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Studies on the Settlement Force of Snow as a Generation Mechanism*

By

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Abstract

Settlement forces of snow on beams which were buried in snowpack were analyzed from the point of view of the settling movement of the snow.

In this study, various measurements were made of the movement of the snowpack around horizontal beams and the settlement force on the beams. In addition, predictions of the settlement force using the Finite Element Method were carried out.

For this study, two new kinds of devices were designed to investigate the behavior of the snow. With these the displacement of the snow around a beam was measured, and a fracture in the snow layer around a beam and stake was detected.

The compressive viscosities of the snow, the density of which was less than about 110 kg/m^3, were obtained from experiments using settlement gauges.

Furthermore, relationships between settlement forces on beams and snow depth, snow load and the shape of the top of the beam were analyzed.

From the measurement of the settlement force it was found that the settlement force sometimes increased during cold nights in the melting season. This increase of the force was assumed to be due to the growth of the crust layer around the beam.

Applying the Finite Element Method to the settling of snow, it was confirmed that the settlement force and the settling movement of snow could be predicted with adequate accuracy.

Through computer simulations using the Finite Element Method the mechanisms of force transmission to the beam could also be identified. Those mechanisms ware as follows : (1) direct pressure from overburden snowpack, (2) shear tranfer from adjacent snowpack, (3) snowpack weakening beneath and on the side of the beam, and (4) snow densification in layers above and to the side of the beam which develops a bridge for the intensified transfer of force.

1. Introduction

Snowpack always settles due to its own weight. The settlement of the snowpack, however, is impeded when some strucure is in the snowpack. Consequently the settlement speed of snowpack above a structure differs from that of the snowpack far from the

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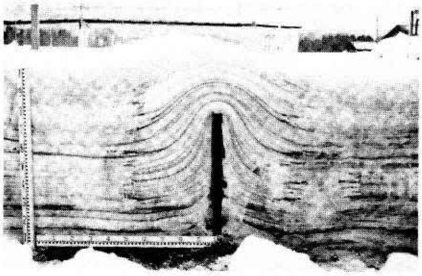

Photo 1 The cross-section of the snow around a horizontal beam.

structure, and snow layers around a structure form consequently a shape such as that shown in Photo 1. The difference of settlement speed produces a force which acts on the structure. The structure also receives the weight of the snowpack on it. The summation of these two forces is called the settlement force of snow.

Because snowpack involved in the force generation is not only snow on the structure but also snow adjacent to it, the force becomes very large. Owing to this factor, many structures such as guard rails, fences and eaves (Oura 1957- a) etc., are destroyed every winter in snowy countries as shown in Photo 2.

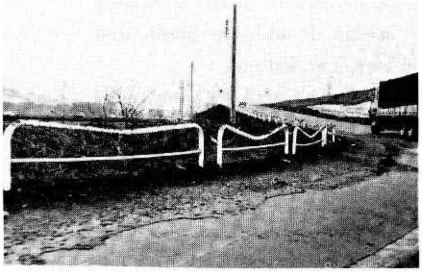

Photo 2 The guard rails bent by the settlement force of snow.

In previous reports, settlement force has almost always been analyzed with reference to the weight of snow or snow depth (e.g. Amano 1943, Shidei et al. 1949, Shoda 1953, Furukawa 1953, Kobayashi et al. 1976, Osada et al. 1975). In some of these papers, the settlement force on a structure was predicted by equations reduced empirically from the field measurements of settlement force using horizontal beams. In these predictions, however, the movement of snow cover was not considered to be a factor that needed to be taken into account. In spite of the fact that the settlement force of snow needs to be analyzed from the point of view of the settling movement since that force is produced as a result of the settling movement, as has been mentioned above, there are few reports which analyzed the settlement force of snow from this point of view (Yoshida 1954, Oura 1955, 1957-b, 1958, 1959). Therefore the objective of this paper is to clarify the generation mechanism of the settlement force of snow and to establish a way to predict the settlement force from the perspective of the settling movement of snowpack.

2. Measurement of behavior of snowpack around the structures

2.1 Two-wired settlement gauge

(1) Design

A settlement gauge with two strings was designed in order to measure the displace-

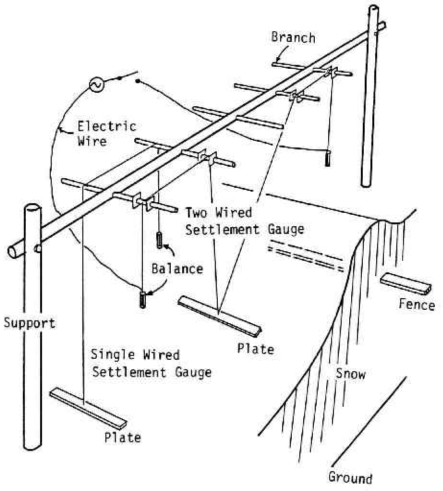

Fig. 1 The two-wired settlement gauge and the single- wired settlement gauge for investigation of the settling mevement of the snow around beam.

ment of snowpack around a horizontal beam. This gauge was made up of a slender plate of vinyl chloride, two fine metal strings wich heat up electrically and two balances, as shown in Fig 1. The size of the plate was 0.3 m× 0.02 m × 0.002 m. Two supports connected by a 3m long beam and 15 branches were set up on the ground in order to hang the strings. The support elevation was set at 1.8 m in order to allow adequate clearance from the snow surface even if the snow depth reached its maximum. Although a balance of 18g was connected to the ends of each string, the strings could slide easily on the branches in accordance with the movement of the plate. This type of gauge will be called a two-wired settlement gauge hereafter in this paper.

It was thought that the plate set up on the snow surface would must probably be covered with fresh snow fall and would move with the snow surrounding the plate. Therefore if the trace of the plate were measured, the two-dimensional movements of the snowpack that made contact with the plate on the plane perpendicular to the beam could be discovered.

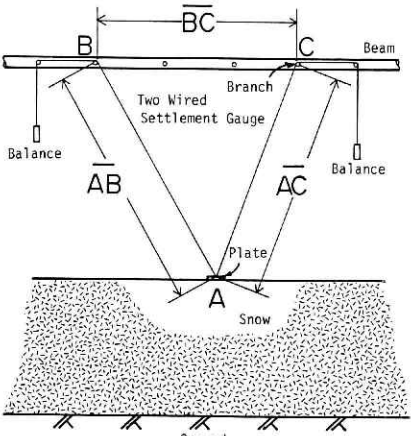

Fig. 2 The position of the plate can be calculated from three distances $\overline{AB}$, $\overline{AC}$ and $\overline{BC}$. $\overline{AB}$ and $\overline{AC}$ are measured by graduations marked on the strings. $\overline{BC}$ is obtained from direct measurement.

It was possible to determine the position of the plate from three distances $\overline{AB}$, $\overline{AC}$ and $\overline{BC}$ (Fig. 2). The length $\overline{AB}$ and $\overline{AC}$, which slowly changes, could be measured by graduations marked on each of the string. $\overline{BC}$ could be figured from direct measurement preceding the experiment. Electric heating wires were used as the strings. Therefore, these strings could be extended straight by the melting snow which surrounded them, even if a part of the strings was buried in the snow.

The settlement gauge with a single string designed by Hirata (1941) is also shown in Fig. 1. Because this type of gauge can measure only vertical movement, it is usually used when the displacement of snowpack has no horizontal motion, such as the settlement of snowpack on an open horizontal plain.

(2) Accuracy

The two types of settlement gauges were set at the same time on the snow surface of an open field, and the traces of those gauges were measured and compared in order to examine the accuracy of the two-wired settlement gauge. Here the single-wired gauge was regarded as the standard gauge. The traces of the two plates are shown in Fig. 3. From this figure, it was found that the heights of the two gauges are almost equal when the two-wired gauge was electrifield.

On Feb.22 1975, the position of the plate of the two-wired gauge calculated from the graduations on the wire differed only 1 cm from the value obtained by direct measurement. Therefore, the two-wired gauge was considered to have an adequate accuracy in order to measure the movement of snowpack around a horizontal beam.

