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STUDY ON ESTIMATING THE SETTLEMENT FORCE OF SNOW COVER LOAD ON NET FENCES

STUDIJA O PROCENI SILE SLEGANJA OD OPTEREĆENJA SNEŽNOG POKRIVAČA NA MREŽASTIM OGRADAMA

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Keywords
- settlement force
- net fence
- strain gauge
- snowmelt season
- heavy snowfall

Abstract

The paper describes a field study concerning the interaction of snow with different types of net fences to understand their durability in various snowy environments. The observation site is selected at Oshirokawa, Uonuma City, Niigata Prefecture which is a heavy snowfall area where maximum snow depth exceeds 3 m annually. The height of the net fence is 2.0 m with strain gauges installed on the upper rail of the frame to estimate the maximal deflection during the observation period which ran from December 2022 to March 2023. It was found that in comparison to the circular wire net, the flat wire net is less affected from the settlement force of the snow cover due to its larger cross-link surface area, making it more rigid. Furthermore, the settlement force induced by the snow cover on the net is estimated from strain data obtained from the top frame. The evolution of the settlement force is also calculated as a function of measured snow depth. The settlement force acts on the netting and occurs initially around the top of the net fence frame. Over time, the force moves toward the bottom reaching a depth around 50 cm above ground in the latter half of the snowmelt season. Observations at different periods are ongoing for future studies on understanding the settlement force of snowfall on the fence frame affected by differences in the shape of the net.

Ključne reči
- sila sleganja
- mrežasta ograda
- merna traka
- sezona otapanja snega
- jake snežne padavine

Izvod

U radu je opisano terensko istraživanje interakcije snega sa različitim tipovima mrežastih ograda kako bi se razumela njihova trajnost u različitim snežnim okruženjima. Odabrano mesto za posmatranje je Oširokava, Uonuma Siti, Niigata Prefektura, područje sa velikim snežnim padavinama gde maksimalna visina snega prelazi 3 m godišnje. Visina mrežaste ograde je 2,0 metra, sa mernim trakama, postavljenim na gornjoj šini rama, za procenu maksimalnog ugiba tokom perioda posmatranja, koji je trajao od decembra 2022. do marta 2023. godine. U poređenju sa kružnom žičanom mrežom, utvrđeno je da je na ravnu žičanu mreža manje uticala sila sleganja snežnog pokrivača zbog svoje veće umrežene površine, što je čini krućom. Osim toga, sila sleganja usled snežnog pokrivača na mreži je procenjena iz podataka o deformacijama dobijenih sa gornjeg rama. Razvoj sile sleganja se takođe sračunava kao funkcija izmerene dubine snega. Sila sleganja deluje na mrežu i javlja se u početku oko vrha rama mrežne ograde. Vremenom, sila se pomera prema dnu i dostiže položaj oko 50 cm iznad tla u drugoj polovini sezone topljenja snega. U toku su posmatranja u različitim periodima za buduća istraživanja sila sleganja snežnih padavina na ram ograde s obzirom na različite oblike mreža.

INTRODUCTION

Snow cover and its mechanical effects pose significant challenges to infrastructure in snow-prone regions, particularly in high-altitude and high-wind environments. Among the structures impacted by snow, net fences play a critical role in snow management, avalanche control, and boundary protection. However, the interaction between snow settling forces and net fences remains an area of limited understanding, requiring both experimental and theoretical investigation. In particular, on the Pacific and Japan Sea coasts of Japan, the durability of facilities is thought to differ due to differences in the natural environment when the same net fences are installed. Therefore, it is necessary to change the specifications to adjust to the local area, but there have been no clear standards. In addition, there are also large regional differences such as on the Japan Sea coast, where the snow quality, wind direction, among others, differ from the northern regions such as Hokkaido and the southern regions of Fukui, Niigata and the Chugoku region. Thus, the required performance also differs.

