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Dynamic observations focused on dry avalanche and occurrence conditions of large-scale dry slab surface avalanche

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Abstract

In order to clarify the release of avalanches every winter, observation site has been established in cold snowy regions where the air temperature is below 0℃ almost all winter to observe the meteorological elements and avalanche occurrences using video camera and seismometers. These observations obtained records of 115 dry surface avalanches, 26 wet surface avalanches and 83 wet full-depth avalanches. The form of large-scale avalanches is a dry slab surface avalanche and they were released at two slopes on 40 degrees between elevations of 1650 and 1850 m a.s.l. The large-scale avalanches with horizontal run-out distance longer than 1000 m were almost all dry surface avalanches.

A study of calculated the snow stability index (*SI*) shows that *SI* was low and conditions for the avalanche release from inside snow cover accumulated during heavy snowfall were satisfied except for two large-scale avalanches occurred under little snowfall when large-scale avalanches occurred. The snow pit measurements near the release area of large-scale dry slab surface avalanches reveal the presence of weak layers such as solid-type depth hoar or depth hoar and stability index of the weak layers are low. Moreover, it is under the condition that solid-type depth hoar layers are apt to be formed around the avalanche release area by regularly measuring snow pits.

Therefore, the conditions for large-scale dry slab surface avalanches occurred in the newly deposited snow layer are satisfied when snowfall is heavy, the release of large-scale avalanches is presumably related to the existence of a weak layer such as solid type depth hoar or depth hoar.

1. Introduction

The state of avalanche occurrences during winter season are now determined mainly by surveys performed after avalanche disasters occur instead of by continuous monitoring at points or over wide areas. When large-scale dry surface avalanches that cause particularly severe disasters have occurred, the available information concerning such disasters is usually obtained after their occurrence. So the information about air temperature and snow cover at the time of avalanche occurrences near the release area and about the characteristics of the avalanche itself can rarely be obtained. Moreover, there is very little information about the state of avalanche occurrences during a single winter in avalanche occurrence region and time-history information that shows changes in the number of occurrences in different winters.

For that reason the acquisition of avalanche data is necessary, but it is difficult to observe avalanche in full-scale conditions owing to the experimental difficulties, dangerousness, cost, social condition, etc.

In Japan, several avalanche observations have been measured using visual observation and measuring avalanche tremors with other measuring instruments. The movement observation has been carried out systematically on the purpose of researching especially powder dry surface avalanche named 'Hou' by using many measuring instruments containing the visual and avalanche tremor observations at Shiaidani in Kurobe, Toyama Prefecture (Kurobe Avalanche Measurement Group, 1989). This research also carried the artificial avalanche observation. Many precious knowledge were gained especially in avalanche dynamics. A video camera and three seismometers were installed at Kanisawa-shinden in Shiozawa, Niigata Prefecture in 1990 (Muramatsu, 1993). Some wet full-depth and surface avalanches were detected. This research referred the detection level of avalanche tremor compared with micro-tremor and artificial ground vibration. Dry snow avalanches observation has been carried out by using visual observation and avalanche tremors at Makunosawa in Myoko, Niigata Prefecture (Takeuchi *et al.,* 2001). These avalanche release data were compared with snow stability index and snow pit wall measurements. The avalanche release point and avalanche mass were estimated by observing dry full-depth avalanches measured in avalanche scale using 2 video cameras and 4 seismometers in 2001 at Toikanbetsu, Hokkaido (Imanishi *et al.,* 2004).

It is true a few observation cases of avalanches are carried out even at present but the accumulation of avalanche data is needed to make clear the phenomenon of avalanche. It is best to observe avalanches themselves for the research, but the condition that an artificial avalanche cannot be carried out because of dangerous and difficulties makes hard to obtain avalanche data. Therefore, it is difficult to observe the avalanche occurrences and natural avalanches are the main target for avalanche research in Japan.

The authors have performed avalanche observations by the visual observation using video camera at 11 points where were proved that an avalanche disaster broke out in the past or avalanche often occurred (Akiyama and Takeshi, 2004). In these observation points, the south slope of Happone in Hakuba Village, Nagano Prefecture had been thought of large-scale avalanche prone area. A large-scale avalanche broke the wing of sabo dam on Kuzure-sawa River in the south slope of Happone in December 1981, and the aerial photograph could take the trace of large-scale surface avalanche with run-out distance of 2300 m along Kuzure-sawa River in March 1996. Only a visual observation of avalanches was started using video camera installed at the point with a view of entire the south slope of Happone every winter from December 1996. The scope of avalanche observation reaches at an elevation of almost 2000 m a.s.l. on the south slope of Happone that is a cold region with heavy snowfall and where the winter temperature is usually below 0℃. The video images have confirmed that many dry surface avalanches including large-scale dry slab surface avalanches occurred (Akiyama and Takeshi, 2004). This observation point has three merits for the research of natural avalanche.

1) Many scale natural avalanches occur.
2) It is possible to view all the avalanche movement using one video camera from avalanche release area to deposit area.
3) It is possible to arrive at a location close to avalanche release areas throughout the winter using the ski resort facilities, so the data of meteorological data and snow condition near the avalanche release area can be measured and commercial power source can be used for observation instruments.

Accordingly, a variety of field measurements newly performed along with video observation near avalanche release and deposit areas began in December 2002. This paper reports on the studies of the characteristics of avalanche occurrences at this site and of the release mechanisms of dry surface avalanches up to March 2005.

2. Contents of the surveys and research

2.1 *Outline of the avalanche observation area and contents of the observations*

The avalanche observation site is a slope containing the drainage basin of Kuzure-sawa valley that is on the south slope of Happone, its elevation ranges from 870 to 1970 m a.s.l., its maximum width is 2.5 km, and its maximum slope length is 2.7 km (Fig. 1).

The observation locations and items are shown in Fig. 2. Visual observation of avalanches using video camera from a point (location 1 in Fig. 2; inside Hakuba 47 Ski Resort) with a distant view of the slopes began in December 1996. The observation periods varied according to snow cover conditions each winter, but extended from December to April centered on January to March. The video observation of avalanches is able to monitor slopes from S1 to S3 (Fig. 2) on a single screen. Many avalanches were released on slope S1; A and B are large-scale surface avalanche release areas, and they sometimes reach to Hirakawa River. On the slopes of S2 and S3, large-scale avalanches have not broken out and avalanche occurrences were fewer than in area S1. The video images help to guide understanding of the occurrences and form of avalanches. The video observations at the site were based on recording one image every 0.5 to 1 second using time-lapse video that is capable of long-term recording, and beginning December 2002, digital recording equipment was also used, making possible of monitoring slopes where avalanches are released throughout the winter without replacing recording media for the long time.

In addition, it is possible to reach a location close to avalanche release areas throughout the winter using the ski resort facilities, beginning in December 2002, meteorological observations, measurements of snow pit walls, and measurements of ground vibration caused by avalanches (avalanche tremor) were performed directly in a higher place of the avalanche release area (location 2 in Fig. 2). At the same time, measurements of avalanche tremors and snow pit walls were performed in the vicinity of avalanche pass or deposit area (location 3 and 4 in Fig. 2).

