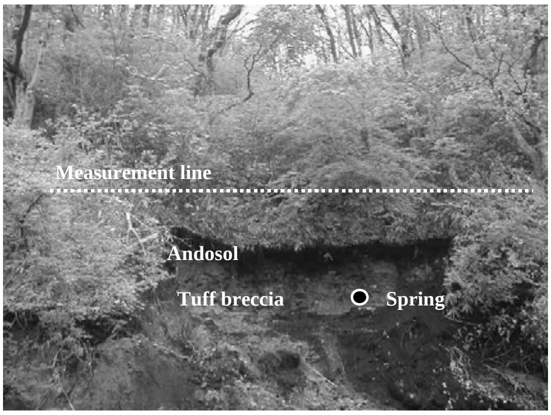
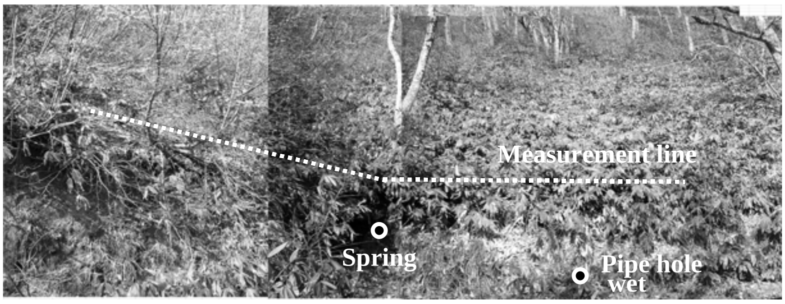


Figure-5 Investigation Sites

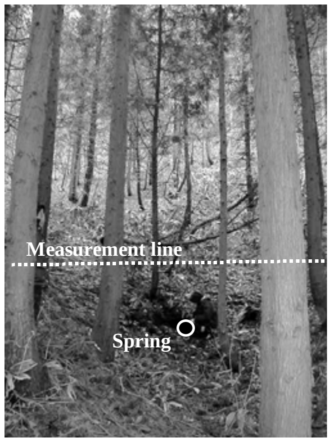
1) Hiruzen A (Picture-6): We carried out a survey, targeting springs which were seen on a cutting of forest road. The surface layer was covered by about 50 cm of Andosol, deposited from Mount Daisan and the lower layer consisted of tuff breccia. There are spring points in the layer of tuff breccia and water flows during heavy rainfall or snow melt. At the time of the survey, there were a small number of springs.
2) Hiruzen B (Picture-7): We carried out a survey, targeting 2 spring points which were seen on a cutting of forest road. The surface layer was covered by about 1.5 m of Andosol and the lower layer consisted of tuff breccia. The spring on the left side of Picture-7 is situated in a layer of Andosol and a very small amount of outflow was seen during the survey. On the other hand, the spring on the right side of Picture-7 is situated in a layer of tuff breccia and there was no outflow during the survey.
3) Hiruzen C (Picture-8): We carried out a survey, targeting springs developed on a colluvial deposit in the spur. The surface layer was covered by about 2 m of Andosol and the lower layer consisted of tuff breccia. A spring is situated on the boundary of the Andosol soil layer and tuff breccia and the spring flows during heavy rainfall or snow melt. During the surveys, no spring was seen but there was some moisture.
4) Misasa: We carried out a survey, targeting springs developed on colluvial deposits in the spur where geological features consist mainly of granite. Springs are in existance during heavy rainfall and snow melt, and a relatively abundant outflow from the springs was seen during surveys.
5) Mount Rokkosan: We carried out the surveys at spring points seen on the colluvial deposit on the end of the valley. The geological features consist of granite. Springs are in existance throughout the year and during the survey, there were a large quantity of springs.
6) Hiru valley (Picture-9); We carried out the surveys, targeting two spring points which have developed in colluvial deposit of the zero-dimension valley located at the head of Hiru valley. The geological features consist of granite porphyry and there is no spring during the dry period in summertime. At the time of the survey, there were a small amount of springs.
In the surveys, we set a measurement line which crossed water paths as shown by the dashed lines in Picture-6 to 9, and measured the groundwater aeration sounds at 0.5 m to 2 m intervals on this measurement line. In addition, although the measuring method is the same as described before, but because winds etc. unexpectedly blew strongly and generated noise, we made sure not to carry out measurements during those periods. In addition, for measuring frequency, we used frequency bands of 400 to 1200 Hz which are less affected by wind.



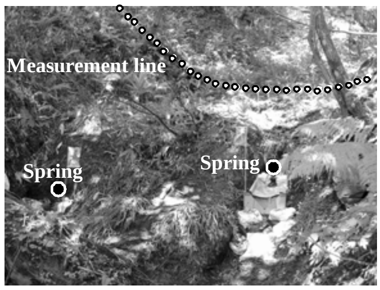
Picture-6 Condition of the Cutting of Forest Road in Hiruzen A



Picture-7 Condition of the Cutting of Forest Road in Hiruzen B



Picture-8 Appearance of Vicinity of Spring Point in Hiruzen C



Picture-9 Appearance of Vicinity of Spring Point in Hiru valley

2.3.2. Survey Result of Water Paths

Figure-6 shows the survey results of groundwater aeration sounds, carried out at each investigation site. The solid line in the figure represents the ground surface and ○ represents the locations of spring points. In addition, ● represents the groundwater aeration sound levels measured at the ground surface and the dashed line represents the distribution of groundwater aeration sounds

At every investigation site, groundwater aeration sounds are the loudest directly above a spring point and become weaker the further from the spring point. In addition, this trend was also confirmed similarly at Hiruzen B and Hiru valley where there are multiple spring points. In addition, although it is hard to compare because the amount of flow varies depending on each investigation site, in comparison to Hiruzen A, B, and Hiru valley where spring points are located at relatively deep position below the ground surface, at Rokko and Misasa where spring points are located shallowly the gradient of waveform distribution of groundwater aeration sounds is steep. These results align with the results confirmed in the model experiment. In addition, it is interesting that even at Hiruzen B and C where springs are not confirmed by visual observation; there are peaks of sound pressure.