Previous research has provided valuable insights into various aspects of snow interaction with structures. For instance, studies such as Carleton University's investigation into snow fencing in Yukon, Canada, highlight the influence of snow fences on snow distribution and ground insulation /1/. Similarly, snow fences have been shown to mitigate snow cover in railway cuttings by optimising snow redistribution under drifting conditions /2/. These findings underline the importance of fence design in managing snow cover and ensuring structural resilience. The behaviour of snow under settlement forces is a critical area of study for understanding its impact on structures and materials embedded in snow cover environments. Settlement forces on horizontal beams in fences are first quantified by Nakamura and Abe /3/, who demonstrated that these forces vary with snow depth and beam cross-sectional shape, particularly in deeper snow. Expanding on this, Lang et al. /4/ use computational modelling to identify the mechanisms driving settlement forces, including snow weight, shear transfer, and densification, emphasizing the complexity of snowpack interactions. The influence of snow texture on settlement rates is further examined by Fierz and Lehning /5/, who highlight the role of snow grain structure and temperature in determining settlement dynamics. Steinkogler et al. /6/ systematically assess the settlement of newly deposited snow, emphasizing the importance of snow grain bonding and temperature in the initial hours and days after snowfall. Lastly, Mahajan /7/ applies microstructural modelling to predict short-term settlement of footings on snow foundations, incorporating effects such as bond deformation and transient creep. Based on these basic studies, the objective of this study is to experimentally analyse the deformation behaviour of net fences subjected to the settlement force of snow and to develop a method for estimating the settlement force from existing meteorological observation data.

In this paper, we discuss the results of observations and monitoring of snow cover on a net fence with strain gauges attached to the fence frame, and the following points are discussed as to whether:
- the environment in which the net fence is subjected to the settlement force of snow cover changes depending on the shape of the net section used in the net fence, and
- if the settlement force estimated from the snow depth can be used as valid analysis data, by calculating the vertical deflection of the fence frame from the time history data of the strain gauges and the snow depth?

MEASUREMENT CONDITION

Observation location

The observation site for this research is Oshirokawa, Uonuma City, Niigata Prefecture whose location is shown in Fig. 1. Four types of net fence with different shapes are prepared for the snow accretion observation.

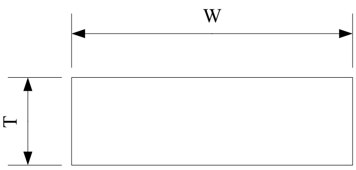
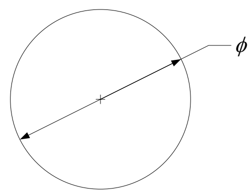
Objective structure condition

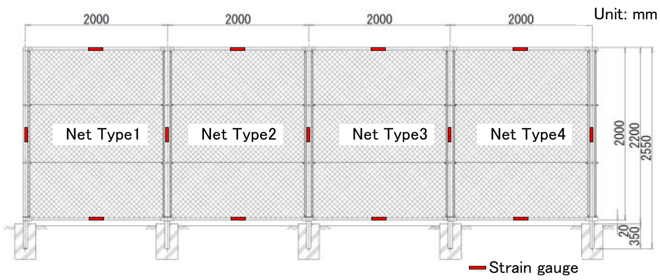
Table 1 gives a list detailing the specifications of the nets. In this study, two types of cross-sectional diameter are prepared such as the standard net with circular cross-section and the special net with a rectangular cross-section. Flat wires with a rectangular cross-section are made by pressing circular section wires, hence the diameter before pressing is shown in Table 1. In the current measurement, in order to simply evaluate the settlement force of snow cover that acts on the net and fence frame, we used a standard rigid frame of a net fence frame commonly used for cold climate regions. Figure 2 shows a schematic diagram of the net fence. The average maximum snow depth in the observation area is generally more than 3 m. In this field observation, the height of the net fence is set at 2.2 m to ensure that it is buried sufficiently deep by snow cover during the snowmelt season. The observation period is set from November 2022 to April 2023.