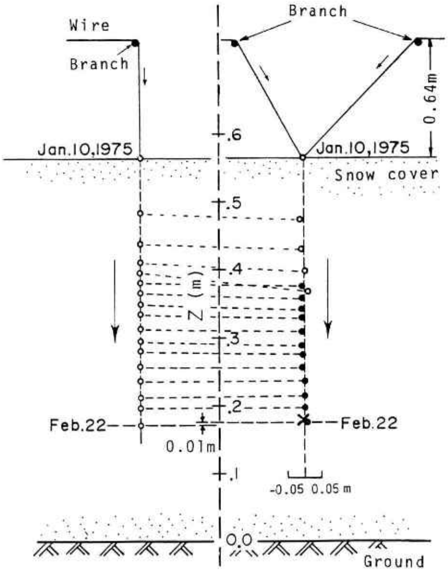

Fig. 3 The examination of the accuracy of the two-wired gauge with the single-wired gauge used as the standard gauge.

(3) Two dimensional displacement of snowpack

During the winter of 1974/75, the movement of the snowpack around a fence was measured using three gauges with two strings, as shown in Photo 3, and the results are shown in Fig.4.

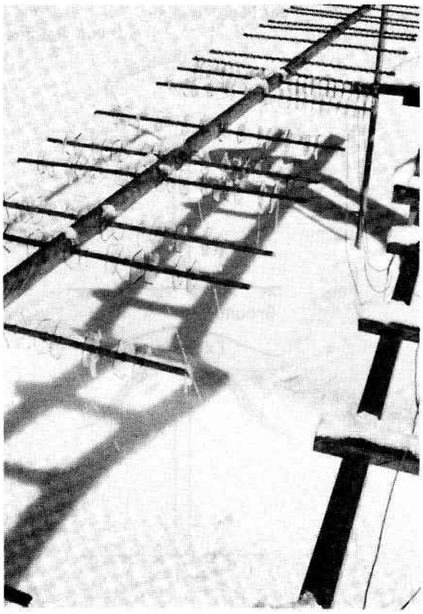

Photo 3 The support with a beam and branches. The strings are separated from each other by small plastic plates.

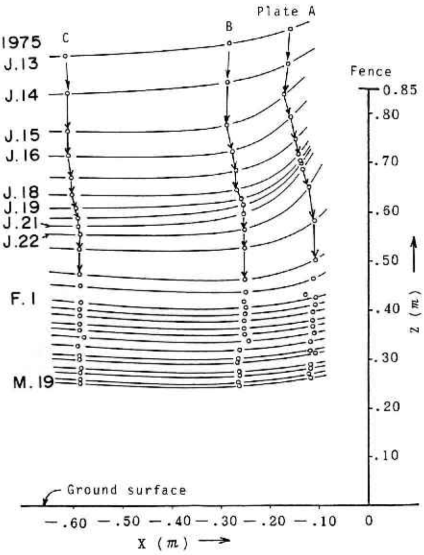

Fig. 4 The movement of snowpack around a fence was measured using the two wired settlement gauge. Plate A moved in an arc-like fashion around the top of the fence.

From this figure, it can be seen that the plate closest to the fence (plate A) moved in an arc-like fashion around the top of the fence, as did the snow around it. The pace of the settlement speed of the snow around plate A decreased rapidly from Jan.18, at which time the snow at plate C (farthest gauge from the fence) had a tendency to move toward the fence. Plate A, however, showed a large displacement from Jan.21 to Jan. 22, and during that time plate C stopped moving towards the fence and moved vertically downward only.

The strange behavior of these plates (i.e. snowpack around these plates) can be understood by examining the snow layer on which these plates were set. This layer might have been cut by the top of the fence at some time around Jan.21. The reason why the settlement speed of plate A increased suddenly, and why the motion of plate C towards the fence stopped on Jan.21 and 22 is because the snow layer which hung on the fence was cut by the fence top and fell down rapidly from the top of the fence.

From these experiments it was found that 1) snowpack settled in arc-like fashion around the fence top and 2) the snow layer is sometimes cut and displaced by horizontal beams although it has been reported that a snow layer, density of which is larger than 100 kg/m^3, has never been cut by a horizontal beam (Shoda, 1953).

2.2 Fracture sensor

Because it was found that layers of snow were cut by a fence top, a new device to detect a fracture of this snow layer on a horizontal beam was designed.

Fig. 5 The mechanism to detect the fracture of the snow layers by the fracture sensor. The fracture is sensed from a rapid increase of electric resistance between both ends of the sensor.

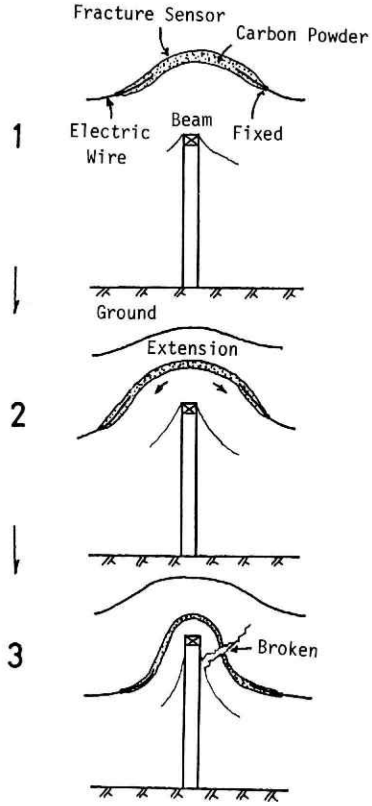

Photo 4 The fracture sensor which was made up of carbon powder wrapped in a soft tissue with two electric wires.

(1) Design

This detector, wich will be called a Fracture Sensor in this paper, is made up of carbon powder wrapped in soft tissue with two electric wires connected to it, as shown in Photo 4. This sensor, as seen in Fig. 5, can extend according to the movement of the snow layer in which the sensor is inserted, and will not been cut if the layer remains intact. Because carbon powder is a good electric conductor, electric resistance between the outer ends of two electric wires is minimal unless the sensor is cut. If, however, the snow layer with the sensor fractures, the sensor will be also broken. In this case the electric resistance is thought to become infinite. Therefore, if the electric resistance is always monitored, the fracture of snow layer will be detected due to the rapid change in the electric resistance.

(2) Detection of the fracture of the snow layer

In order to confirm the ability of the sensor to detect a fracture in the snow layer, the following two experiments were carried out.

1) Detection of a fracture of the snow layer hanging on a horizontal beam

A box with a horizontal beam was set up and new snow was put into the box until the box was filled, setting three sensors at heights of 10, 20 and 30cm from the top of the beam, in order to determine the impact of the snow layer on the electric resistance of the sensor.

The changing of the snow in the box, observed through the clear wall, is shown in Photo 5, and the change of the electric resistance after the setting of the sensors is shown

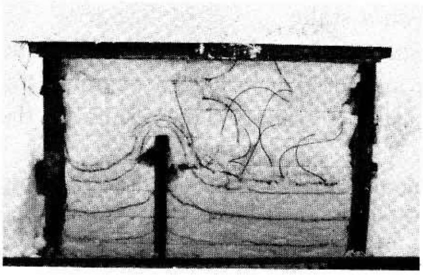

Photo 5 A fracture of the snow layer occurs around the beam. The electrical resistances of the sensors are still small (3 days after).

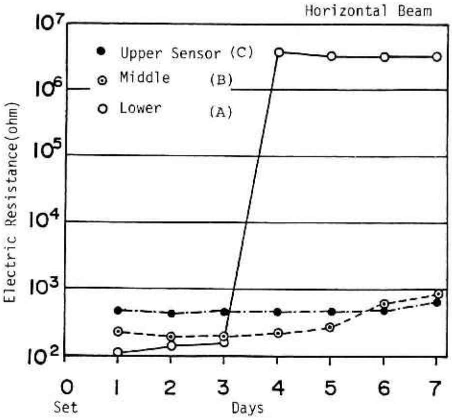

Fig. 6 The changing of electric resistance between both ends of the sensor set in a snow layer over the horizontal beam. The rapid increase in the electric resistance suggests that the fracture just occurred at that time.

in Fig. 6. From this figure it was discovered that the resistance of sensor A, which was set at a height of 10cm from the top of the beam, increased rapidly 4 days after the setting. This rapid increase of the resistance suggests that, at that time, sensor A was cut, and the snow layer where the sensor had been inserted was also fractured. Three days after that, the situation of the sensors was observed by shoveling the layers of snowpack in the box. At that time the electric resistance from the other two detectors still remained smaller than 10^3ohms. It was ascertained that sensor A had been cut as shown in Photo 6, though the others were intact though stretched. From the change of electric resistance and the situation of sensor A, it can be seen that the fracture of the snow layer in which sensor A had been inserted must have occurred 4 days after the setting of the sensor. This experiment proved that this type of sensor is very useful for detecting a fracture of the snow layer hanging on a horizontal beam.