Next, we summarized the x-coordinate of spring points and peaks of groundwater aeration sounds at each investigation site and their deviations (Dx) on Table-1. The largest deviation seen in a direction of x-coordinate is Hiruzen B where a deviation of 0.48 m occurred. On the other hand, at other investigation sites, locations of spring points and locations of peaks of groundwater aeration sounds are aligned, and locations of spring points were able to be estimated using the distribution of groundwater aeration sounds. For these reasons, the groundwater aeration sound surveys were able to identify water path locations with accuracy of approximately 50 cm.

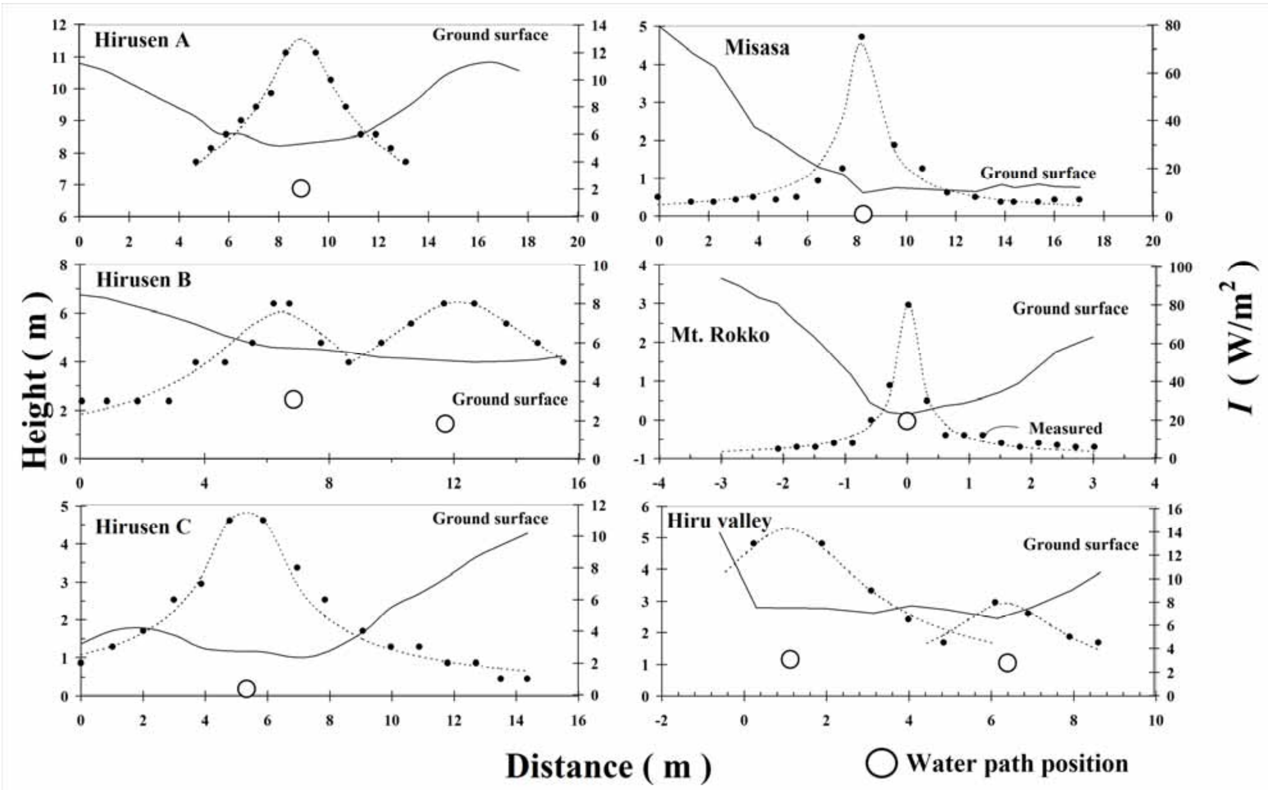


Figure-6 Locations of Spring Points and Survey Results of Groundwater Aeration Sound

Table-1 Correlation between Locations of Spring Points and locations of Groundwater Aeration Sound Peak

	Measured X (m)	Estimated X (m)	Deflection Dx (m)
Hirusen A	**8.90**	**8.90**	**0.00**
Hirusen B	**6.89**	**6.41**	**0.48**
	11.76	**12.13**	**-0.36**
Hirusen C	**5.33**	**5.33**	**0.00**
Misasa	**8.25**	**8.25**	**0.00**
Rokko	**0.00**	**0.00**	**0.00**
Hiru Valley	**1.13**	**1.13**	**0.00**
	6.40	**6.40**	**0.00**

2.4 Summary of Groundwater Aeration Sound Survey

We examined a method to identify water path locations using sounds generated from the water flow through water paths. The characteristics of this method can be summarized as follows.

1) Water path locations can be estimated by measuring groundwater aeration sounds at random intervals in a direction crossing the water path. When applying the method to local sites, there were some cases in which a deviation of maximum appropriately 50 cm occurred.

2) This can be carried out even when springs can not be confirmed by the naked eye.

3) The groundwater aeration sound measuring device is compact and light weight and it can be used easily in difficult to access mountain districts.

Since the groundwater aeration sound survey can easily identify water path locations at local sites, it is expected that it can be applied to various problems related to groundwater discharge. In addition, this article does not discuss the measuring time and usability at local sites, etc.; but after carrying out the surveys on mountain slopes using this measuring device, we realize (1) it is very light weight and the degree of fatigue is low and (2) it is able to measure the groundwater aeration sounds in a short time.

3. Application of Groundwater Aeration Sound Survey to Collapse Area

3.1 Outline of Investigation Sites, and Investigation Method

In order to study the correlation between routes of water paths and locations where collapses occur, we investigated the groundwater aeration sounds at 10 shallow landslides which occurred at 4 locations on natural slopes in Okayama prefecture, and at 63 slope landslides which occurred at 40 locations on forest roads in Tottori prefecture and Okayama prefecture. Figure-4 shows locations of investigation sites.