Created by editing the digital topographic map 25000 of Geospatial Information Authority of Japan

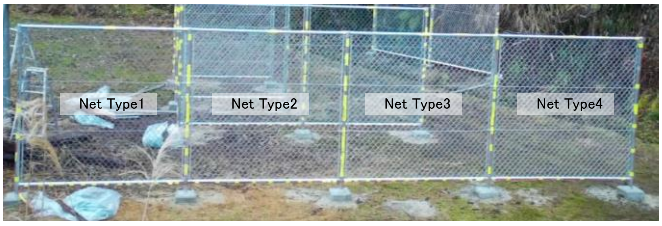
Figure 1. Observation location for this research.

Table 1. List detailing the nets specifications.

	Type 1	Type 2	Type 3	Type 4
	Rectangular		Circular	
Cross-section shape				
Cross-section diameter (mm)	T = 1.4 W = 4.5 Original diameter was ϕ 3.2	T = 1.8 W = 5.5 Original diameter was ϕ 4.0	ϕ 3.2	ϕ 4.0



Dimensions and layout of net fences



Situation of installed net fences

Figure 2. Schematic diagram of the net fence.

OBSERVATION RESULTS

Meteorological observation data

In this study, meteorological data is obtained from the Japan Meteorological Agency. The data obtained is for the Sumon area, which is closest to the observation site. In addition, we have installed a trail camera at the observation site that records local conditions every 30 minutes. Therefore, we monitored the snow depth and snow accumulation on the net fence from these images. Figure 3 shows the change in snow depth and the change in daily average temperature during the observation period. The variation in snow depth determined from the images of the observation site are almost the same as the data from the Japan Meteorological Agency. Therefore, it can be assumed that the temperature data from the observation site is also almost the same as the data from the Japan Meteorological Agency. Snowfall began in mid December 2022 with intermittent snowing and melting continuing until mid February 2023. Note that the temperature data collected on the site is not usable. After that, the depth of snow gradually decreased until March 2023, and the snowmelt season began in earnest from March to April 2023. In addition, negative temperatures were no longer observed from early March, and it is thought that the snowmelt season began at this time.

Status of snow accretion on the net fence

We compared the snow accumulation on the net fences. We monitored the status of snow accretion every two hours from 7:00 to 15:00 on December 6, 2022, when the depth of snow increased at the beginning of the snow season. Figure 4 shows the status of snow accretion. From the photos, we find that there was no noticeable difference in snow accretion depending on the type of net fence. Therefore, this suggests that the net fences are not affected by the snow load during the snowy season.

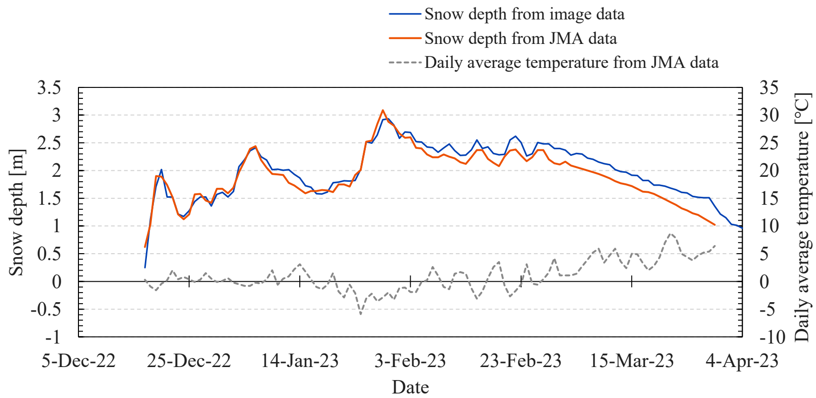


Figure 3. Meteorological data for the observation location.

The vertical deflection of the net fence frame

Furthermore, we compare the final vertical displacement of net fence frames measured after the snowmelt season. The vertical displacement of the posts was very small and could not be confirmed visually, and the lower frame had a vertical deflection of a few millimetres in the central span. The top frame had a vertical deflection of a few to a dozen centimetres. Table 2 shows vertical deflection of the central span on the top frame for each type of net. The amount of vertical deflection is not the same for each type. In addition, there is less vertical deflection in fences with flat wire than in those with circular wire. Furthermore, we can see that the vertical deflection increases in fences with circular wire and flat wire with smaller diameters or smaller cross-sectional areas. Therefore, this suggests that the settlement force of snow acting on the net fence is caused by differences in the shape of the net.