Two seismometers, Tokyo Sokushin VSE-15D (range: 0.2–100Hz, natural frequency: 1Hz) and Mark Products L-22D (range: 2–: 40Hz, natural frequency: 2 Hz) were installed for measuring avalanche tremors at location 2 and 3, respectively. Tremors data were measured on the vertical motion of ground vibration every 0.01 second (100Hz) recording at all times near the avalanche release area (location 2) , and recording only triggered when ground vibration exceeded the standard value near the avalanche pass (location 3). These seismometers may catch all the ground vibration data including noises. The ground shock such as mass snow falling from trees or movement of animals is able to be distinguished easily because these waveforms have the characteristics of short duration and instant vibration. If avalanches occur and flow, either or both seismographs sometimes measure avalanche movement. Earthquakes can also be detected but two seismometers can not always catch them because of the difference in the ground conditions where installed, characteristics of seismometers and recording method. The Hakuba Earthquake Observation Station (E.HKB) of the Earthquake Observation Center of Earthquake Research Institute in the University of Tokyo measured only earthquake records, so these records were used in order to extract avalanche tremors exactly.

Fig. 1. Avalanche observation site (south side slope of Happone in Hakuba Village).

Snow pit walls were regularly measured in the interval for 10 to 15 days. Snow depth, temperature, grain shape, density, hardness and shear strength of weak layer were measured.

Furthermore, meteorological records from automated meteorological data acquisition system of Japan Meteorological Agency (AMeDAS Hakuba: located elevation 703 m a.s.l.) and meteorological data observed Hakuba 47 Ski Resort (observed elevation 1160 m a.s.l.) were used.

2.2 Analysis of the measured avalanche data

When the video recording media were replayed and video images for the release of avalanches until their deposition were obtained, 1) time of release, 2) forms, 3) scale and location information, and 4) motion of avalanches were revealed. Some image had only the trace after the avalanche occurrence. In this case, 1) and 4) are not clear but it was possible to obtain records of 2) and 3) as avalanche information.

The forms of the avalanche were classified using those factors such as form of release (slab or point-

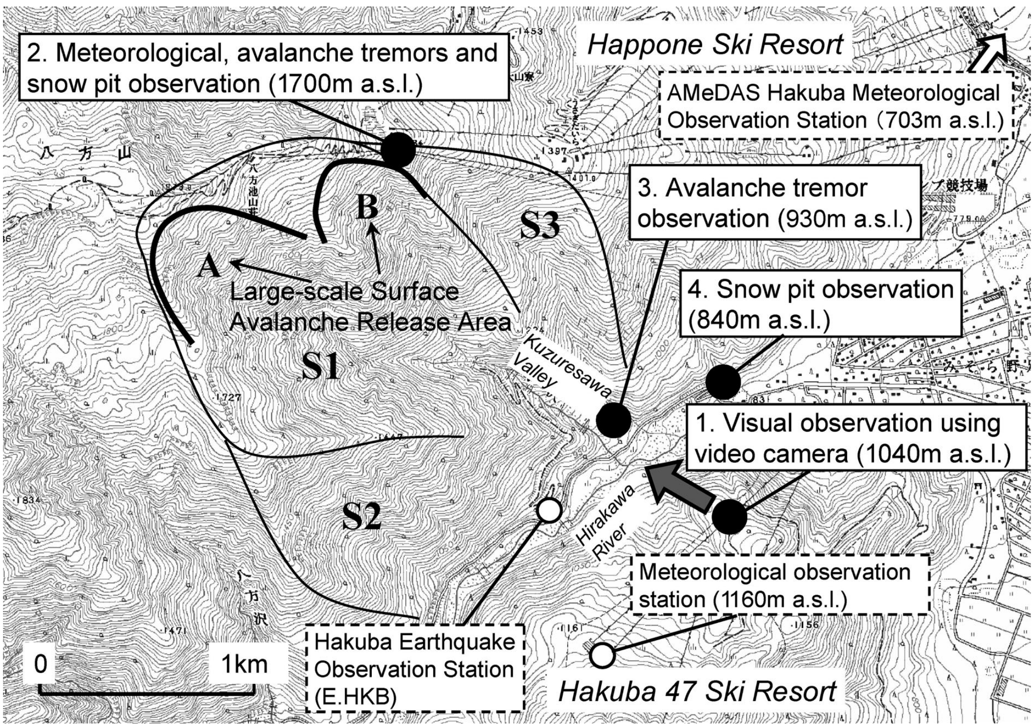

Fig. 2. Location map of the avalanche observation points.

starting), water content of the snow (dry or wet) and position of the slip (surface or full-depth). When the form of release is a small-scale surface avalanche, it may be difficult to perform a classification. It can be assumed that it is dry snow when a surface avalanche that is clearly accompanied by snow cloud, however, it is difficult to classify as dry or wet based only on the image when it is a flowing avalanche without a snow cloud. In this case, the judgment is made based on snowfall and changes in air temperature shown in meteorological records obtained before the avalanche occurrence.

The specifications such as release location and run-out distance were calculated by setting the elevation of the release and deposition using 1/10000 topographical maps. In addition, 50 m mesh DEM (digital elevation model) was used to obtain the slope inclination for each mesh to perform the inclination classification of the entire slope that was observed.

Video observation often fails to watch slopes when snow is falling or at night. So when an investigation was done to determine if it is or is not possible to see an avalanche release slope in one hour units in nine winters from December 1996 to March 2005, it was possible to monitor the slope for between 28% and 56% of the time (an average of approximately 40%) during a single winter. Surface avalanches differ from full-depth avalanches in that the ground is not exposed where they breaks out. If small-scale avalanches break out, surface avalanches are hard to be recognized rather than full-depth avalanches because it is difficult to see judging from the color tones. Therefore, it is impossible to record all avalanches by visual observations. So the avalanche occurrences are detected by observing avalanche tremors using seismometer that can be detected when observation by video is impossible. Using video and seismometer together for avalanche detection is an effective method and various analyses were done by combining both data (Sabot *et al.,* 1998; Imanishi *et al.,* 2004).

3. Characteristics of detected avalanches

Figure 3 shows the results of classifying the inclines in 5 degrees classes of those slopes higher than 900 m where avalanches occurred. Observing slopes were classified as slope S1 where many avalanches were released and the other slopes S2 and S3, but the characteristics of the inclination frequency distribution are similar, the commonest inclinations are between 35 and 40 degrees, and almost none are more than 50 degrees. The inclination on slope S1, A and B, where large-scale surface avalanches occurred released is approximately 40 degrees.

The results of the observations clarified the specifications of avalanches in 224 cases (141 surface avalanches, 83 full-depth avalanches) until March 2005.

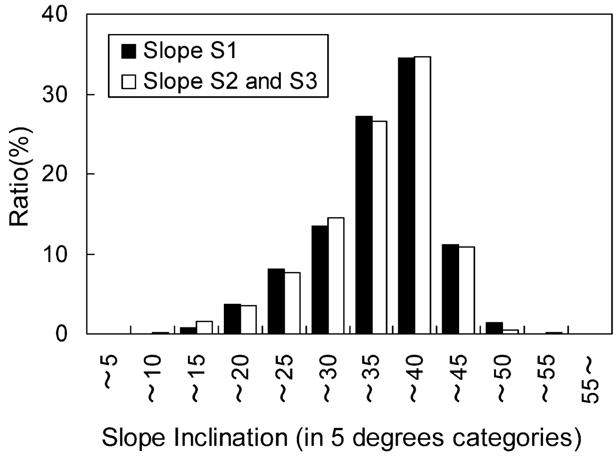

Fig. 3. Inclination of the observed slopes (elevation of 900 m a.s.l. or higher).