The shallow landslides (◎ A to D in Figure-7) surveyed on natural slopes occurred at a young forest where Japanese cedar and Japanese cypress were planted after clear cutting. We selected and surveyed geological features of collapses thought to be common shallow landslides which occurred in granite areas. The geological features of collapses all consist of granite and the width of the collapses are 2 to 16 m and depth of the collapses are approximately 1 to 2 m.

All collapses (●A to E in Figure-7) surveyed on forest road slopes occurred at the road cut slopes, and we didn't select those thought to be influences by the surface current generated on road surface of forest roads during rainfall. The geological features consist of granite, granodiorite, Sangun metamorphic rocks, black schist, tuff, etc. and the widths of the collapses are approximately 2 to 30 m and the depth of the collapses are approximately 0.5 to 5 m.

Because immediately after rainfall, groundwater aeration sounds are loud everywhere it is difficult for the groundwater aeration sound survey to identify the routes of water paths, we carried out surveys after more than 2 to 3 days passed after rainfall. The surveys were carried out according to the following procedures.

1. Measurement lines were set at 5 m above the collapse positions on natural slopes in order that both collapse positions and non- collapse positions are included so as to understand the differences of distribution of sound pressure between those areas.
2. For forest road slopes, measurement lines are set at a 1 m above forest road so as that both collapse positions and non collapse position are included.
3. The groundwater aeration sounds are measured at 1 m or 2 m interval on this measurement line. In addition, we measured at frequency bands of 400 to 12000 Hz in order to as much as possible curb the influence of noise caused by wind.

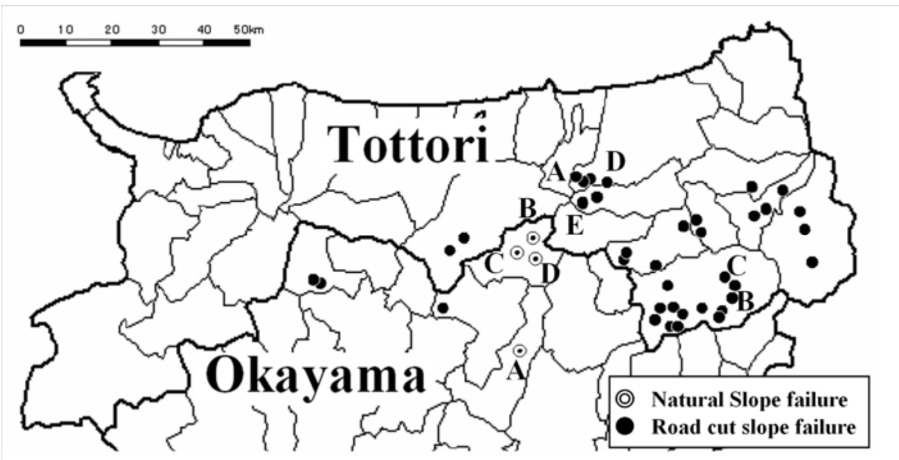


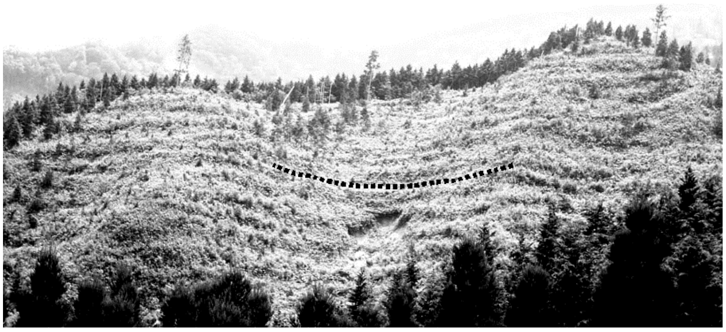
Figure-7 Locations of Investigation Sites

3.2 Correlation between Collapse Occurring Locations and Distribution of Groundwater Aeration Sound

We studied the differences of groundwater aeration sound levels on collapse slopes and non collapse slopes. Here, we explain, taking some collapse areas where we surveyed as examples.

1) Case Examples of Shallow Landslides

Pictures 10 to 13 show the situation of shallow landslides occurring on natural slopes A to D and Figures 8 to 11 show the survey results of groundwater aeration sound levels. In addition, we measured groundwater aeration sounds at locations indicated by dashed lines in the picture. Also, hatches in Figure-8 to 11 indicate collapse occurring locations.



Picture-10 A Shallow Landslide Occurred at Natural Slope A

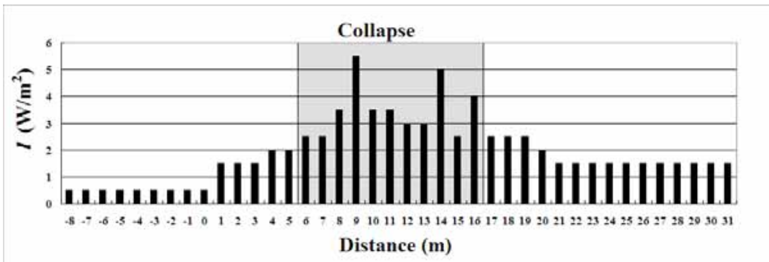
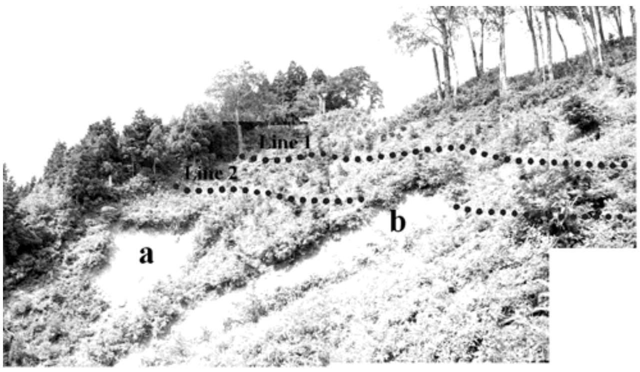


Figure -8 Distribution of Groundwater Aeration Sounds on Natural Slope A

(1) Natural Slope A (Picture-10, Figure-8)

There is a shallow landslide at one location of cutover area of Japanese cedar. The geographical feature of the ground surface is water catchment topography. The collapse is 10 m wide and and has a 1 to 1.5 m collapse depth and at the boundary there are slides in the bedrock. Traces of water flow were not confirmed at the scarp but there were spring points approximately 15 m below in a direction downstream of the collapse. It is thought that the saturation zone expanded upstream of the slope from the vicinity of this spring point and collapsed.