Table 2. Vertical deflection of central span on the top frame.

Type	1	2	3	4
Deflection (cm)	3.0	1.5	11.0	9.0

The net fence used in this experiment is made of a chain-link type of wire mesh. Figure 5 shows a close-up view of the woven wire mesh. If we assume that external forces acting on the net are converted into axial forces which are transmitted to the net and then act on the fence frame, the amount of the vertical displacement of the centre of the top frame is proportional to the total strain energy of the net part. Thus, it is expected that the elastic modulus and cross-sectional area of netting members will have a larger effect on the vertical deflection at the target position. The elastic modulus of net members used in this measurement is constant because these members are made of the same material, and the only parameter that differs is the cross-sectional area. In the case of flat wire, the cross-sectional areas are 6.3 mm^2 for Type 1 and 9.9 mm^2 for Type 2.

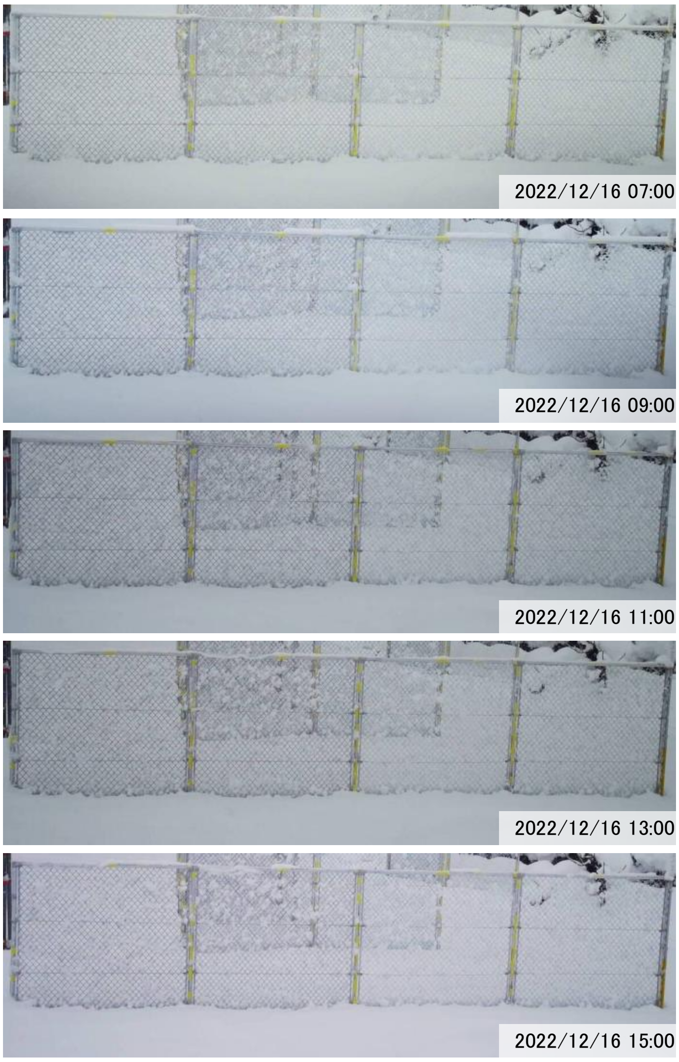


Figure 4. Status of snow accretion on the net fences.

However, the vertical deflection of Type 1, with a smaller cross-sectional area, is larger. In the case of using circular wires, the cross-sectional area of Type 3 is 8.04 mm^2 and Type 4 is 12.57 mm^2, and the vertical deflection of Type 3, with a smaller cross-sectional area, is larger. On the other hand, if we compare Type 1 flat wires with Type 3 circular wires, the vertical deflection of Type 1 flat wires is larger than that of Type 3 circular wires, even though the cross-sectional area of Type 1 flat wires is smaller than that of Type 3 circular wires. For this reason, it can be assumed that the effect of the settlement force applied as an external force will change depending on the cross-sectional shape of the wire mesh.