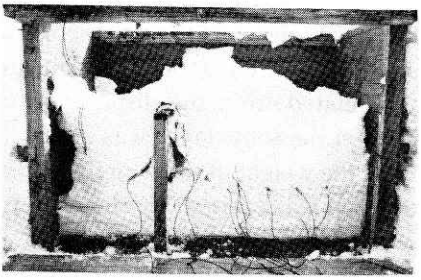

Photo 6 Only the fracture sensor which was set at the lowest height (10cm above from the top of beam) was broken, although the others were all intact.

2) Detection of the fracture of the snow layer on a stake

A Fracture Sensor was also set up on the snow surface above a stake driven into the ground, and the change of electric resistance was measured in order to examine the ability to detect the fracture of the snow layer using a stake. The results of the experiment are shown in Fig. 7.

In this experiment, because the electric resistance became very large on the 13th day after the setting of the sensor, the snow layer on the stake was considered to have been cut by the top of the stake. When the layers of snow around the stake were removed it was confirmed that the layer in which the sensor had been inserted had been cut by the stake top. Therefore it was confirmed that this sensor was also useful in detecting the fracture of the snow layer on top of a stake.

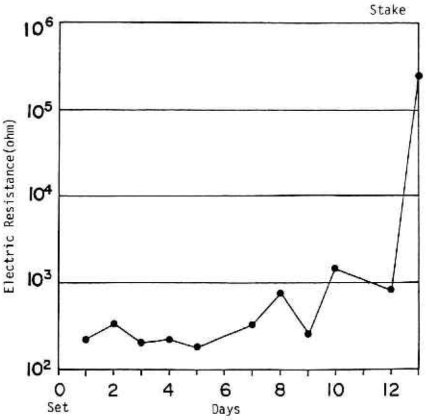

Fig. 7 The electric resistance of the fracture sensor set in a snow layer over a stake. The snow layer is considered to have been cut on the 14th day after the setting.

2.3 Measuring the compressive viscosity of snow using settlement gauges

Later in this paper, the settlement force of snow on a beam will be predicted using the Finite Element Method. In order to carry out the prediction, it is necessary for the compressive viscosity of snow to be known.

The viscosity of snow has been measured by several researchers (Shinojima, 1962; Kojima, 1955, 1956, 1957, 1974; Saito et al. 1971), but there are few papers on the viscosity of snow with a density of less than 100kg/m^3. It was therefore necessary to investigate the compressive viscosity of snow especially in those regions with densities of less than 100kg/m^3. For this reason, the viscosity of light snow was measured using two settlement gauges, as shown in Fig. 8. The gauges used in this experiment were developed to measure displacement of the plate automatically by potentiometers.

A settlement gauge plate was set on top of the newly fallen snow and the plate of another gauge was inserted underneath in order to measure the thickness of the snow layer. The initial interval between the two plates was measured by a scale, and its change after the initial setting of the plates was calculated from the displacements measured by each potentiometer. The load which acts on the snow layer was assumed to be the summation of half weight of the snow layer plus the weight of snow on the upper plate, if there was any snow. The measurement of the load was carried out about every two hours after setting the plate. Compressive viscosity η_c is expressed as follows :

$$\eta_c = \sigma / \dot{\varepsilon}, \tag{1}$$

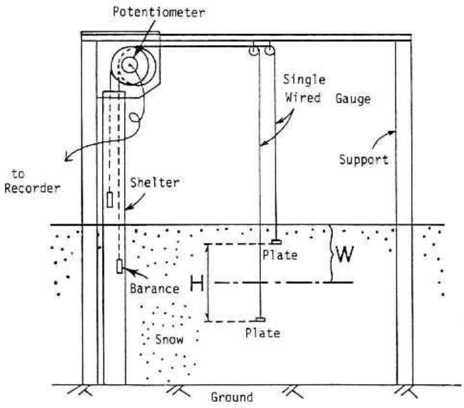

Fig. 8 The measuring system of the thickness variation of the snow layer using two single-wired settlement gauges.

where σ is the normal stress in the snow layer and $\dot{\varepsilon}$ is the strain rate of the layer.

When the thickness H and the load W change from H_1 to H_2 and from W_1 to W_2 in time interval ΔT, the viscosity can be represented in the following equation where σ and $\dot{\varepsilon}$ are regarded as $(W_1+W_2)/2$ and $2(H_1-H_2)/\Delta T(H_1+H_2)$:

$$\eta_c = \frac{\Delta T(H_1+H_2)(W_1+W_2)}{4(H_1-H_2)} \qquad (2)$$

Compressive viscosities of snow obtained from these measurements are shown in Fig.9 by black dots. Because the snow temperature was about -2°C in the region where the density was smaller than $110\mathrm{kg/m^3}$, the relationship between compressive viscosity and snow density when the snow temperature was equal to -2°C was derived as follows:

$$\eta_c = 2.12\times10^5\ \mathrm{Exp}(5.24\times10^{-2}\rho), \qquad (3)$$

where η_c is in $\mathrm{N\cdot s/m^2}$ and ρ is the density of the snow in $\mathrm{kg/m^3}$. Assuming that the relationship between the viscosity and temperature is the same as that derived by Shinojima (1962), the previous equation (3) was modified as follows :

$$\eta_c = 1.75\times10^5\mathrm{Exp}\ \{10^{-2}(5.24\rho+9.58|T_s|)\}, \qquad (4)$$

where T_s is the snow temperature in °C.

Since the values calculated from equation (4) matched with the results achieved by Shinojima (1962) at a snow density of $110\mathrm{kg/m^3}$, in a simulation of settlement force using Finite Element Method, η_c for snow of densities larger than $110\mathrm{kg/m^3}$ was calculated using Shinojima's equation, and for snow smaller than this density, after equation (4).

3. Measurement of the settlement force of snow

In Japan, the settlement force on stakes or beams has been measured by many researchers, mainly in Niigata prefecture in the Hokuriku district, which is a rather warm area among the snowy regions of Japan. In the colder areas such as Shinjo, however, few systematic measumerents of settlement force have been carried out. Furthermore, settlement force is supposed to depend on the snow properties, and

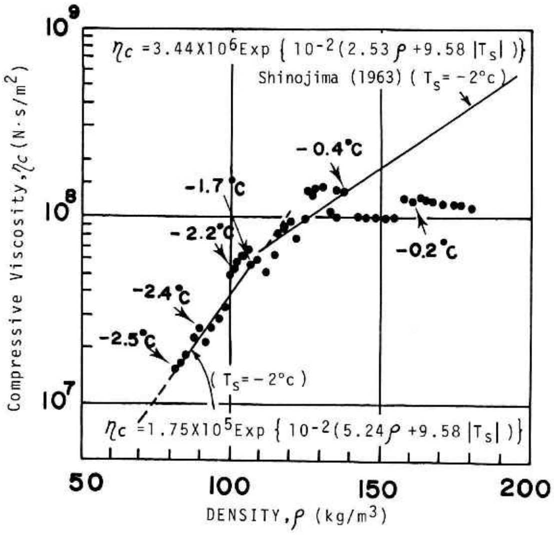

Fig. 9 The compressive viscosities obtained from the measurement using two single-wired settlement gauges.

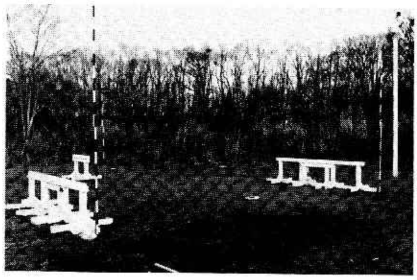

Photo 7 The two types of beam at the Hijiori experimental site. The settlement force on the middle part of each beam is measured by the electric force gauge.

although the Japanese islands are small, snow properties vary significantly from region to region.

For these two main reasons, the settlement force of snow cover onto horizontal beams has been measured since the winter of 1977/78 in the test field of the Shinjo Branch of the National Research Center for Disaster Prevention, and since the winter 1978/79 at the Hijiori experimental site (Photo 7). The maximum snow depths on the ground at Shinjo and Hijiori experimental sites are, on the average, 1.5 m and 4.5 m, respectively.