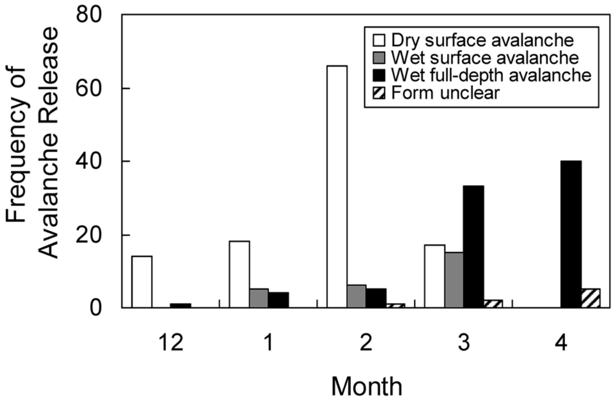

Fig. 4. State of avalanche occurrences by forms.

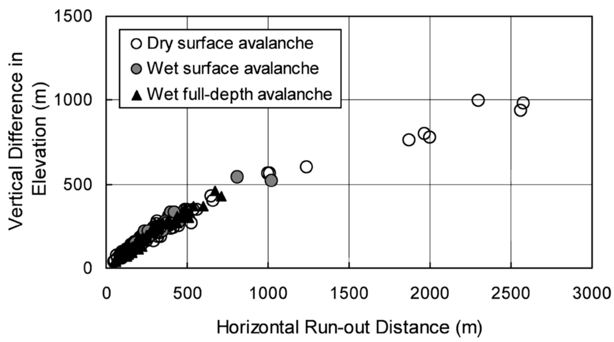

Fig. 5. Relation between horizontal run-out distance and vertical difference in elevation of avalanches.

Figure 4 shows the state of avalanche occurrences every month by form of these avalanches. At this site, during the observation period, the most common form of avalanche was dry surface avalanche and mostly occurred in February, with none occurring in April. Many full-depth avalanches were broken out since March.

Figure 5 shows the relationship of the horizontal run-out distance by form of avalanche with the elevation difference from the avalanche release area to the deposit area. In the case of a large-scale avalanche, the run-out distance is lengthened along its course. The run-out distance of almost all avalanches was approximately up to 700 m, and the wet full-depth avalanches are all in this range. Large-scale avalanches with run-out distance exceeding 1 km were dry surface avalanches excluding one wet surface avalanche. In case of dry surface avalanches, run-out distance exceeding 2500 m also occurred.

Figure 6 shows the relationship with horizontal run-out distance and release area elevation of avalanches. The avalanche release points of almost all surface avalanches are between elevations from 1300 to 1900 m a.s.l., but large-scale cases occurred on slopes at A (approximate elevation of 1850 m a.s.l.) and B (approximate elevation of 1650 m a.s.l.) in Fig. 2. Wet full-depth avalanches occurred at elevations between 1000 and 1600 m a.s.l., but not above 1600 m, and many avalanches broke out on parts other than the slopes of A and B. The wet surface avalanches show characteristics intermediate between dry surface avalanches and wet full-depth avalanches.

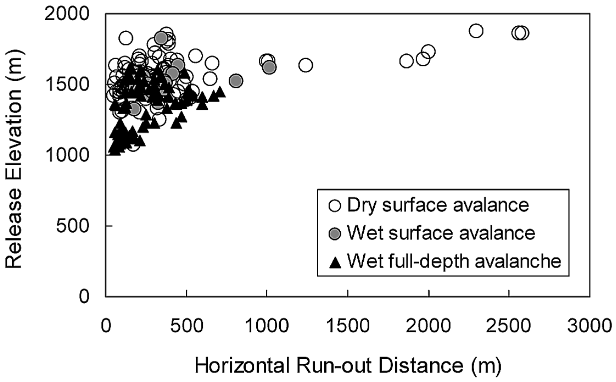

Fig. 6. Relation between horizontal run-out distance and release elevation of avalanches.

4. Examples of the large-scale avalanche occurrence

Table 1 shows the large avalanches in the detected data that occurred during each of the past six winters. It was possible to obtain video records from the release to the deposition of only three large-scale avalanches that occurred in February 2000 and in March 2003; the rest were judged based on video images of avalanche trace, field surveys during measurements of snow pit walls, and avalanche tremor observations. During the winter period from December

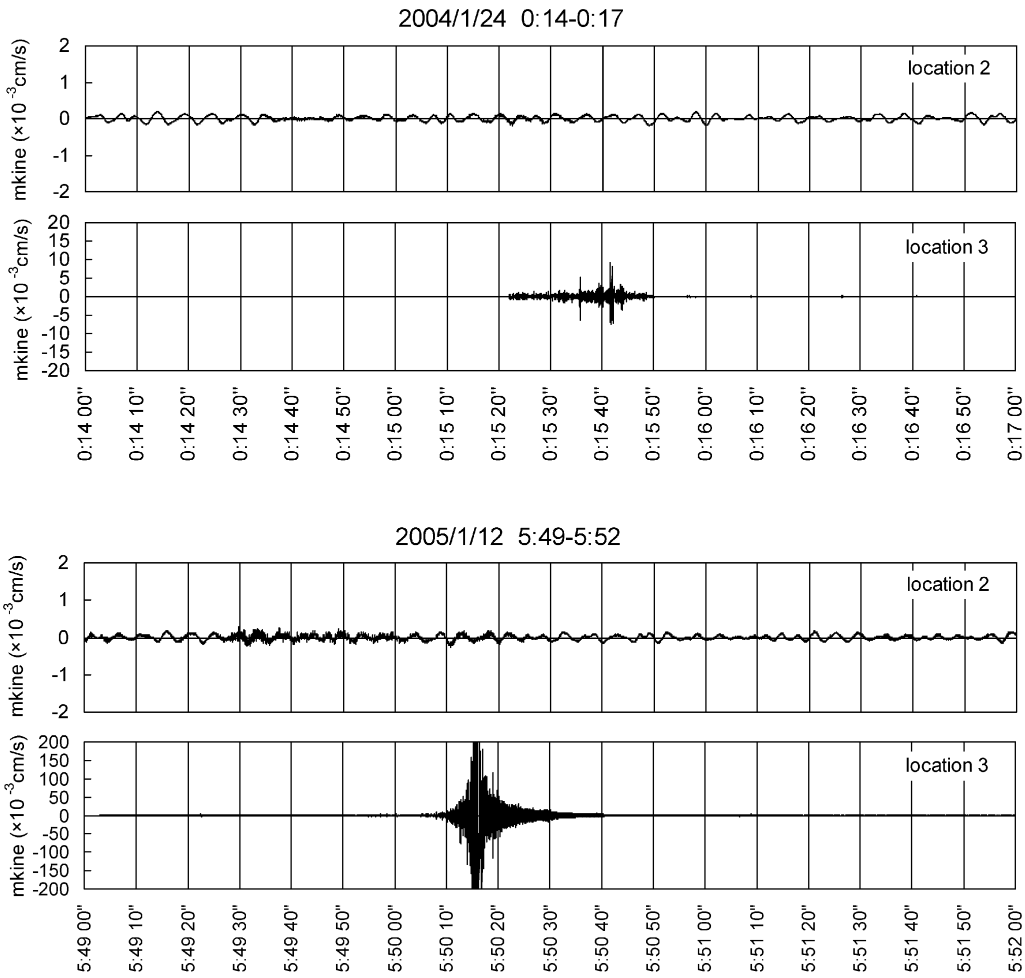

Fig. 7. Avalanche tremors of large-scale dry slab surface avalanches released from slope A.