It can be seen from Fig. 5 that the contact area between the flat and circular wires touching the joint is different. In the case of flat wires, the wires overlap and touch each other on a surface, whereas in the case of circular wires, the wires overlap and touch each other on a line. Therefore, the friction at the joint of circular wires is smaller than that of flat wires. Furthermore, if the diameter of the circular wire is small, the contact area becomes narrower. In other words, it can be estimated that circular wires have less rigidity at the joint, whereas flat wires have high rigidity. Therefore, it can be thought that the vertical deflection of the top of the fence frame is smaller with flat wires than with circular wires.

a)
b)

Figure 5. Close-up view of woven wire mesh: a) circular; b) flat.

ESTIMATION OF SETTLEMENT FORCE ACTING ON TOP FRAME

Estimating settlement force from frame strain data

In this section, we estimate the settlement force that acts on the net fence. We perform an analysis to estimate the vertical deflection of the top frame from strain data. The frame and net are coupled together. As such, we can obtain the settlement force of snow cover that affects the fence frame by calculating the vertical deflection from strain data which can then be used to back-calculate the load acting on the fence frame. At the beginning, Fig. 6 shows the time history of strain data obtained from the central span at the top of each fence frame. In this observation, the Type 1, Type 2 and Type 4 measurements are not obtained due to wire breakage in the early stages of the observation while only Type 3 data is obtained. The strain data obtained shows a rapid increase after the start of the snow season in early February 2023, followed by a repeated increase and decrease in line with the repeated snowfall and melting, then a rapid increase in strain is seen again when the snow stops falling and the temperature rises. As the variation in strain data is linked to the variation in snow depth, the former can be used as data to estimate the settlement force of the snow. Then, we

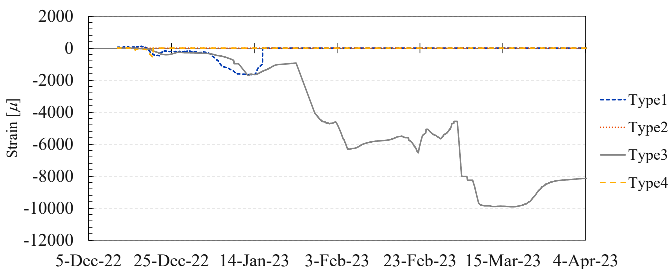


Figure 6. Time history of strain data obtained from the central span at the top of each fence frame.

estimate the vertical deflection of the central span at the top of the frame from the strain data. For the calculation of vertical deflection, we assume that the superimposed load acting on the fence frame is a distributed load. In addition, the fence frame used in this measurement has a structure in which the cross members and posts are rigidly connected.

Therefore, we assume that boundary conditions of the frame are fixed at both ends. Considering the frame as a beam fixed at both ends under uniformly distributed load, the vertical deflection of the central span on the fence frame is obtained from the following classic solution:

$$\delta_d = \frac{wL^4}{384EI}, \quad (1)$$

where: δ_d is vertical deflection at the centre of the span of the fence frame; w is distributed load; EI is bending rigidity of fence frame; L is span length; and ε is bending strain obtained at the centre of span. On the other hand, the distributed load acting on the fence frame can be back-calculated from the relationship between bending stress and moment, i.e.,

$$w = \frac{48EI}{L^2 D}\varepsilon, \quad (2)$$

where: D is cross-sectional diameter of fence frame. When Eq.(2) is substituted into Eq.(1), the vertical deflection can be rearranged as follows:

$$\delta_d = \frac{wL^4}{384EI} = \frac{L^2}{8D}\varepsilon. \quad (3)$$

As a result, the parameters required to calculate vertical deflection are span length, the diameter of fence frame, and bending strain at the centre of span length. The span length is set to 2.0 m, and the fence frame diameter to 38.1 mm. The results of vertical deflection calculated using the strain data obtained from the measurements are shown in Fig. 7.