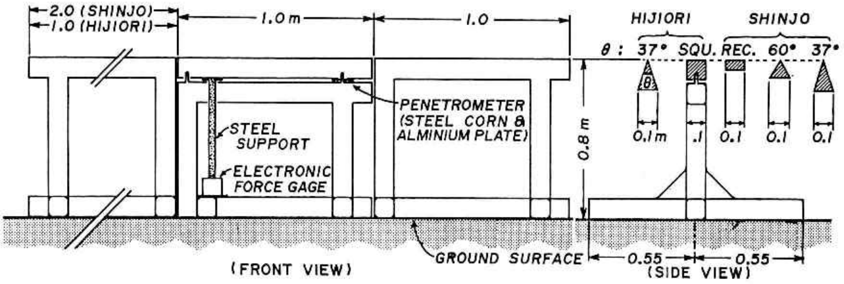

Fig. 10 The horizontal beam with force measurement devices, and the cross-sections of different types of beam.

3.1 Apparatus

The cross-sections of beams used in this research were rectangular, square, equilateral triangular and triangular with a 37° vertical angle, as shown in Fig.10. The height of all beams was 0.8 m above the ground, and the horizontal width of all beams was 0.1 m. Each beam consisted of three horizotal parts, having a length of 1.0 m (2.0 m at Hijiori). The settlement force on the middle part of the beam only was measured. A penetrometer consisting of a steel corn and an aluminum plate was also inserted between the horizontal bar of the beam and another support in case the electric gauge should fail.

3.2 Seasonal variation of the settlement force

(1) The relationship between the maximum settlement force and the maximum snow depth during each year

A variation in the settlement forces obtained from measurements taken during the winter of 1980/81 at Shinjo is shown in Fig 11. In this case, forces were created when the snow depth exceeded the beam height (0.8 m) and then increased with increasing snow depth. The forces began to decrease two weeks later after the snow depth reached its maximum as reported by Shoda (1953). It is thought that the difference in the maximum settlement force (1.3kN/m) between the rectangular beam and the triangular beam (60°) was caused by the difference of shape of the beams tops. The forces vanished when the snow depth was less than the beam height again in spring.

As a particular case, sudden sharp increases of force were observed at the end of the winters 1980/81 and 1983/84 at Hijiori. Because they appeared during the melting season only, they might have been due to crust formation, as pointed out later.

In Fig. 12, the increment of settlement force onto a beam due to the increase of the snow depth is shown in comparison with the maximum force under maximum snow depth. From the measured values shown in Fig.12, the relationships between the

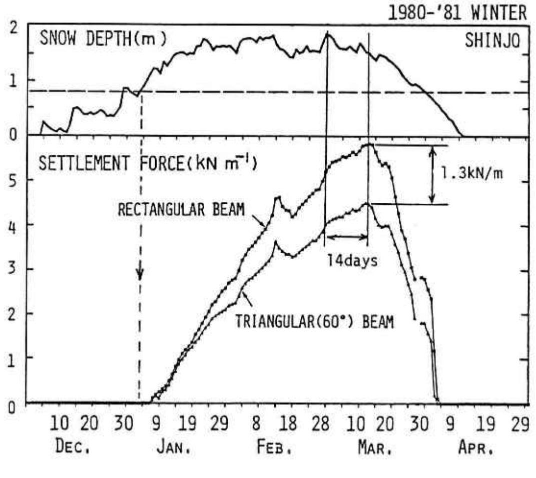

Fig. 11 The daily change of the settlement force on two different types of beam in comparison with the snow depth (Shinjo).

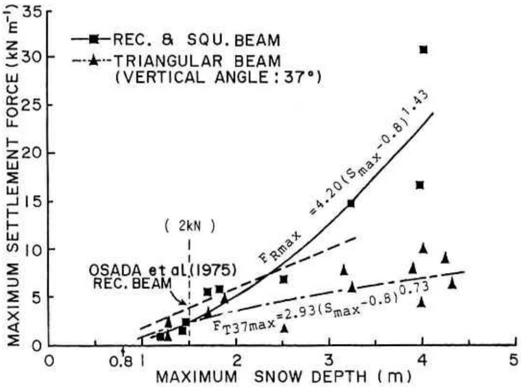

Fig. 12 The increase of the settlement force on a beam due to increase of snow depth.

maximum settlement force onto a rectangular beam (F_{Rmax}) and a triangular beam of 37° (F_{T37max}) and the maximum snow depth in each winter (S_{max}) were obtained as follows (beam height = 0.8m) :

$$F_{Rmax} = 4.20(S_{max} - 0.8)^{1.43}, \tag{5}$$

$$F_{T37max} = 2.93(S_{max} - 0.8)^{0.73}, \tag{6}$$

where F_{Rmax} and F_{T37max} are in kN/m, and S_{max} is in m.

Osada and others (1975), analyzing settlement force data measured at Niigata prefecture, proposed an equation to estimate maximum settlement force on a rectangular horizontal beam from the maximum snow depth only. Their relationship between the force and the maximum snow depth is shown in Fig.12 by a dashed line. The magnitude of maximum settlement force on the rectangular and the square-section beams, measured during each winter, coincided with the values calculated from Osada's equation when snow lies less than about 3 m on the ground.

It is thought that the reason why the maximum settlement force onto a rectangular beam increases exponentially with the maximum snow depth, as shown in Fig. 12, is that the average snow density throughout the depth of snow cover becomes larger in general with the increase in snow depth before the melting season (Shoda 1953).

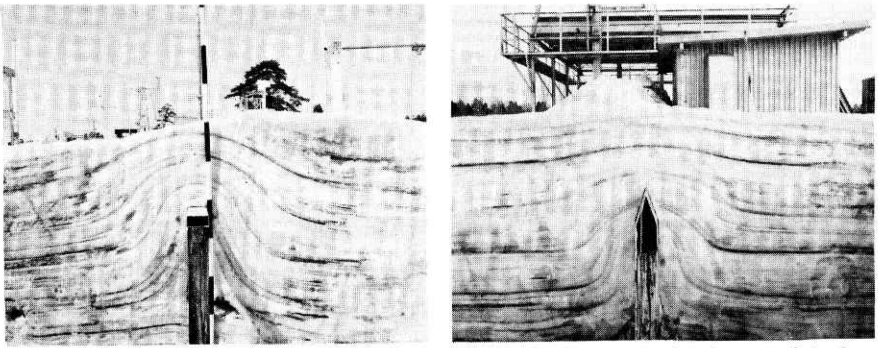

Photo 8 The snow layers on the triangular beam (37°) were cut by the top of the beam like a blade, though on the rectangular beam, the snow layers are intact though stretched.

On the other hand, it is thought that the reason why the maximum settlement force on a triangular beam (37°) doesn't show such a tendency, but rather shows a saturation curve, is that a part of the snow on the beam was perhaps cut by the beam top, acting like a blade under high pressure. Therefore it is thought that the amount of snow hanging on the beam became less than before the cutting, and that the forces didn't become as large as that in the case of the rectangular beam. It has often been observed that a part of the snow layers on the triangular beam (37°) had been cut by the top of the beam, as shown in Photo 8.

(2) Sensitivity of the settlement force to the increase of the snow load hanging on the beam

It is well known empirically that the settlement force on a beam increases with the load of snow on the beam. Hence the sensitivities of the force to the snow load were investigated.

The sensitivity was defined as ratio of the settlement force increment to the addition of the snow load. Fig. 13 shows the relationships between the settlement force and the

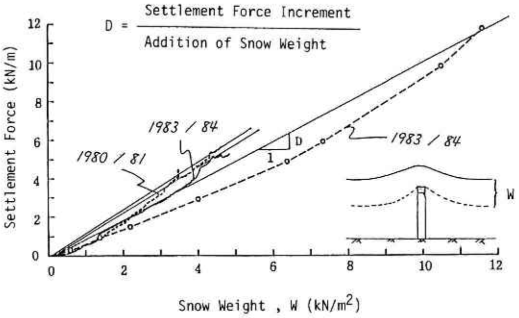

Fig. 13 The relationship between the settlement force and the snow weight. The inclinations of the curves represent the sensitivities of the settlement force to the increase of the snow weight.