Table 1. Examples of Large-scale Avalanche.

Observation year/month (winter)	No.	Avalanche release/ detection time	Avalanche form	Form of movement	Release zone	Run-out distance m	Avalanche volume m^3	Remarks
1999/12-2000/4	1	2/5 13:10	Dry slab surface avalanche	Powder avalanche	A	2600	160000	Detected by video (avalanche tremor was un-measurement)
	2	2/23 1:37	Dry slab surface avalanche	Mixed flowing and powder avalanche	B	2000	120000	Detected by video (avalanche tremor was un-measurement)
2000/12-2001/4	3	3/21 6:35	Wet slab surface avalanche	Flowing avalanche	—	810	—	Largest avalanche of the winter detected by video (avalanche tremor was un-measurement)
2001/12-2002/4	4	1/5〜6	Dry slab surface avalanche	Mixed flowing and powder avalanche?	B	>2000	—	Video impossible. Crown surface confirmed in release area on Jan. 6 in the morning (avalanche tremor was un-measurement)
2002/12-2003/4	5	3/19 8:27	Dry slab surface avalanche	Flowing avalanche	A	560	—	Largest avalanche of the winter detected by video Avalanche tremor was not recorded
2003/12-2004/4	6	12/20 12:56, 13:44	Dry slab surface avalanche	Mixed flowing and powder avalanche?	B	1250	—	Video impossible. Detected by avalanche tremors Crown surface confirmed in release area.
	7	1/24 0:15	Dry slab surface avalanche	Mixed flowing and powder avalanche?	A	>2000	—	Video impossible. Detected by avalanche tremors Crown surface confirmed in release area.
2004/12-2005/3	8	1/12 5:50	Dry slab surface avalanche	Mixed flowing and powder avalanche?	A	2600	—	Video impossible. Detected by avalanche tremors Crown surface confirmed in release area.

2000 to April 2001, the largest avalanche was a wet slab surface avalanche, but the others were dry slab surface avalanches.

On January 24, 2004 and January 12, 2005, records of avalanche tremor of large-scale surface avalanches were obtained. There are no video records of avalanches when they occurred because snow was falling, but visible images after the avalanche occurrences and field surveys have shown that two dry slab surface avalanches broke out from the slope A. Figure 7 shows avalanche tremor records at those times. The wave form in the avalanche pass area (location 3) shows characteristic in spindle shape, but near the release area (location 2), there is no distinctive shape, it is unclear, and even the wave forms of the micro tremors are disrupted. This is a result of the fact that the avalanche tremors were observed in a higher place of the slope B, it is estimated that vibration declines because of a long distance from release area in the slope A. On December 20, 2003, large-scale surface avalanche occurred from slope B and seismometer in a higher place of the avalanche release area caught the avalanche tremor. Unfortunately, another seismometer was off line so it is not clear if two seismometers could catch the avalanche tremor simultaneously.

5. Comparison of large-scale avalanche occurrences and snow stability index

5.1 Snow stability index

Snow stability index (*SI*) in the snow on the slope is represented as follows based on the shear stress τ (N m^{-2}) and the shear strength *SFI* (N m^{-2}) inside the snow layer (Roch, 1966).

$$SI = SFI/\tau.$$

The shear stress τ is the force component in the direction of incline of the snow load per unit of horizontal area of the snow on a slope, and if the inclination is represented by θ;

$$\tau = W \cdot \cos\theta \cdot \sin\theta.$$

Danger of avalanche occurrence is high when *SI* becomes smaller than 4 (Roch, 1966).

Shear strength *SFI* was measured using the 250 cm^2 shear frame (Sommerfeld, 1984) and comparing many avalanche occurrences and *SI* using the data measured by the 250 cm^2 shear frame; danger of surface avalanche occurrence was critical when *SI* became smaller than 1.5 (Schleiss and Schleiss, 1970; Perla, 1977).

Regarding that snowfall changes from new snow to lightly compacted snow, then to compacted snow under the condition of equi-temperature metamorphism in snow, stability of snow on the slope is able to be calculated. Shear strength of each snow layer is able to be estimated based on the concept of changing snow density according to viscous compression theory of snow and the relation between shear strength and density of snow (Endo, 1993). The calculation method of *SI* was described in detail mainly reviewed based on Endo, 1993, what is more, it was added to the ideas of the coefficient changed by snow temperature between compressive viscosity and snow density up to 300kg m^{-3}, calculating snow temperature for judging dry or wet in a snow layer and calculating initial snow density using snow temperature (Suizu, 2002). In case of calculating *SI* at Happone, air and snow temperature were usually below 0℃ and snow density sometimes became more than 300kg m^{-3}. Accordingly, only a dry snow is thought and another relationship between the coefficient of compressive viscosity and snow density (Kojima, 1967) is used when calculated density exceeds 300kg m^{-3}. In accordance with this method, stability index (*SI*) of each snow layer in the snow cover was calculated at intervals of six hours from December to March of each winter and these values were compared with the occurrences of avalanche. The initial snow density was assumed to be 60kg m^{-3} and snow layer inclination was adopted to 40 degrees which equals to the inclination of slopes A and B where large-scale surface avalanches were released. The rainfall was set by a correction based on wind speed (Ohno *et al.*, 1998) as snowfall in a case of air temperature of 2℃ or less. The snow depth and snowfall obtained by calculating were estimated values at the elevation of 1700 m a.s.l. in the avalanche release areas. Therefore, records of the snow depth and snowfall (measured twice a day) at the Hakuba 47 Ski Resort (1160 m a.s.l.) near the avalanche release area were compared to assess the suitability of the calculation.

As meteorological and snow conditions for the calculation for *SI*, records of observation at location 2 in Fig. 2 were used as meteorological information from December 2002. Data from AMeDAS Hakuba was used up to that time, so for air temperature and rainfall were estimated using correlation between location 2 and AMeDAS Hakuba meteorological data from December 2002 to March 2005. Data of air temperature (℃) and rainfall (mm) were calculated as follows.

$$Air\ temp._{\,(\mathrm{location\ 2})} = 0.9 \times Air\ temp._{\,(\mathrm{AMeDAS\ Hakuba})}{}^{-4.6},$$
$$Rainfall_{(\mathrm{location\ 2})} = 1.26 \times Rainfall_{(\mathrm{AMeDAS\ Hakuba})}$$

The snow stability index was calculated by obtaining the *SI* of the bottom surface of each layer at intervals of six hours, then obtaining the minimum *SI* value of all *SI* values within the snow layers as the snow stability index of the snowpack.

Next part explains meteorological conditions, snow and avalanche release conditions, and change of the snow stability index from December to March during the winters, 1999 to 2000, 2001 to 2002, 2003 to 2004, and 2004 to 2005, when large dry slab avalanches exceeding 1000 m in run-out distance occurred.

5.2 Results for the winter of 1999 to 2000

During the winter of 1999 to 2000, only video observation was made and the meteorological conditions were represented by corrected values from AMeDAS Hakuba. Video observation found 16 dry surface avalanches and 6 wet full-depth avalanches (Fig. 8). On February 5 and 23, large-scale dry slab surface avalanches were released (No. 1 and 2 in Table 1).