The groundwater aeration sounds within the collapse position are louder than the area where collapses did not occur. In addition, looking at the groundwater aeration sounds within collapse area, there are 3 peaks of groundwater aeration sounds. Looking at the picture, the collapse is divided into 3 blocks and each block corresponds with a peak of groundwater aeration sounds.



Picture-11 Shallow Landslide Occurring on Natural Slope B

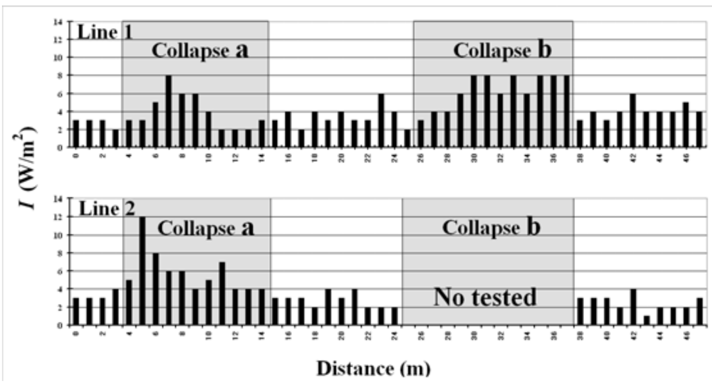


Figure-9 Distribution of Groundwater Aeration Sounds on Natural Slope B

(2) Natural Slope B (Picture-11, Figure-9)

There are shallow landslides at two

locations in a forest of Japanese cypress which was planted short while ago. The shape of the ground surface is level. Collapse a is 10 m wide and approximately 1 m of deep and Collapse b is 11m wide and approximately 1 m deep. Both collapsed at the boundary of the bedrock. In addition, on the day of survey when clear weather had continued for one week after rainfall, we could not confirm the existence of springs on the bare ground of the collapse. However on the next day of rainfall with a total amount of rainfall of 55 mm, seeping of groundwater from the collapse bare ground was confirmed. On the day of survey, it was thought that there was groundwater below the granite bedrock.

We measured groundwater aeration sounds at Line 1 and 2 indicated by dashed lines in Picture-11. Because it was dangerous to measure in the zone of collapse b on Line 2, we did not measure the groundwater aeration sounds there.

It is understood that groundwater aeration sounds are loud at the locations of collapse a in Line 1 and 2 and there are water paths at the head of the collapse. In the same way, groundwater aeration sounds of collapse b in Line 1 are relatively stronger than in positions that have not collapsed.

(3) Natural Slope C (Picture-12, Figure-10)

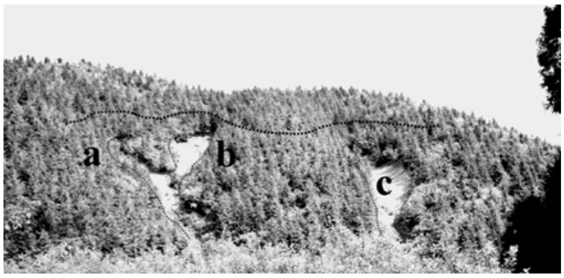
There are shallow landslides at 3 locations in a 14 year old Japanese cedar forest. The shape of the ground surface is catchment geography.

Collapse a is 12 m wide and approximately 2 m deep and Collapse b is 16 m wide and approximately 2 m deep and Collapse c is 10m wide and approximately 1 m deep. All of these collapses had bedrock slides as boundaries. At every collapse, on the day of survey when clear weather had continued for 1 week after rainfall, we could not confirm traces of water flow or springs. However, similarly as in natural slope B, on the day after 55 mm total rainfall, seeping of groundwater from the bare ground of the collapse was confirmed. On the day of survey, it was thought that there was groundwater below the granite bedrock.

Every distribution of groundwater aeration sounds showed strong values at collapse occurring locations. In addition, it was confirmed that all scarps of collapse b and c were divided into 2 blocks to the left and right at the local sites. It is very interesting that the distribution of groundwater aeration sounds of collapse b and c also has 2 peaks on the left and right.

(4) Natural Slope D (Picture-13, Figure-11)

There are small scale collapses which occurred at 4 locations in a 10 year old young forest of Japanese Cypress. The shape of the ground surface is ridge type. Collapse a is 2 m wide and



Picture-12 Shallow Landslide Occurring on Natural Slope C

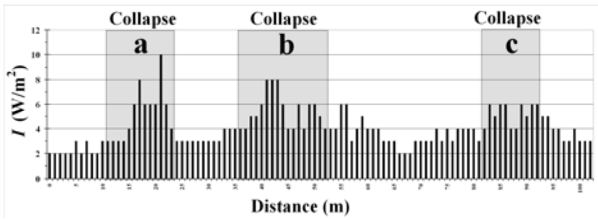
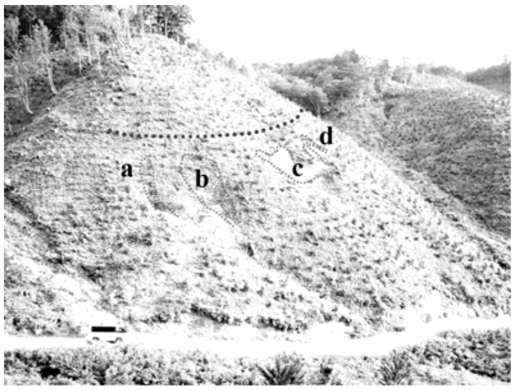