Table 1 Sensitivity (D)

Year	Place	Researcher	Beam Height	Maximum Snow Depth	D
1977/78	Shinjo	Nakamura et al.	80 CM	147 CM	1.30
1980/81	〃	〃	〃	183	1.53
1981/82	〃	〃	〃	138	0.58
1983/84	〃	〃	〃	171	1.30
1984/85	〃	〃	〃	128	0.86
1978/79	Hijiori	〃	〃	252	1.08
1980/81	〃	〃	〃	402	1.43
1981/82	〃	〃	〃	398	1.17
1983/84	〃	〃	〃	425	1.00
1951/52	Shiozawa	Shoda	77	170	1.86
1952/53	〃	〃	80	240	1.41
1954/55	Sapporo	Oura	60	112	0.42
1967	Sekiyama	Kobayashi et al.	68	210	1.58
1967/68	Koide	Osada et al.	90	332	1.71
1968/69	〃	〃	〃	217	1.00

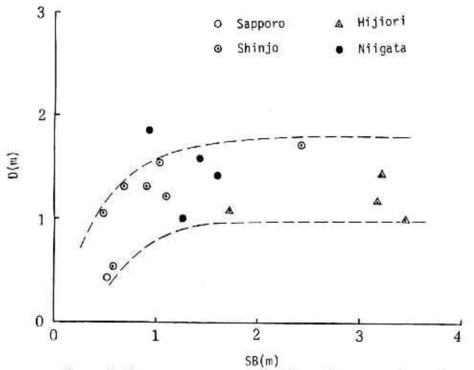

Fig. 14 The sensitivity of the settlement force to the snow weight (D) versus the difference between the maximum snow depth and beam height (SB). The magnitude of D is thought to depend upon the degree of formation of the hard layer on the top of the beam.

snow load for a rectangular beam in three cases.

The average sensitivities, (D), over each winter were regarded as the mean inclination of each somewhat irregular curve, as shown in Fig. 13. Values of D obtained from the experiments and results by other researchers (Shoda 1953, Oura 1955, Kobayashi et al. 1976, Osada et al. 1975) are listed in Table 1 and the same results are plotted in Fig. 14. In this figure the X-axis is chosen as the difference between the maximum snow depth and the beam height, (SB), because beam heights are not always just equal to 0.8m.

It was found from this figure that in the region where SB is larger than 1m, values of D are almost constant, though the deviation is a little large. On the other hand, in the region where SB is less than 1 m, D decreases rapidly according to the decrease of SB.

Because it has been found from the simulation of the settlement force using the Finite Element Method that the force becomes larger if a hard snow layer is formed on the beam, the reason why D is small in the region where SB is less than 1m was also considered to have been a result of the fact that the hard layer hadn't been formed on the beam adequately in such cases. In other words, there was not sufficient snow in the winters for such a hard layer to be formed on the beam.

(3) Relationship between the settlement force and the shape of top of the beam

Comparison of the settlement forces on beams, the tops of which are flat, and on triangular beams with angles of 37° and 60° are shown in Fig. 15 and 16. It was found that in the region where the settlement forces on flat beam were smaller than 2kN/m, the settlement force on triangular beam was almost equal to the force on the flat beam. The

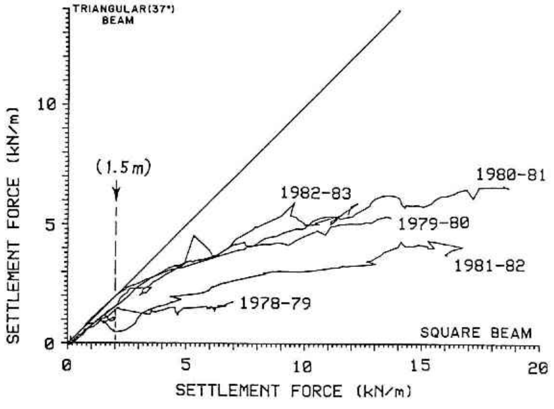

Fig. 15

A comparison of the settlement force on the triangular beam (37°) with that on the square beam. In the region where snow depth is smaller than 1.5m, both are almost equal.

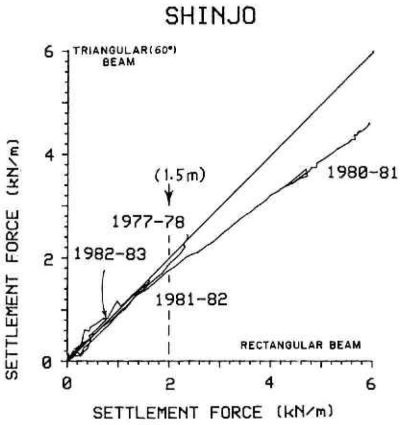

Fig. 16 A comparison of the settlement force on the triangular beam (60°) with that on the rectangular beam. The results are similar to those found in the case of the triangular beam (37°C).

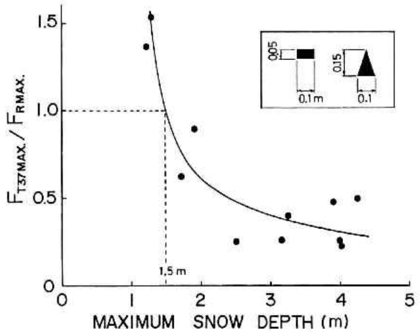

Fig. 17 The ratio F_{T37MAX}/F_{RMAX} is larger than 1.0 when the maximum snow depth is less than 1.5m. It is thought that the cause is due to the difference between the thickness of each beam.

snow depth when the force on the flat beam equalled to 2kN/m was about 1.5 m.

On the other hand, the relationship between the ratio of the annual maximum settlement force on the triangular beam(37°) to the annual maximum force on the rectangular beam, and the annual maximum snow depth are shown in Fig. 17. Though the ratio was 0.3-0.5 when maximum snow depth was larger than about 1.5 m, it became larger than 1.0 when the maximum snow depth was less than 1.5 m. It is thought that the reason why the ratio was small in the region where the maximum snow depth was large is because the snow layer on the triangular beam was easy to be cut by the top of the beam due to the snow load, and because the amount of snow hanging on the triangular beam decreased as the result.

The reason why the ratio is larger than 1.0 when the snow depth is less than about 1.5m, is considered to be due to the thickness of the beams. Because the triangular beam (37°) was three times thick than the rectangular beam as shown in Fig. 17, the amount of the snow hanging on the triangular beam was larger than that on the rectangular beam except when the snow layer on the each beam was cut by the beam top. The settlement force in this region was not so large that the cutting of snow layer could not occur. Due to these two factors, the maximum settlement force on the triangular beam was becomes greater than that on the rectangular beam in the region where the maximum snow depth was small.

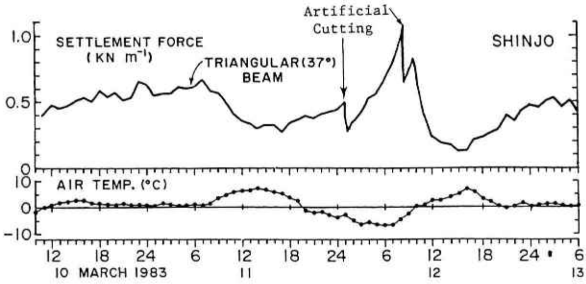

Fig. 18
The changes in the settlement force and air temperature at the Shinjo experimental site. The sudden decrease of the settlement force was due to the artificial cutting of the hard snow layer, as will be mentioned later.

3.3 Increase of settlement force due to hardening of snow

It was found that on a cold night during the melting season the settlement force increased even if there was no addition of snow.

One example of such a phenomenon was observed on Mar.11, 1983 at the Shinjo experimental site and it is shown in Fig. 18. Variations in the settlement forces and air temperature are shown in the figure. The variations occurred during a period in which there was no snowfall though this is not indicated in the figure. A sudden decrease in the settlement force during the night of Mar.11 to Mar.12 was caused artificially, as will be mentioned later.

Because there had been positive air temperature since the daytime of Mar.10, the snow cover was wet and of a granular type. Under these conditions the settlement forces increased during the night of Mar.11. Details of the variations in the settlement forces, air temperature and thickness of the crust layer from Mar.11 to Mar.12 are shown in Fig. 19 and a cross-section of snow cover adjacent to the beam on Mar.11 is shown in Fig. 20.

Although it was warm in the daytime on Mar.11 (maximum air temperature: 7.7°C), it became colder in the night and the air temperature dropped to −7.6°C in the early morning of Mar.12. The snow cover surface turned to a hard crust as the air temperature fell, the thickness of the crust reaching 15 cm at 7.35 a.m. The settlement force increased with the growth of the crust.

This increase of the force was assumed to be due to hardening of the snow, because, although the settling speed of the snow was almost the same as before the hardening, the viscosity of the snowpack of the surface became very large, and the resultant shear stress (=viscosity × strain rate) also became large. Because the shear force transferred from the adjacent snowpack to the beam and therein intensified the settlement force, this mechanism was assumed.

This hypothesis was confirmed in two ways. One method was to cut the hardened snow layer along the beam and the other was to perform calculations using the Finite Element Method.