Snow stability index at release time was 4.6 on February 5 and 5.2 on February 23, and concentrated snowfall did not occur immediately before these avalanches. During this winter, snow pit walls were not measured, so it was not clear if there were any weak layers.

5.3 Results for the winter of 2001 to 2002

During the winter of 2001 to 2002, only video observation was done again and the meteorological conditions were set using corrected AMeDAS Hakuba data. The video observation found 9 dry surface avalanches and 6 wet full-depth avalanches (Fig. 9). It was determined that on January 6, a large-scale surface avalanche (No. 4 in Table 1) was released at the slope at B in Fig. 2, but because of continuous snowfall that started 15: 00 on January 4, it was impossible to obtain video image of this avalanche, so the precise time of its release was not known. The series of snowfall that ended this period of snowfall increased the snow depth by 42 cm (added up difference per hour of 60 cm and precipitation of 63 mm) according to values measured by AMeDAS Hakuba. Snow stability index from January 4 to 6 was within a range from 1.0 to 2.9, so it can be estimated that the period had been under the condition of avalanche danger. The

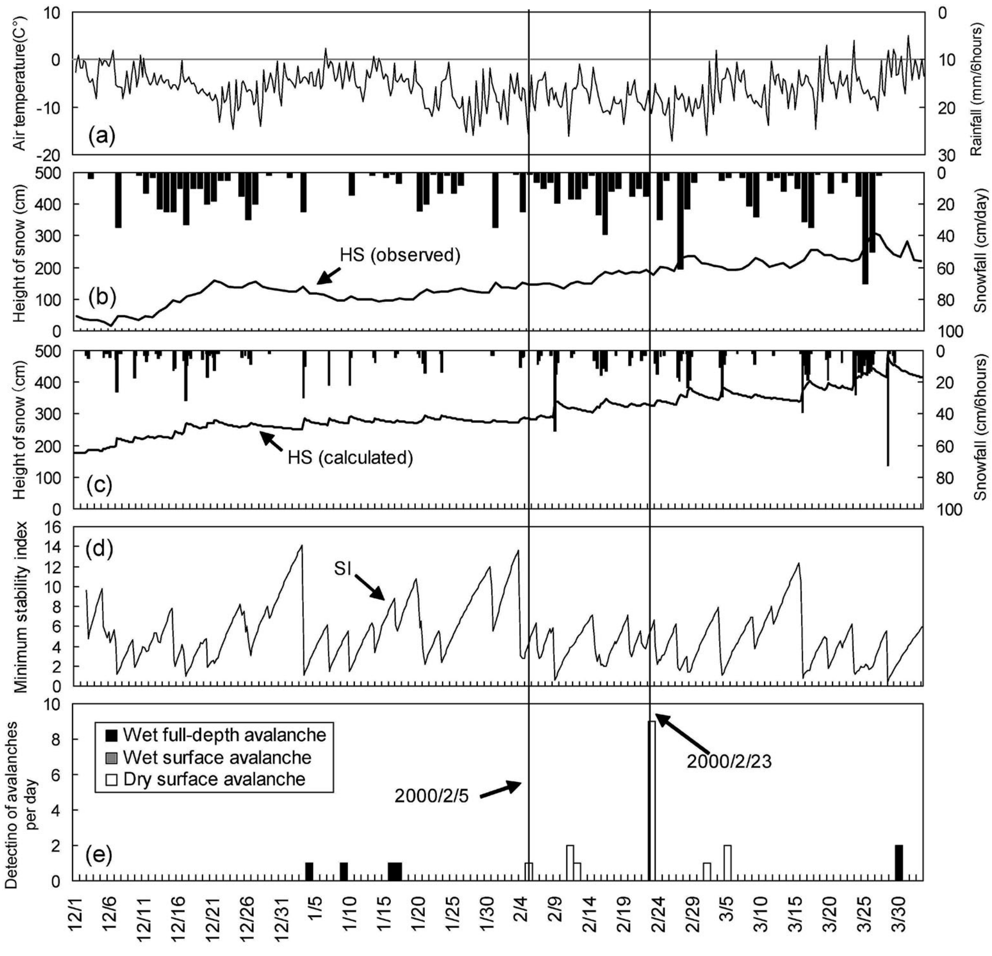

Fig. 8. Meteorological conditions, variation of stability index and avalanche detections (Dec. 1999–Mar. 2000)
(a) Air temperature and rainfall at the avalanche release area (1700 m a.s.l.) estimated by AMeDAS Hakuba meteorological data.
(b) Height of snow observed at the meteorological station (1160 m a.s.l.) in Hakuba 47 Ski Resort.
(c) Height of snow on the avalanche release area (calculated).
(d) Snow stability index (calculated).
(e) Avalanche detection by the visual observation.

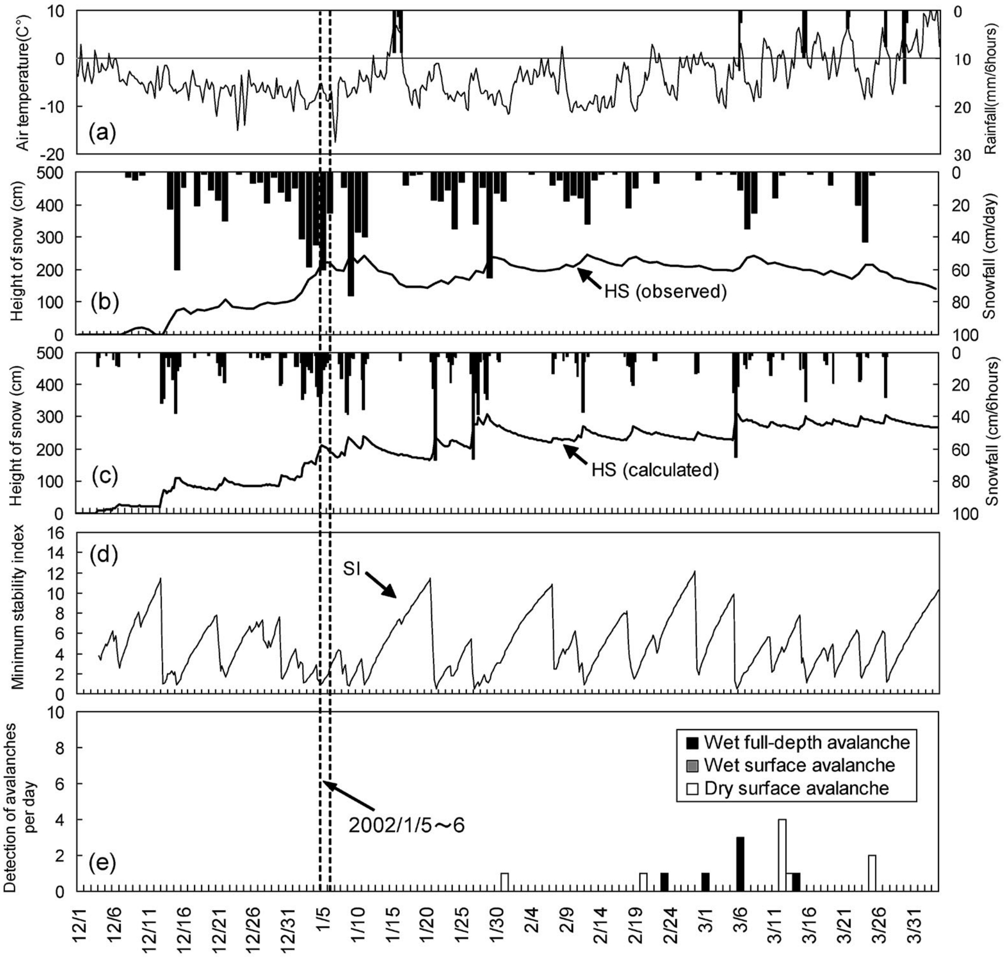

Fig. 9. Meteorological conditions, variation of stability index and avalanche detections (Dec. 2001–Mar. 2002).
(a) Air temperature and rainfall at the avalanche release area (1700 m a.s.l.) estimated by AMeDAS Hakuba meteorological data.
(b) Height of snow observed at the meteorological station (1160 m a.s.l.) in Hakuba 47 Ski Resort.
(c) Estimated height of snow on the avalanche release area (calculated).
(d) Snow Stability index (calculated).
(e) Avalanche detection by the visual observation.

snow pit wall measurements performed near the large-scale avalanche release area on January 6 reveal that there were solid-type depth hoar layers with total thickness of 91 cm below 150 cm from the snow surface.