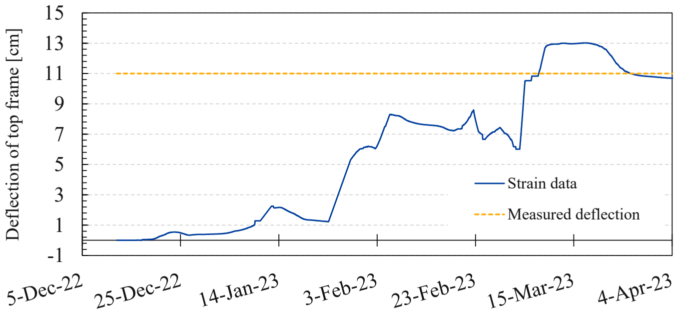


Figure 7. Vertical deflection calculated using strain data.

Figure 7 also shows the vertical deflection value measured in May 2023 for the central span at the top of the fence frame. Vertical deflection changes estimated from strain data show that vertical deflection fluctuates in conjunction with increases and decreases in snow depth. Moreover, it can be seen that the observed and estimated vertical deflections are almost the same in the latter half of the snowmelt season. For this reason, it is thought that the time history of vertical deflection can be correctly estimated from strain data.

Estimating settlement force from snow depth data

The time history of the vertical deflection obtained from strain data is the result of measurements taken by installing strain gauges on the fence frame. On the other hand, if the vertical deflection can be indirectly obtained from the snow depth, it will be possible to estimate the settlement force of snow from meteorological observation data for many cases. In this section, we estimate the settlement force acting on the fence frame from the time history of the snow depth. As a method for estimating snow depth, we use the settlement force estimation equations for protective fences proposed by Nakamata, /8/, i.e.,

$$F_s = AW_s, \quad (4)$$

where: A is area affected by the settlement force acting on the target structure; and W_s is the weight of snow cover that acts as the settlement force. The snow cover load is calculated by

$$W_s = \rho_s \rho H_s, \quad (5)$$

where: ρ_s is density of snow layer; and H_s is height of snow layer used to calculate the weight of the snow cover. Figure 8 shows the area affected by the settlement force acting on the structure. In this study, L is the span length of the net fence, and D is the diameter of the net fence frame. In addition, the value of R, which is closely related to the influence area of snow cover around the top frame, is determined by observing the cross-section of the snow cover net fence.

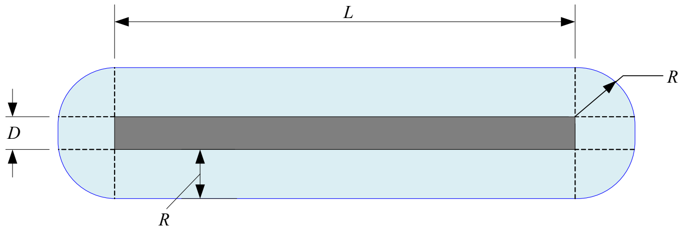


Figure 8. The area affected by the settlement force.

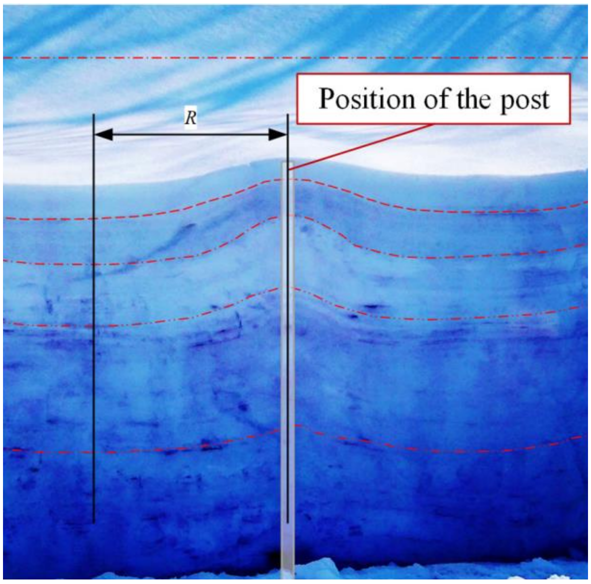


Figure 9. The area affected by the settlement force.