When the crust was cut off along a section of the triangular-topped beam (Fig 20), it was found that the settlement force decreased suddenly by 200-300 N/m (Fig. 19). On the other hand, the simulation of the settlement force using Finite Element Method which took into account the hardening of the snow (i.e. using the viscosity of snowpack of negative temperature) showed that the settlement force increases if the snow becomes hard, as is shown in Fig. 19 by a dotted line. Therefore, it is believed that the growth of the crust layer on the beam caused the gradual increase of the settlement force.

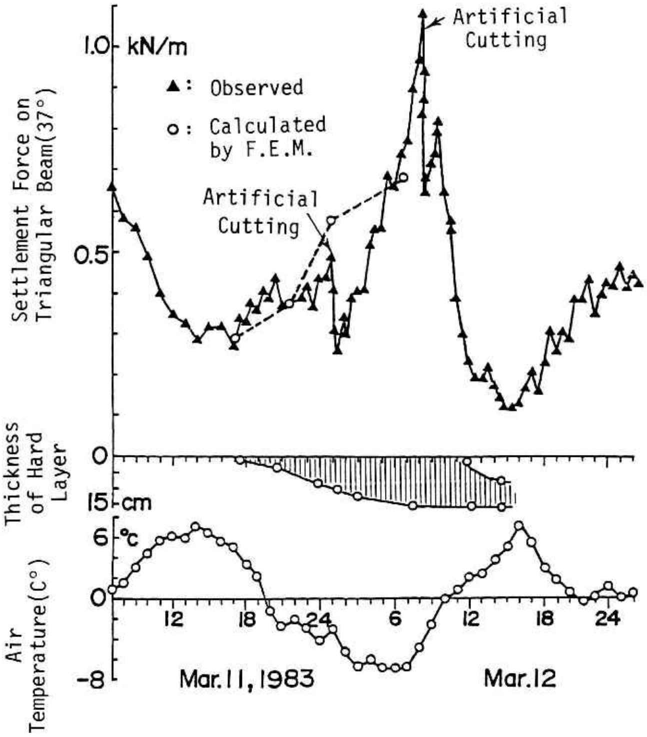

Fig. 19 The details of the variation of the air temperature, settlement force and thickness of the crust layer. The settlement force increased with the growth of the crust.

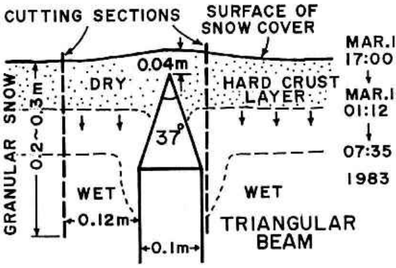

Fig. 20 A cross-section of the snow cover adjacent to the triangular beam, and the growth of the hard crust layer adjucent to the beam. The downward arrows indicate the growth direction of the crust layer.

A similar process of bridging was derived through a computer analysis of snow settlement, i.e. the increase of the settlement force from the snow densification of a snow layer within the snowpack (Lang and others 1984).

4. Simulation of the settlement force by computer modeling

4.1 Settlement force simulation assuming the density distribution of the snow around a beam

The settlement force of snow is produced due to a lack of uniformity of the settlement speed of snow around a beam. Therefore it is necessary to analyze the force taking into account the movement of the snow as mentioned before.

However, simple estimates with many attendant approximations do not generally yield accurate predictions of force. The reasons for this are that snowpack is a layered continuum of viscoelastic material which in the vicinity of a structure has a complex pattern of flow and force transmission. To incorporate these physical effects into an analysis of settlement requires the use of a numerical method such as the Finite Element Method. Settlement forces measured during the winter of 1980/81 at the Shinjo observation site were simulated using the Finite Element Method.

(1) Experimental Data

Experimental data were taken on the settlement force on the beam, on the new snow deposition and on the density. These were measured in the area once each day after the intial burial of the beam. The distribution of the density in the snowpack was also known from the pit data taken at 10-day intervals at a location in the vicinity of the beam test site (but not at the test site itself).

(2) Computer program

A computer program that uses the Finite Element Method in analysis of planar elasticity problems, including material orthotropy (Lang et al. 1984) was used to analyze the beam settlement problem. While ordinarily used for elastic material problems, the computer code can also be applied to secondary or steady creep problems by simple redefinition of the material constants. The program does not incorporate material densification, which occurs in snow settlement, but with the density distribution known at 10 day intervals, stepwise liner interpolation on a daily basis can be made. The approach is to use the density and force data as reference information and to investigate the conditions by which a finite element representation of the beam-snow configuration fits the data.

Several considerations dictate the finite element model that is selected to analyze the snow-beam settlement problem. Knowing that the material flow should vary most rapidly in the local region surrounding the beam, the finite element array should account for this gradation. Also, at some horizontal distance away from the beam, the snow settlement should approach the infinite slab condition of the simple vertical deflection. Advantage is also taken of the symmetry about the vertical axis through the center of the beam. In assimilating these factors, a grid of finite elements was selected with 115 gridpoints and 107 elements. The boundary condition with no horizontal displacement was imposed at the gridpoints on the vertical axis throubh the beam and at the vertical boundary 1.0 m to the left of the beam. At the ground surface and on top of the beam no vertical and horizontal displacement was permitted.

(3) Material description

Several assumptions are made to reduce the complexity of the material description and make a solution tractable. One assumption is that of plane strain, that a section of the beam cross-section and snow-slab is "typical" in the sence of constancy in the third coordinate direction. And another assumption is that transient material response is negligible. So that only sencondary (steady) creep of the material needs to be defined,

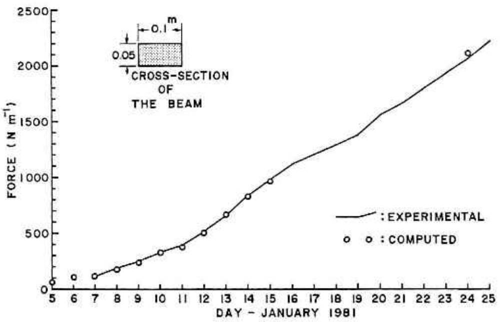

Fig. 21
The experimental and computed settlement force on the beam.

and this in turn is limited to linear viscoelastic representation. From these assumptions the following constitutive equation for steady creep was derived by T. E. Lang and T. Nakamura (1984):

$$\begin{Bmatrix} \sigma_x \\ \sigma_z \\ \tau_{xz} \end{Bmatrix} = \frac{\eta}{(1-2\nu)(1+\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & 1-2\nu \end{bmatrix} \begin{Bmatrix} \dot{\varepsilon}_x \\ \dot{\varepsilon}_z \\ \dot{\gamma}_{xz} \end{Bmatrix} \quad (7)$$

The matrix in this equation corresponds to the [B] matrix in the Finite Element Method. The Poissonic coefficient of snow, ν, in compression is set at 0.27.

(4) Computation result

Computation of the settlement force by the Finite Element Method was carried out assuming the density distribution around the beam based on the pit observations carried out at a location in the vicinity of the beam test site. As has been described, the experimentally measured beam settlement force was used as a means of finding the internal arrangement of finite elements in order to predict the force correctly. The resulting comparison between the experimental and computer predicted settlement force from 5 January through 14 January is shown in Fig. 21.

Despite the fact that this calculation was carried out assuming the density distribution around the beam, from these simulations, the mechanisms of the force transmission to the beam could be identified. They are 1) direct pressure from overburden snowpack, 2) shear transfer from adjacent snowpack, 3) snowpack weakening beneath and to the side of the beam, and 4) snow densification in layers above and to the side of the beam to develop a bridge for an intensified transfer of force. It is thought that due to the bridging mechanism of step 4) the force intensification on the beam became as large as has been measured empirically. Results of this computer study show the bridging region to extend horizontally from the beam by a factor of 2 to 3 times the width of the beam.

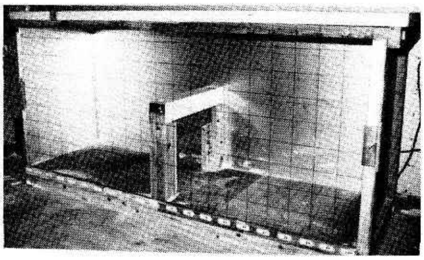

Photo 9 The experimental box with a horizontal beam (2m × 0.6m × 0.85m).