5.4 Results for the winter of 2003 to 2004

The video observations confirmed 15 avalanches by April 3, but almost all were small-scale full-depth avalanches (Fig. 10). Avalanche tremors were observed 41 times above the avalanche release areas (location 2) ,65 times in deposit areas (location 3) and 17 times in both areas, but judging from a field survey and avalanche tremor results, two large surface avalanches occurred on December 20 and January 24, when video observations could not record images (No. 6 and 7 in Table 1).

The series of snowfall ending on December 20 when the avalanche occurred increased the snow depth prior to the avalanche release by 43 cm according to AMeDAS Hakuba measurement values (added up difference per hour 46 cm, precipitation of 39 mm). The measured precipitation based on meteorological observations at location 2 was 96 mm. Snow stability index at the time of the avalanche occurrence was 0.9 that is less than 1.0.

The series of snowfall prior to the avalanche release on January 24 increased the snow depth prior to the avalanche release by 56 cm according to AMeDAS Hakuba measurement values (added up difference per hour 59 cm, precipitation of 43 mm), and the measured precipitation at location 2 was 35 mm. Snow stability index at the time of the avalanche release was 1.1. In both cases, it can be estimated that the snowfall period had been under the condition of avalanche danger.

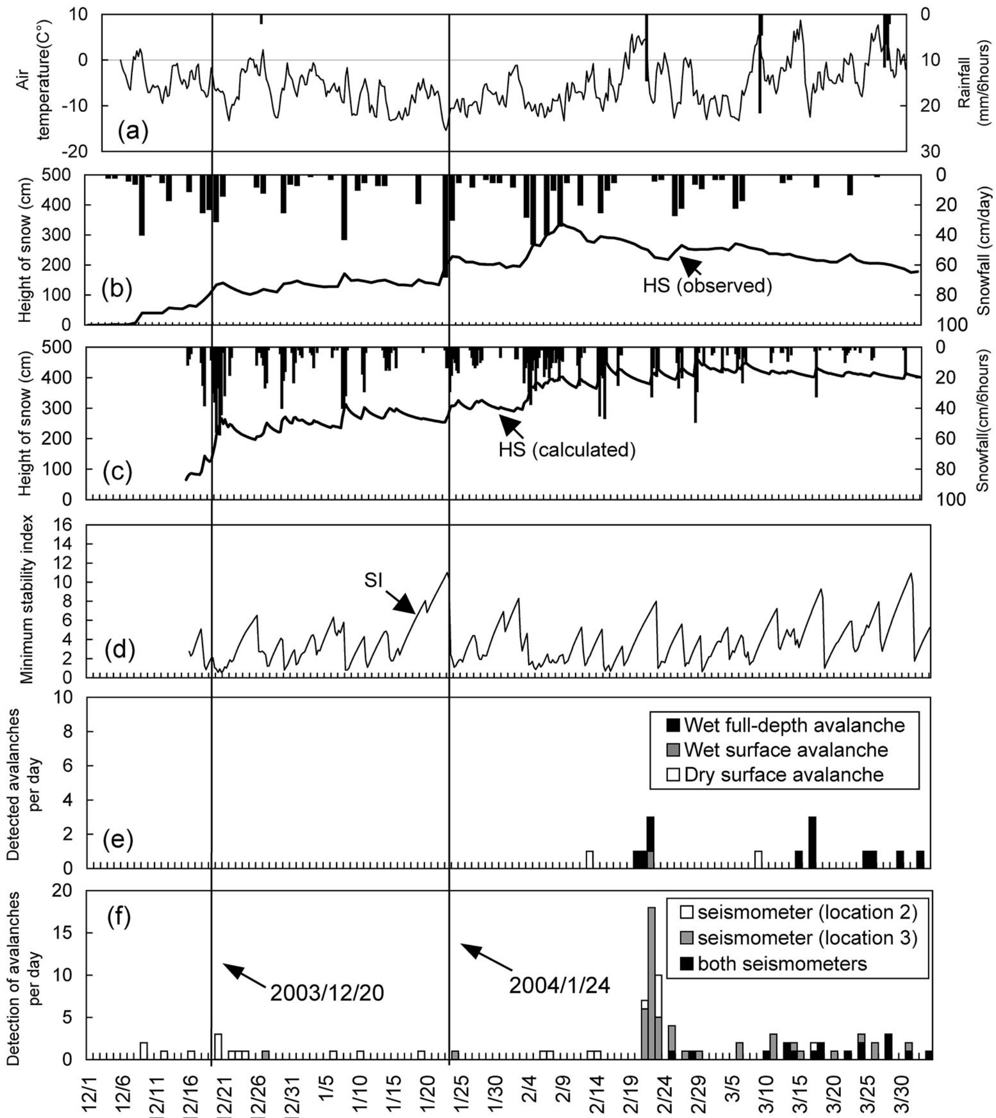

Fig. 10. Meteorological conditions, variation of stability index and avalanche detections (Dec. 2003–Mar. 2004).
(a) Air temperature and rainfall at location 2 (1700 m a.s.l.).
(b) Height of snow observed at the meteorological station (1160 m a.s.l.) in Hakuba 47 Ski Resort.
(c) Height of snow on the avalanche release area (calculated).
(d) Snow stability index (calculated).
(e) Avalanche detection by the visual observation.
(f) Avalanche detection by the seismometers.

The snow pit wall measurements were not done near the avalanche release area after the occurrences of large-scale avalanche, each four times near the release area (location 2) and near the deposit area (location 4) in Fig. 2. The stratigraphies of snow near the release area were formed of mostly new snow and compacted snow with a weak layer of solid-type depth hoar. However, the snow structure near the deposit area was mostly formed compacted snow and granular snow. There were cases of snow temperature of 0℃ and no weak layer like that found near the release area was detected.

During this winter, video images revealed a wet surface avalanche and four wet full-depth avalanches triggered by the effects of a rise of the air temperature and rainfall caused by low atmospheric pressure from February 20 to 22. These avalanches broke out at elevations lower than 1450 m a.s.l. Many avalanche tremors recorded during this period were detected in the low elevation deposit area (location 3) from February 21 to 23.