Figure 9 shows the observed cross-section of the snow cover. The cross-section observed in this study is created on January 23, 2023. It can be seen that layers curve around the fence frame. It is known that such curved layers affect the friction caused by the force of snow settling on the structure, and when determining the load of the settlement force /3, 4, 9/ the calculation is carried out within the area of these curved layers. The area is the influence area A of snow, and the value of R can also be obtained from there. The R value obtained in this observation is about 100 cm. From the above, the area of influence A can be obtained using the following equation:

$$A = \pi R^2 + 2R(D+1) + DL \cdot \tag{6}$$

Furthermore, it is necessary to determine the density of snow layers. In this study, the change in density of each snow layer is not observed. Therefore, it is necessary to estimate the change in density of each layer over time. The density within the snow cover increases over time due to its own weight, and it also increases due to the weight of additional snowfall. There are many models used to predict the time-dependent changes in the density of snow layers, including compression models and linear elasticity models, and there are also more complicated models that consider the effects of outside air temperature /10-14/. One method that is relatively easy uses an exponential model /11/. In this measurement, during the snowfall season before the snowmelt season, the outside air temperature is mostly below 0 degrees. Therefore, we estimate the density distribution within the snow layer using a simple exponential model which assumes that the density is not affected by the outside temperature during the snow melting season. The density estimation formula used in this study is as follows:

$$\rho(t) = \rho_0 + (\rho_i - \rho_0)(1 - e^{-k \cdot t}), \tag{7}$$

where: $\rho(t)$ is snow density at time t; ρ_0 is initial snow density; ρ_i is density of ice, which is generally 917 kg/m^3; k is the consolidation velocity constant, and t is time. The initial snow density is set to 90 kg/m^3, because the density of new snow that falls on the observation area is generally around this value. The consolidation velocity constant is an unknown parameter. In this study, the parameter that produces the most accurate result for the time history of snow depth obtained from the measurements is adopted. Figure 10 shows results of plotting the measured snow depth and estimated snow depth from the density within the snow cover. The figures show results for the consolidation velocity constants of 0.01, 0.005, and 0.001. From the results, it can be seen that the condition which accurately reproduces the measured snow depth is the case where the consolidation velocity constant is 0.005. Therefore, this study adopts a consolidation velocity constant of 0.005.

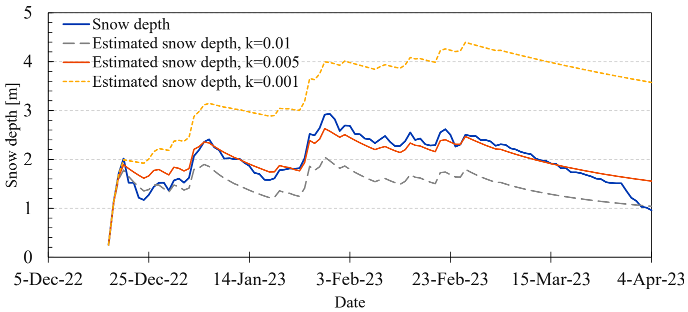


Figure 10. The relationship between the snow layer thickness used for calculating the superimposed load

Nakamata's formula calculates the superimposed load from the height at which the settlement force acts to the snow surface. Therefore, it is necessary to determine in advance the height at which the settlement force acts. Figure 11 shows the height of the snow layer used in the calculation of the settlement force acting on the net fence. Nakamata's equation sets the height of h_1 in the figure as the snow layer that affects the net fence frame. However, it is thought that the settlement force of snow cover also affects the netting of the net fence. In this study, the height h_2 in the figure is set as the weight of snow cover that acts on the net fence. In addition, it is not known at what height the settlement force acts. Therefore, this study calculates three cases where the height h_3 from the ground surface to the netting is 50 cm, 100 cm, and 150 cm. After that, we applied the obtained superimposed load to the top of the fence frame and calculated the vertical deflection at the centre of the fence frame. Furthermore, the load conditions for calculating the vertical deflection are set to be the same as when estimating the vertical deflection from strain data, i.e., distributed load, and the boundary conditions are set to be fixed at both ends.