Figure-10 Distribution of Groundwater Aeration Sounds on Natural Slope C



Picture-13 Shallow Landslide Occurring on Natural Slope D

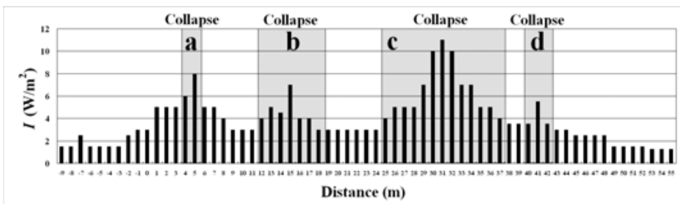
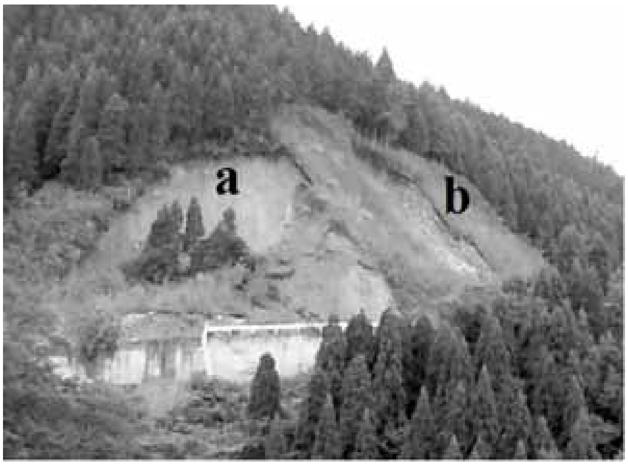


Figure-11 Distribution of Groundwater Aeration Sounds on Natural Slope D

approximately 1 m deep. At the bottom of the collapse, there is one spring. Collapse b is 6 m wide and approximately 1m deep and at the bottom of the collapse there are two constant springs. Collapse c is 12 m wide and approximately 2 m deep and there are bedrock slides as the boundary. No spring was confirmed on the collapse bare ground; however, it was revealed on later surveys that when there is rainfall of over 100 mm, a spring occurs at the leg of the collapse. Collapse d is 2m wide and approximately 1m deep and there are bedrock slides as the boundary. The collapse bare ground is generally very moist compared to the surrounding area but no spring was confirmed. However, the groundwater survey conducted later revealed that the head of collapse d is a location where groundwater is likely to be generated during rainfall.
The distribution of groundwater aeration sounds is strong within collapse area. In addition, at collapse b where 2 spring points were confirmed, there are 2 peaks in the groundwater aeration sounds.

2) Case Examples of Slope Landslides

Pictures 14 to 17 show the situation of slope landslide which occurred in forest roads A to D and Figure-12 to 15 show survey results of the groundwater aeration sounds. In addition, hatches in the figure represent locations where slope landslides occurred.



Picture-14 Slope Landslide Occurring on Forest Road A

(1) Forest Road A (Picture-14, Figure-12)

There are two collapses which occurred on a forest road which was constructed on ridge type slopes. Collapse a was caused by typhoon No. 23 in 2004 and collapse b was caused by typhoon No. 21 in the same year.

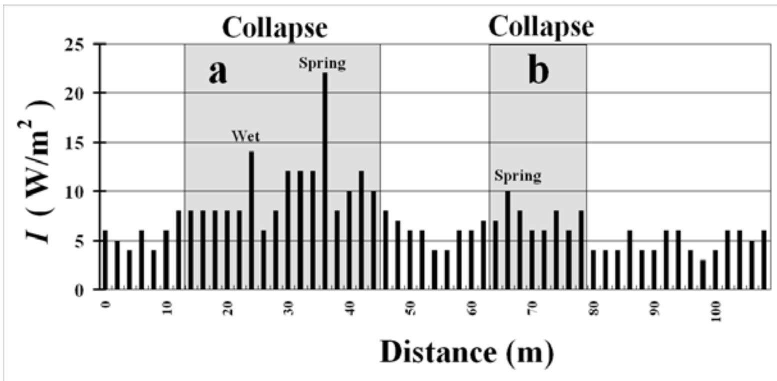
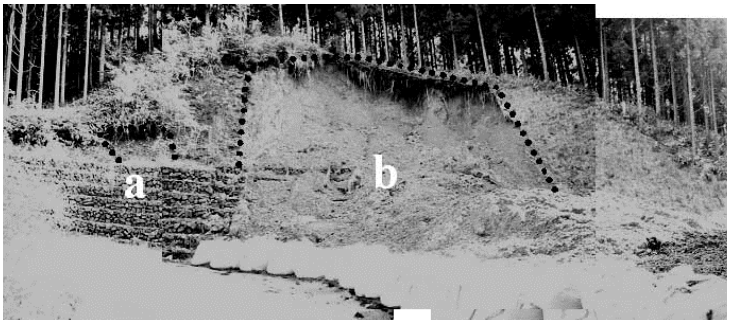


Figure-13 Distribution of Groundwater Aeration Sounds on Forest Road A

- Collapse a: 30 m wide and approximately 5 m deep and was created by a slide in the soil layer on the bedrock. In surveys conducted immediately after the collapse, a spring point and a relatively moist area were confirmed.
- Collapse b: 14m wide and approximately 1m deep and there was a slide in the soil layer on the bedrock. At surveys conducted after the collapse, one spring point was confirmed.

Compared to slopes which did not collapse, at positions a and b where collapses occurred, the groundwater aeration sounds are loud. In addition, the spring points within collapse area, the moist position within the soil layer, and the peaks of groundwater aeration sounds are aligned. On the other hand, in the soil layer remaining between collapses a and b, groundwater aeration sounds are diminished.

(2) Forest Road B (Picture-15, Figure-13)
Collapse occurred at valley a and ridge b in a forest road due to typhoon No. 21 in 2004. The geological features consist of granodiorite.
- Collapse a: 3m wide and approximately 0.5 m deep and is created by a thin slide of surface soil on the slope. Since it is located in a valley, the soil layer was moist.
- Collapse b: 14 m wide and approximately 1m deep and was created by the soil layer on the bedrock sliding and liquidizing. There are 3 traces of water flow confirmed within the collapse area. All groundwater aeration sounds are loud within collapse area. In addition, in collapse b, there are three traces of water flow confirmed. Peaks of groundwater aeration sounds are well aligned with them.