5.5 *Results for the winter of 2004 to 2005*

During this winter, no avalanche occurrence was

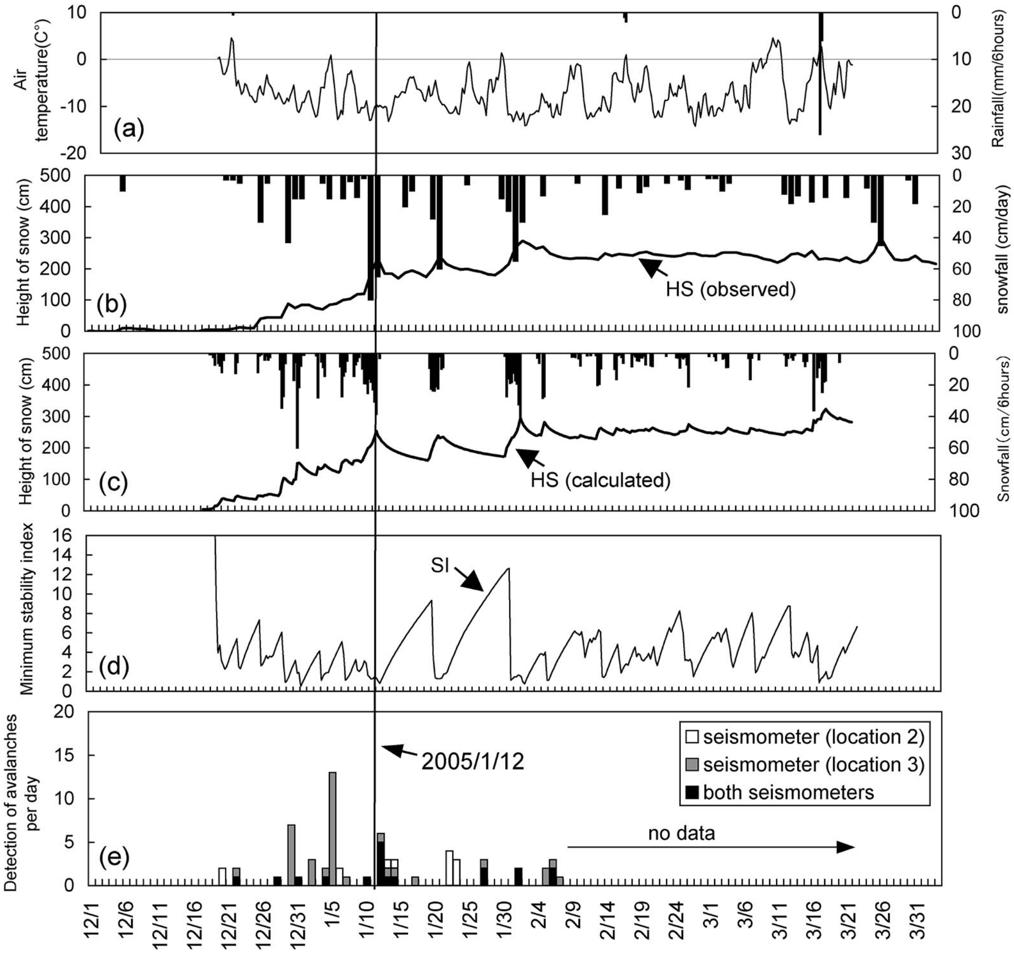

Fig. 11. Meteorological conditions, variation of stability index and avalanche detections (Dec. 2004–Mar. 2005).
(a) Air temperature and rainfall at location 2 (1700 m a.s.l.).
(b) Height of snow observed at the meteorological station (1160 m a.s.l.) in Hakuba 47 Ski Resort.
(c) Height of snow on the avalanche release area (calculated).
(d) Snow stability index (calculated).
(e) Avalanche detection by the seismometers.

detected during the period when video observation was possible, so the number of detections by avalanche tremors were compared (Fig. 11). Avalanche tremor observations were not performed after February 8. The large-sale surface avalanche occurred on January 12 (No. 8 in Table 1). The continuous snowfall up to the release time increased the snow depth by 70 cm (added up difference per hour of 73 cm, precipitation of 65 mm) according to values measured by AMeDAS Hakuba, and 121 cm (added up difference per hour of 124 cm, precipitation of 78 mm) according to values measured at location 2 and the *SI* was 1.4. On January 12, Avalanche tremors were detected five times near the release and deposit area (location 2 and 3) at the same time including the large-scale surface avalanche, so it can be estimated that the period had been under the condition of avalanche danger.

Measurements of snow pit walls were performed each four times near the release area (location 2) and the deposit area (location 4) on and later than January 19 after the large-scale avalanche. In the former case, there was a minus snow temperature and forming solid-type depth hoar layers. In the latter case, the snow temperature was also minus but granular snow and compacted snow were dominant and solid-type depth hoar was not formed. On January 19, another snow pit wall measurements were performed near the area of large-sale surface avalanche release. Its measurements reveal that there was solid-type depth hoar and depth hoar layers with a total thickness of 49 cm on the ground surface.

6. Snow stability index and snow pit wall measurements

The snow wall pit measurements near the large-

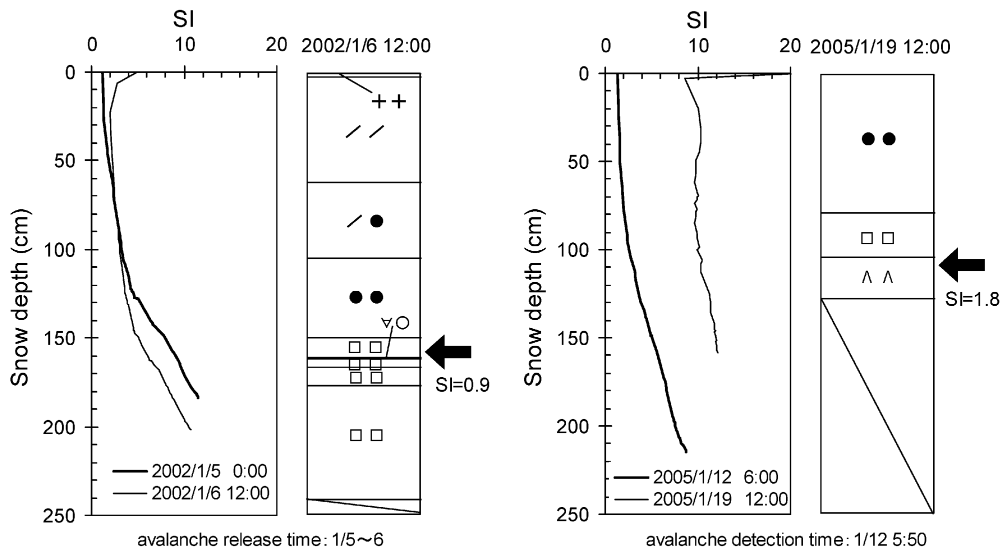

Fig. 12. Snow stability index calculated by the meteorological data, snow pit walls measurement after the release of large-scale dry slab surface avalanches and snow stability index measured by shear frame.

scale dry slab surface avalanche release area could be done in January 2002 (No. 4 in Table 1) and in January 2005 (No. 8 in Table 1). Fig. 12 shows the snow stability index at the time of large-scale avalanche occurrences and the stratigraphies of snow measured by snow pit wall performed near the release area of large-scale avalanches after its occurrences.

The trace of large-scale avalanche No. 4 was dis covered in the morning on January 6 but it was impossible to obtain video image because of snowfall. Snow pit wall near the release area was measured on January 6, 2002. Profiles of *SI* and stratigraphies of snow related avalanche No. 4 were shown in the left figure. Two profiles of *SI* are shown when the maximum height of snow was appeared (1/5 0:00) and snow pit wall was measured (1/6 12:00). The value of *SI* was low at the upper parts of the snow and this period had been under the possibility of avalanche occurrence.