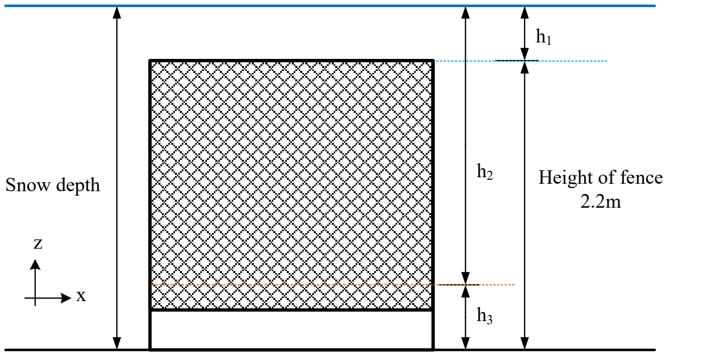


Figure 11. The relationship between the snow layer thickness used for calculating the superimposed load

Figure 12 shows the time history of the vertical deflection calculated from snow depth. In addition, there are also final values of vertical deflection estimated from strain data and measured vertical deflection shown in the figure. From a comparison with the results of vertical deflection obtained from strain data, there are points where vertical deflection values obtained for each of the h_3 values set in this study are close to each other. From the beginning of the snowfall to late January 2023, the results are similar to those for h_3 = 150 cm, and then until early March 2023, h_3 = 100 cm is close, and after that, the values fluctuate in a similar way to the vertical deflection for h_3 = 50 cm. From these results, it can be thought that in the early stages of snowfall, the settlement force acts on the net section around the top of the fence frame, and then the position of the force gradually moves towards the bottom, and the height of the snow weight affected by the settlement force increases up to around 50 cm from the ground surface.

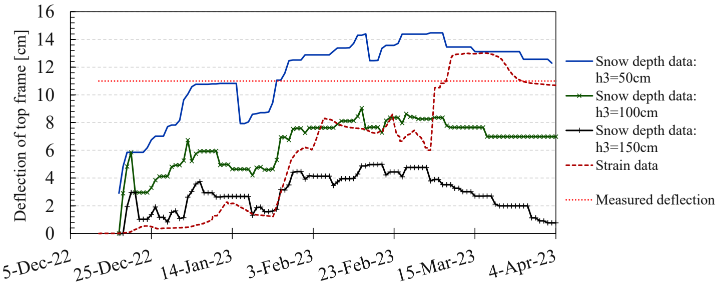


Figure 12. Time history of vertical deflection that is estimated using distributed load.

CONCLUSION

In this study, we conduct field measurements with the objective of evaluating mechanical effects of the settlement force of snow cover on net fences. In the measurements, we focus on the vertical deflection that occurs at the top of the net fence frame and confirm the effect of the settlement force of snow acting on the net fence. As a result, it is found that the flat wire used in the netting of the net fence is less affected by the settlement force of snow cover when compared to the circular wire. In this measurement, the netting part of the net fence is made using a mesh with cross-links. In this case, the area where the nets touch each other at the mesh joints changes depending on the shape of the cross-section. Therefore, it is thought that the flat wire has a larger cross-linked area, hence more rigid and less affected by the settlement force. In addition, the vertical deflection of the top frame is calculated using strain data obtained from the top frame of the net fence, and the settlement force acting on the net fence is estimated. Also, the settlement force is calculated from snow depth data, and the degree and state of the load affecting the net fence frame are considered. As a result, it is found that the settlement force of snow acts on the netting of the net fence, and that the height at which this occurs is initially around the top of the net fence frame. After that, the force moves towards the bottom over time, and it is found that it reaches around a depth of 50 cm above the ground surface in the latter half of the snowmelt season.

However, in this measurement it is not possible to successfully obtain strain data for cases where the shape of the netting is different. In this study, we only consider the results of calculations for the case of using a circular wire mesh, and it is possible that different results would have been obtained for a flat wire mesh. In the future, we shall continue to make observations and conduct studies using data obtained in different periods, and we shall try to understand how the settlement force of snowfall on the fence frame is affected by differences in the shape of the net.

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