Picture-15 Slope Landslide Occurred on Forest Road B

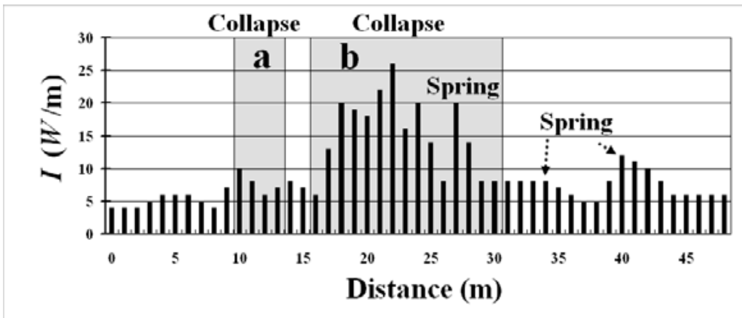


Figure-13 Distribution of Groundwater Aeration Sounds on Forest Road B

(3) Forest Road C (Picture-16, Figure-14)
The collapse which occurred at ridge on forest road opened on ridge type slope is 18 m wide and 1.3 m deep. The geological features consist of granodiorite. Although no spring was confirmed on the day of the survey, there are 3 traces of water flow confirmed.
All distribution of groundwater aeration sounds are loud within the collapse area and locations where traces of water flow were confirmed and peaks of groundwater aeration sounds are aligned.

Picture-16 Slope Landslide Occurred on Forest Road C

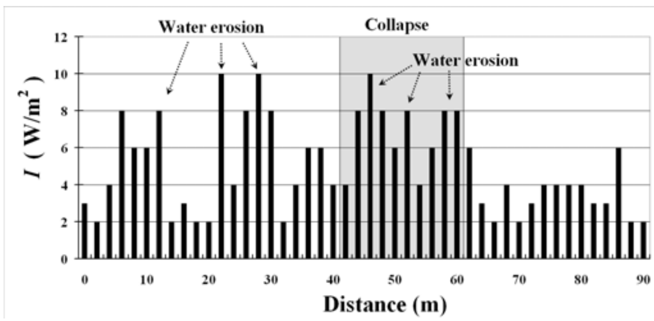


Figure-14 Distribution of Groundwater Aeration Sounds on Forest Road C

(4) Forest Road D (Picture-17, Figure-15)
In forest road slopes which were constructed on ridges and graded slopes, there are collapses at four locations (a to d) and there are traces of surface erosions at two locations (e and f). Collapse a and b

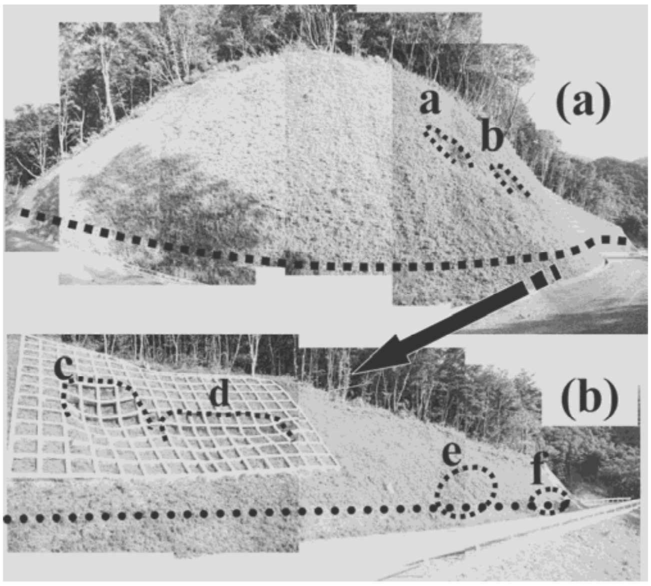
are collapses which occurred on a ridge type slope and collapse c and d are collapses which occurred on graded slopes, where grating crib work was constructed.

- Collapse a: 2 m wide and approximately 1 m deep. There was no spring seen on the day of the survey.
- Collapse b: 4 m wide and approximately 1 m deep. There was no spring seen on the day of the survey.
- Collapse c: 6 m wide and approximately 1 m deep. A spring occurred during heavy rainfall. On the day of the survey, it was in a moist condition but there was no spring confirmed.
- Collapse d: 4 m wide and approximately 1 m deep. Spring can be seen during heavy rainfall. On the day of the survey, it was in a moist condition but there was no spring confirmed.

All distribution of groundwater aeration sounds is loud within collapse area. In addition, at e and f where trace of surface erosion was seen, groundwater aeration sounds were loud.

We studied the correlation between collapse positions and the distribution of groundwater aeration sounds, targeting collapses occurring on natural slopes and forest road slopes. As a result, it was revealed that there are obvious correlations between them and groundwater aeration sounds are loud at locations where collapses occurred compared to the surrounding area. It is considered that this means collapses occur at points of subsurface water concentration. In addition, it is also revealed that at points where groundwater aeration sounds are loud, even if there were no collapses, springs and surface erosions occur.

Next, Figure-16 shows correlation between groundwater aeration sounds in the area where collapses occurred (within hatched area in the distribution of groundwater aeration sounds figure mentioned above) and groundwater aeration sounds in the area where no collapse occurred. Here, I_{in} represents the average groundwater aeration sound levels within a collapsed area and I_{out} represents the average groundwater aeration sound levels outside of