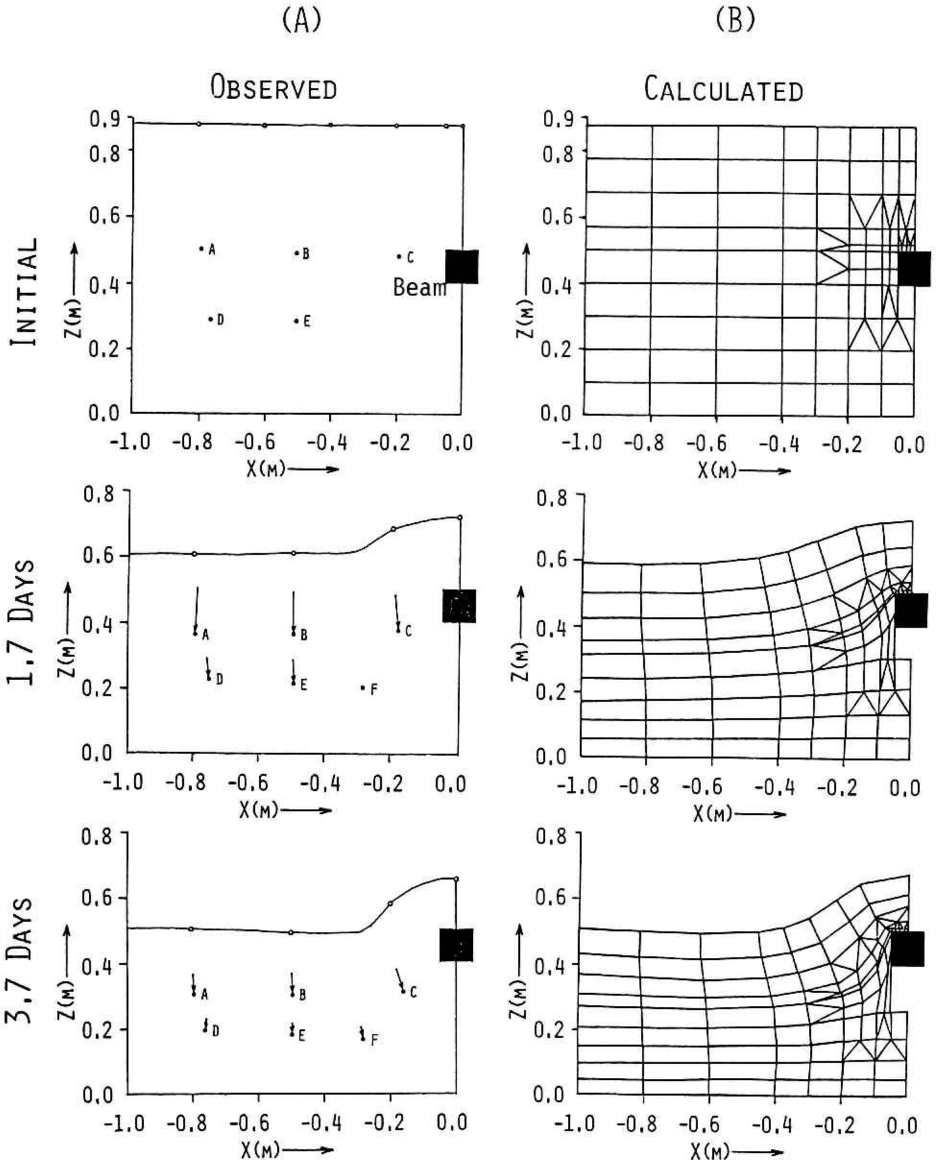

Fig. 22 The displacement of the snow in the box. (A) observed (B) calculated by F.E.M.. The shape calculated is quite similar to the measured value.

Because this calculation was carried out assuming the density distribution as mentioned above, in the next stage, the settlement force was calculated based on the density distributions that had been actually measured.

4.2 Settlement force simulations based on measured density distribution of the snow

(1) Apparatus

The measurement of the settlement force and the density distribution was done using a box (1.0m × 0.9m × 2.0m) as shown in Photo 9. Because the front wall of the box was made of clear acrylic board, the densification of snow in the box was measured through the board without disturbing the snow. The densification pattern was meanured using straws as marks of snow displacement.

Newly fallen snow which had accumulated naturally on the ground was put into the box gently. The box, the top of which was sheltered, was covered with snow in order to insulate it from the outer air. The measurements of the densification were carried out after the snow which had covered the front side of the box had been removed.

(2) Experimental result

The results of the movement of the snow in the box are shown in Fig. 22 along with the results calculated using the Finite Element Method. The shape of the snow calculated by the Finite Element Method is quite similar to the measured value. It bears an accuracy of within 1cm. The movement of the marks showed a similarity to the displacements which had been found in the observations using several two-wired settlement gauges around the fence. Therefore the results achieved from this experiment are thought to be reasonable.

Settlement forces measured and calculated are shown in Fig. 23. Both forces are almost equal in the initial stage of the experiment although there is a difference between the two forces of about 50 N/m in the later stage.

The density distributions are shown in Fig. 24. From these figures it was found that a high density zone was formed on the beam, and a low density zone beneath the beam. From Fig.22 and Fig.24 it was found that the snow flows to the lower density zone below the beam.

Distributions of shear stress on the X-Z plane were shown in Fig. 25. Snow in the region where the sign of the shear stress is positive intensifies the settlement force, while

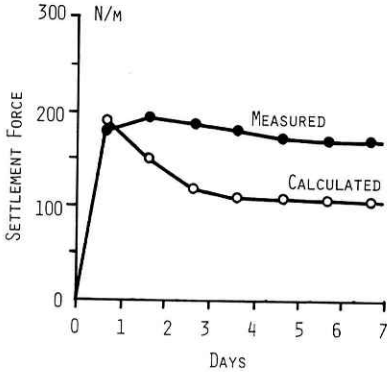

Fig. 23 The settlement force measured and calculated using the Finite Element Method.

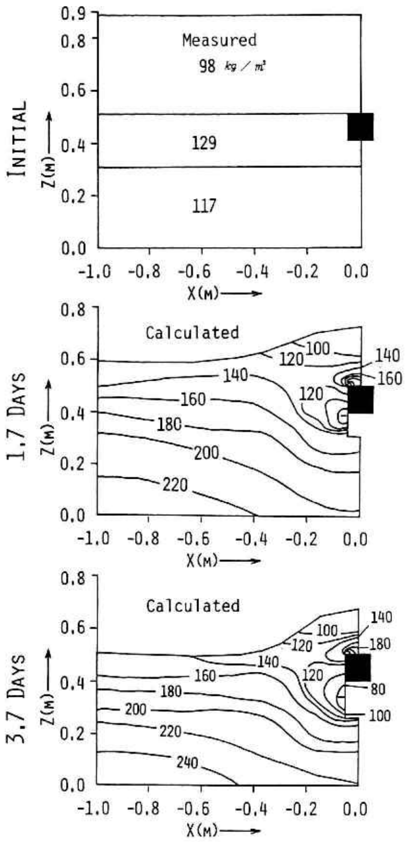

Fig. 24 The variation of density distribution. It was found that a high density zone was formed on the beam.

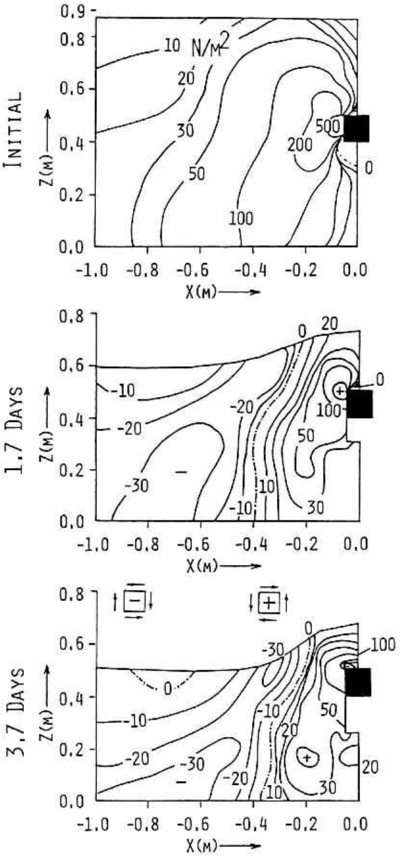

Fig. 25 The distribution of the shear stress. It was found that the area of snow which intensified the settlement force on the beam became narrow fast.

snow in a negative zone doesn't. The zero-line is the boundary between the two zones. Values of the settlement force calculated using the Finite Element Method became rapidly smaller than the measured values after setting the snow, due to the fast approach of the zero-line towards the beam. In other words, the area of snow which was concerned with the intensification of the settlement force became narrow fast.