The lower parts of the snowpack were almost all consisted of solid-type depth hoar by measuring snow pit. The weak layer was found about 161 cm under the surface of snow cover by strength test of weak layer. Stability index of the weak layer was 0.9 by measuring shear strength *SFI* using the 250 cm^2 shear frame and snow load on the spot.

The large-scale avalanche No. 8 was detected by seismometer January 12, 2005, but it was impossible to obtain video image because of snowfall. Snow pit wall near the avalanche release area was measured on January 19. Profiles of *SI* and stratigraphies of snow related avalanche No. 8 were shown in the right figure. Two profiles of *SI* are shown when the avalanche occurred (1/12 6:00) and snow pit wall was measured (1/19 12:00). The value of *SI* when the large-scale avalanche occurred is low at the upper parts of the snow and the new snow snowpack had the possibility of avalanche occurrence.

The lower parts of snowpack were consisted of solid-type depth hoar and depth hoar by measuring snow pit. The weak layer was found in the depth hoar layer about 108 cm under the surface of snow cover by strength test of weak layer. Stability index of the weak layer was 1.8 by measuring shear strength *SFI* using the 250 cm^2 shear frame and snow load on the spot.

A study of the snow stability index calculated by meteorological data shows that the stability index inside snow layers was low and conditions for the release of an avalanche from inside snow cover accumulated during heavy snowfall were satisfied other than two large avalanches that occurred in February 2000 (No. 1 and 2 in Table 1). However, the snow pit wall measurements near the large-scale avalanche release area reveal the existence of solid-type depth hoar or depth hoar that is the weak layer of the avalanche, and it is assumed that a rise of the load produced by the heavy snow caused the avalanche with this layer as the slip layer. Moreover, many solid-type depth hoar layers were found in the regularly snow pit wall measurements at location 2. These layers had 1–22 cm of thickness and the weak layers detected strength test of weak layer had stability index from 1.6 to 5.2. Although the avalanche observation area is the south slope of Happone in this study, solid-type depth hoar or depth hoar were confirmed on the north slope of Happone by the investigation as to the avalanche accident (Ikeda, 2002). For these reasons, it is under the condition that weak layer such as solid-type depth hoar or depth hoar is apt to be formed around the large-scale dry slab surface avalanches release area.

If cases where large-scale avalanches occur even when little snow has fallen and the snow stability index is high are included, large-scale dry slab surface avalanches are presumably caused mainly by weak layers that are solid-type depth hoar or depth hoar. However, it can be concluded that conditions for the occurrence of large-scale dry slab surface avalanches are able to be caused only by heavy snowfall even without existing a weak layer.

7. Conclusions

Although the slopes observed were wide and the observation items were not necessarily a uniform observation system because it was periodically improved, the state of avalanche release and the characteristics of large-scale avalanches were clarified. The main conclusions from this study are as follows.

- The avalanche observations obtained records of 224 avalanches and 115 (51%) of them were dry surface avalanches. Many dry surface avalanches occurred in February.
- The large-scale avalanches with horizontal run-out distance longer than 1000 m were all dry surface avalanches excluding one wet surface avalanche.
- The large-scale dry slab surface avalanches occurred on two slopes at elevations between 1650 and 1850 m a.s.l. The wet full-depth avalanches did not occur above an elevation of 1600 m a.s.l.
- The occurrences of large-scale dry slab surface avalanche include cases that can be explained as the result of a decline of snow stability index inside snow layers accumulated by heavy snowfall. However, there are also cases when avalanche occurred without heavy snowfall and when the minimum snow stability index inside the snowpack was high. These cases are difficult to explain as those released only by falling snow.
- Regular measurements of snow pit show that the weak layer such as solid-type depth hoar was often detected around the release area but no weak layer like that found near the release area was found alound the deposit area.
- The results of snow pit measurements near the release area of large-scale dry slab avalanches after its release reveal the presence of solid type depth hoar or depth hoar layer and stability index of weak layer is low. So the conditions for large-scale dry avalanches occurred in the newly deposited snow layer are satisfied when snowfall is heavy, the release of large-scale dry slab surface avalanches is presumably related to the existence of a weak layer such as solid type depth hoar or depth hoar.

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References

Akiyama, K. and Takeshi, T. (2004): Analysis of avalanche movement using video images, Proceedings of 2004 cold region technology conference, **20**, 284–291 (In Japanese)

Endo, Y. (1993): Forecasting of direct-action avalanches in terms of snow accumulation rates, Seppyo, J. Jpn. Soc. Snow Ice, **55**, 113–120 (In Japanese)

Ikeda, S. (2002): A report on the avalanche accident in garagara-sawa, Japan North Alps, Seppyo, J. Jpn. Soc. Snow Ice, **64**, 33–37 (In Japanese)

Imanishi, N., Nishimura, K., Moriya, T. and Yamada, T. (2004): Observations of seismic signals induced by snow avalanches, Seppyo, J. Jpn. Soc. Snow Ice, **66**, 3–10 (In Japanese)

Kojima, K. (1967): Densification of seasonal snow cover, Physics of snow and ice, ed. H.Oura, The Institute of Low Temperature Science, Hokkaido University, 929–952

Kurobe Avalanche Measurement Group (1989): KUROBE HOU AVALANCHE —Studies of Powder-snow Avalanches in Kurobe Canyon—, Contributions to Mountain Sciences, No. 2, Tateyama Laboratory of Mountain Sciences, Toyama University (In Japanese)

Muramatsu, I., (1993): Jishinkei ni yoru nadare kansoku, Kisyo, **37**, 3, 4–8 (In Japanese)

Ohno, H., Yokoyama, K., Kominami, Y., Inoue, S., Takami, S. and Thomas Wiesinger (1998): Catch ratios of gauges for solid precipitation in Hokuriku region, Seppyo, J. Jpn. Soc. Snow Ice, **60**, 225–231 (In Japanese)

Perla, R. (1977): Slab avalanche measurements, Canadian Geotechnical Journal, **14**, 206–213

Roch, A. (1966): Les declenchements d'avalanches, Int. Ass. Sci. Hydrol. Publ., **69**, 182–192

Sabot, F., Naaim, M., Granada, F., Surinach, E., Planet, P. and Furdada, G. (1998): Study of avalanche dynamics by seismic methods, image-processing the techniques and numerical models, Annals of Graciology, **26**, 319–323

Schleiss, V.G. and Schleiss, W.E. (1970): Avalanche hazard evaluation and forecast, Roger Pass, Glacier National Park. In Ice engineering and avalanche forecasting and control, Tech. Mem., **98**, Natl. Res. Counc. Can., Ottawa, 115–122.

Sommerfeld, R.A. (1984): Instruction for using the 250 cm^2 shear frame to evaluate the strength of a buried snow surface, US Dept. Agr. Forest Service Res, Note, RM-446, 1–6

Suizu, S. (2002): A hazard evaluation model of dry snow avalanches caused by heavy snowfall, Seppyo, J. Jpn. Soc. Snow Ice, **64**, 15–24 (In Japanese)

Takeuchi, Y., Akiyama, K., and Irasawa, M. (2001): Avalanche detection and meteorological observations at Makunosawa valley in Myoko, Japan, Data of Glaciological Studies, **93**, 126–132