Picture-17 Slope Landslide Occurred on Forest Road D

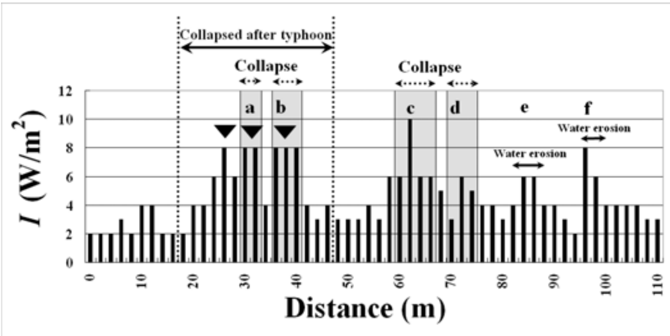


Figure-15 Distribution of Groundwater Aeration Sounds on Forest Road D

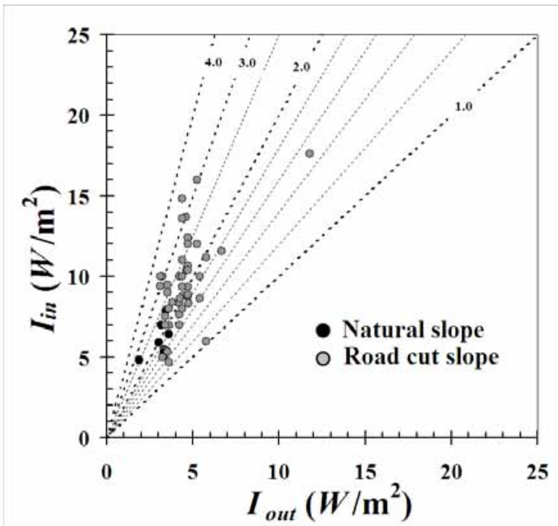


Figure-16 Relationships between I_{in} and I_{out}

collapsed area. In addition, dashed lines in the figure represent I_{in} / I_{out}, which show how many times larger the groundwater aeration sounds within collapsed area are compared to outside the collapse area. Suppose that $I_{in} = I_{out}$, it is plotted on the dashed line of 1.0, and suppose that $I_{in} > I_{out}$, it is plotted above the dashed line of 1.0 and suppose that $I_{in} < I_{out}$, it is plotted below the dashed line of 1.0.
The correlation between I_{in} and I_{out}, which are calculated from the groundwater aeration sounds measured at 10 shallow landslides which occurred at 4 locations on natural slopes in Okayama prefecture, and at 63 slope landslides which occurred at 40 locations on forest roads in Tottori prefecture and Okayama prefecture, was plotted above the dashed line of $I_{in} = I_{out}$ in the figures for all locations and it was revealed that average groundwater aeration sound levels within the collapsed area were larger than those outside of the collapsed area. Comparing to I_{out}, I_{in} is as much as 1.2 to 3 times larger on natural slopes and as much as 1.2 to 3.5 times larger on slopes.
With all these factors, it can be said that a collapse occurs on the route of water path where groundwater aeration sounds are loud. In addition, it was revealed that when using these properties, slopes in danger of collapse can be pinpointed with certain accuracy.

4. Predicting Locations where Collapses will Occur Using Groundwater Aeration Sounds

As a result of measuring groundwater aeration sounds in collapsed areas, it was found that collapses occurred at the positions where groundwater aeration sounds were loud. On the other hand, we identified slopes where there are peaks of groundwater aeration sounds similar to the ones in collapsed area but no collapse occurred. Here, we study how the slopes where peaks of groundwater aeration sounds, which measured in 1 or 2m interval on forest road route of total length of 10km, registered changes after rainfall.

(1) Forest Road D

On forest road D, we measured groundwater aeration sounds on July 12, 2004. After that, typhoon No. 21 which struck on September 29 to 30, 2004 brought a large quantity of rainfall. Figure-17 (a) shows the conditions of rainfall observed at a rainfall observation point closest to forest road D. It was recorded that the peak of rainfall intensity was approximately 30 mm/hr and the total amount of continuous rainfall was 200 mm.

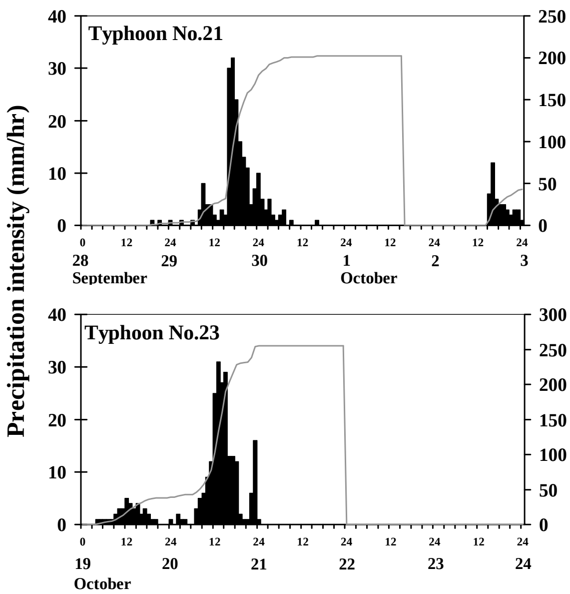
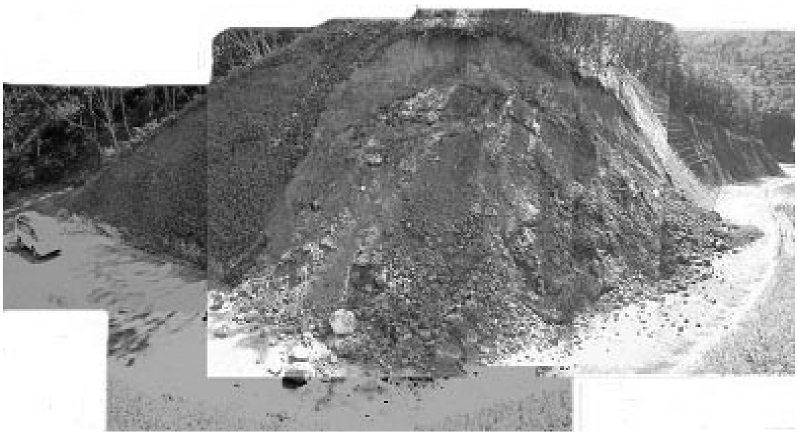


Figure-17 Rainfall Events on Forest Road D and E

Picture-18 shows the situation of forest road D on October 1 after the typhoon passed. The collapse occurred on a ridge of the slope with scale of 30m width and 1.5 m of collapse depth. Compared to the situation before collapse, shown in Picture-17, it is noticed that area on the left side of the grating crib, position of Picture-17 (a), was greatly collapsed.
Figure-15 is where this collapse position is aligned with the figure of distribution of groundwater aeration sounds measured on July 12, 2004 before the collapse occurred. The collapses occurred at locations sandwiched by dashed lines and they occurred at the positions where 3 peaks of groundwater aeration sounds were detected (▼ in the figure).