5. Cocluding remarks

Measurements of the movement of the snowpack around the horizontal beams and the settlement force of the snowpack onto the beams, and the prediction of the settlement force on the beams using the Finite Element Method were carried out in order to make clear the mechanism of the settlement force generation. The results can be summarized as follows :

(1) Snowpack around the top of a horizontal beam settles in an arc-like fashion.

(2) The compressive viscosity of snow, the density of which is less than 110kg/m^3, is represented in the following equation :

$$\eta_c = 1.75 \times 10^5 \mathrm{Exp}\ \{10^{-2}(5.24\rho + 9.58|\mathrm{Ts}|)\},$$

where η_c is compressive viscosity in N・s/m^2, ρ is snow density in kg/m^3 and T_s is snow temperature in °C. Then the relation of the snow temperature to the viscosity is assumed to be the same as the result of Shinojima's experiments.

(3) Annual maximum settlement forces on the rectangular beam (F_{Rmax}) and the triangular beam of 37° (F_{T37max}), the elevation for both of which is 0.8m, are represented in the following equations as a function of maximum snow depth (S_{max}) in each winter:

$$F_{Rmax} = 4.20(S_{max} - 0.8)^{1.43},$$
$$F_{T37max} = 2.93(S_{max} - 0.8)^{0.73},$$

where F_{Rmax}, F_{T37max} are in kN/m and S_{max} is in m.

(4) The ratio of the increase of the settlement force versus the addition of the load of snow layer hanging on a beam is almost a constant in the region where the difference between maximum snow depth and beam height is larger than 1m. However in the region where that difference was less than 1m, the ratio became very small.

It is thought that the value of the ratio depends upon the formation of a hard layer on the beam top.

(5) In general, the force on a beam of triangular shape is smaller than the force on a square-type beam, but, in the region where the maximum snow depth is smaller than 1.5 m, the forces on both types are almost equal.

(6) The settlement force increased due to the hardening of the surface layer of the snow cover, even if there was no snowfall.

(7) It was found by computer simulations using the Finite Element Method that mechanisms of force transmission to the beam can be identified as follows; 1) direct pressure from overburden snowpack, 2) shear transfer from adjacent snowpack, 3) snowpack weakening beneath and the side of the beam, and 4) snow densification in layers above and to the side of the beam to develop a bridge for intensified transfer of force.

(8) Settlement movements and settlement force of snowpack can be calculated with adequate accuracy using the Finite Element Method.

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References

1) Amano, I. (1943) : Settlement force of snow cover. Seppyo, Japanese Society of Snow and Ice, Vol. 5, No.11, 357-368.

2) Furukawa, I. (1953) : Study on snow settlement force. Researches on Snow and Ice, Japanese Society of Snow and Ice, No.1, 155-166.

3) Hirata, T. (1941) : Settlement of snow and bending of horizontal bar buried in snowpack. Seppyo, Japanese Society of Snow and Ice, Vol.13, No.5, 225-236.

4) Kobayashi, K., Onuma, T. and Takahashi, K. (1976) : Studies on the snow damage of fruit-trees caused by settling force. Bulletin of the Hokuriku National Agricultural Experiment Station, No19, 179-207.

5) Kojima, K. (1955) : Viscous Compression of Natural Snow layers I. Low Temperature Science, Ser. A-14, 77-79.

6) Kojima, K. (1956) : Viscous Compression of Natural Snow layers II. Low Temperature Science, Ser. A-15, 117-136.

7) Kojima, K. (1957) : Viscous Compression of Natural Snow layers III. Low Temperature Science, Ser. A-16, 167-196.

8) Kojima, K. (1974) : A field experiment on the rate of densification of natural snow layers under low stress. Proceedings of the Grindelwald Symposium. IAHS-AISH Publ. No.114, 298-308.

9) Lang, T. E. and Nakamura, T. (1984) : Finite element computer analysis of snow settlement. Research Notes of the National Research Center for Disaster Prevention, No.59. 139-187.

10) Lang, T. E., Nakamura, H. and Abe, O. (1985) : Settlement force on a beam in snowpack by computer modeling. Annals of Glaciology, No.6, 95-99.

11) Osada, T., Mikazuki, S. and Kobayashi, T. (1975) : Snow pressure acting upon a fixed beam under the snow by total of daily new snowfall depth. Research Notes of the National Research Center for Disaster Prevention, No.13, 1-13.

12) Oura, H. (1955) : A Rheological Consideration about the Increase of the settling Force of snow. Seppyo, Japanese Society of Snow and Ice, Vol.17, No.1 13-18.

13) Oura, H. (1957-a) : On the fracture of the eaves by the settling force of snow. Low Temperature Science, Ser. A-16, 249-250.

14) Oura, H. (1957-b) : On the force with which a beam supports the ceiling of a snow cave. Low Temperature Science, Ser. A-16, 55-71.

15) Oura, H. (1958) : On the deformation of a snow cave. Low Temperature Science. Ser. A-17, 65-79.

16) Oura, H. (1959) : On the deformation of a snow cave II. Low Temperature Science. Ser. A-18, 47-58.

17) Saito, H., Ikarashi, T., Shimizu, M. and Kenmotsu, K. (1971) : profile Observation of Snow Cover in Irihirose-mura, Niigata-ken. Seppyo, Japanese Society of Snow and Ice, Vol.11, No.2, 76-86.

18) Shidei, T. and Takahashi, K. (1949) : Settlement force of snow cover. Seppyo, Japanese Society of Snow and Ice, Vol.11, No.2, 76-86.

19) Shinojima, K. (1962) : Study on the visco-elastic deformation of deposited snow. Railway Technical Research Report, Railway Technical Research Institute, No.328, 1-56.

20) Shinojima, K. (1967) : Measurements of the Compressive, Tensile and the Torsional Deformations of Columnar Snow Samples under Uniaxial and Constant Load. Quarterly Report, Railway Technical Research Institute, Vol.4, No.4, 8-14.

21) Shoda, M. (1953) : Studies on settling force of deposited snow. Researches on Snow and Ice, Japanese Society of Snow and Ice, No.1, 136-154.

22) Yoshida, J. (1954) : A theoretical study on subsidence force of snow. Low Temperature Science, Ser. A-12, 25-35.

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積雪の沈降力の発生機構に関する研究(和文要旨)

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要　旨

積雪が流動するという観点から，積雪の沈降力の解析を行った。

このため，水平桁の周りでの雪の振舞いおよび積雪の沈降力の測定を行うとともに，有限要素法を積雪の沈降現象へ適用して，積雪の沈降力や沈降量の推定を行った。

まず，積雪の動きを知るために，2線式の沈降計および積雪層切断検知器を考察した。これらを自然積雪中にセットし，雪の動きを測定した結果，積雪が桁の周りをゆるやかに円弧を描きながら沈降する事などの知見を得た。また，沈降計を用いて，従来測定データが極めて少なかった低密度の雪の圧縮粘性係数の測定を行った。このデータは後述の有限要素法を用いて行うシミュレーションには欠く事のできないものである。

次に，高さ80cmの水平桁を用いて積雪の沈降力の実測を行った。用いた桁はその頂部の形状がそれぞれ四角形，三角形(頂角60°)および三角形(頂角37°)をした3種類の桁である。

深さが4mまでの雪について行った測定から，最大積雪深さと最大沈降力との関係を求めると次のようになった。

四角桁　　　：$F_{Rmax}=4.20(S_{max}-0.8)^{1.43}$　　kN/m
三角桁(37°)：$F_{T37max}=2.93(S_{max}-0.8)^{0.73}$　　kN/m

ここでF_{Rmax}，F_{T37max}はそれぞれ最大沈降力，S_{max}は最大積雪深(m)である。

一般に積雪量が増加すると沈降力も増加するが，融雪期には積雪量が増加しなくても沈降力が増える事がある事を見出し，その原因が積雪表面の硬化によるものと結論づけた。

最後に，桁のまわりの雪の流動現象に対し，有限要素法を適用し，積雪の沈降力および沈降量を計算のみで求める試みを行った。

水平桁を組込んだ2m×0.6m×0.85mの箱の中に雪を入れ，その沈降力および沈降量を有限要素法を用いてシミュレーションし，その計算結果と実測値とを比較した。その結果，沈降力に関しては最大40%の誤差が生じたが，沈降量については1cmの精度で一致した。

有限要素法を用いたシミュレーションを通して，沈降力の発生機構として，①桁上の積雪の重量，②桁の側方からの剪断力の伝達，③桁の下方の雪の弱化および④桁頂部での圧密層の形成，の4つの機構がある事が判明した。