(2) Forest Road E

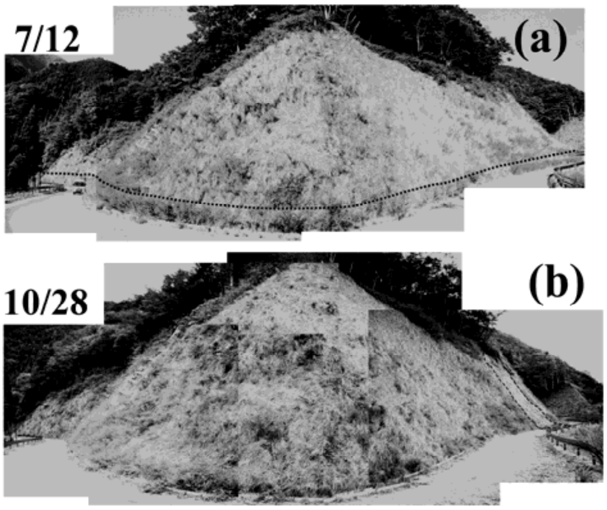
On forest road E, we measured groundwater aeration sounds on July 12, 2004. After that, typhoon no. 23 which approached on October 20 to 21, 2004 brought a large quantity of rainfall. Figure-17 (b) shows the conditions of rainfall observed at a rainfall observation point closest to forest road E. It was recorded that the peak of rainfall intensity was approximately 30mm/hr and the total amount of continuous rainfall was 250 mm. Picture-19 (a) shows the situation of forest road E, which was taken on July 12 before the typhoon approached and Picture-19 (b) shows the situation on October 28 after typhoon passed. The collapse occurred on a slope on the right side of the picture, which is part of a small valley on the slope. It slid at a scale of 10 m wide and 0.5 m deep.



Picture-18 Situation of Forest Road D after Typhoon

Figure-18 shows the distribution of groundwater aeration sounds measured on July 12, 2004 before the collapse occurred and the location where the collapse occurred. In addition, hatches in the figure represent locations where collapses had already occurred on July 12, 2004 and the area sandwiched by dashed lines represents a location where a collapse was newly triggered by typhoon no. 23. Looking at the figure, a new collapse occurred at the location where high groundwater aeration sounds were detected.

A non-collapsed slope where high groundwater aeration sounds were detected collapsed after heavy rainfall. It is considered that on slopes there are areas (water paths) where subsurface water routinely concentrates and great quantities of subsurface water is fed into those area by heavy rainfall, which leads to collapse. On the other hand, as seen in figure-18, the existence of peaks of groundwater aeration sounds doesn't necessary mean that collapses occur. Slopes collapse when the predispositions and triggers align, however groundwater aeration sounds can only identify locations where the predispositions are strong.



Picture-19 Situation of Forest Road E before and after Typhoon

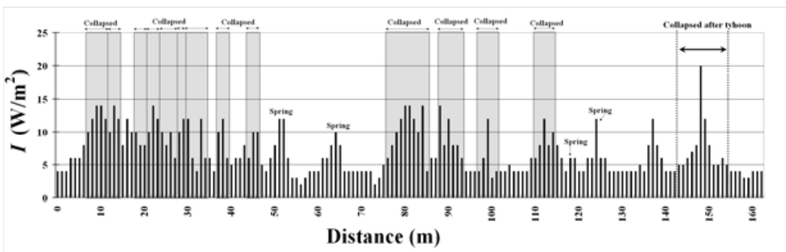


Figure-18 Distribution of Groundwater Aeration Sounds and Locations of Newly Occurring collapses

5. Conclusion

In this study, we examined a method to identify water path locations using "groundwater aeration sounds" generated from the water flowing underground in mountainous slopes. As a result, the following was revealed.

1) When water moves within the bedrock, air and water are exchanged. At this time, a water screen is generated in the gap between soil particles and at the moment this breaks up, aeration sounds such as "*Poko*" (plop) occur. The groundwater aeration sound refers to this aeration sound.
2) When measuring groundwater aeration sounds in a direction going across a water path, the groundwater aeration sound is the loudest at the water path location. The method can identify water path locations based on characteristics of distribution of this groundwater aeration sound. As results of applying the method to local sites, there were some cases in which deviation of of a maximum of appropriately 50 cm occurs.
3) The groundwater aeration sound survey can be carried out even when springs can not be confirmed by the naked eye. In addition, the groundwater aeration sound measuring device is compact and light weight and is able to carry out measurements in a short time. Therefore, the surveys can be carried out with less fatigue in mountain regions where the ground underfoot is in bad condition.

   Next, we measured groundwater aeration sounds on natural slopes and forest road slopes and studied the relationship between the distribution of groundwater aeration sounds and positions where collapse occurred. As a result, the following were revealed.
4) Compared to the surrounding area, groundwater aeration sounds were strong at areas where collapses occurred and collapses occurred on the route of water path where subsurface water concentrated.
5) The forest road slopes, where multiple peaks of groundwater aeration sounds were confirmed but no collapse occurred, later collapsed in heavy rainfall. It was confirmed that the groundwater aeration sound survey is an effective method to predict locations where collapses occurred.
6) We can draw the conclusion that there are water paths where subsurface water routinely concentrates on mountainous slopes and great quantities of subsurface water are fed into those positions by heavy rainfall, which leads to collapse.

   In the past, it was observed that even though they have similar topography and geology, there are some slopes which collapse and there are some slopes which do not and the reasons were often not able to be clearly answered. As a result of this study, we were able to understand that groundwater is fed in fundamentally different way between slopes which collapse and slopes which do not collapse. When investigating disasters in the future, we should also turn our gaze to these differences in the ways groundwater is fed. In addition, in the past, the prediction of locations in danger of collapse has been carried out by evaluating the predispositions for collapse of the topography and geological features using aerial photographs and small-scale topographical maps. However, it wasn't possible to obtain satisfactory estimated accuracy. It is regarded that this is because there was no evaluation of groundwater caused by rainfall, which becomes trigger for collapse. From this study, we gained the knowledge that a collapse occurs on the route of water path. From now on, by adding in groundwater, which becomes a trigger for collapse, as an additional factor to conventional methods, it is regarded that the accuracy of estimating locations where collapses occur will be improved.

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