Reply to RC2

General comments

I appreciate very much for the efforts to observe the particle motion carefully in the wind tunnel and investigate the growing mechanism of the thin snow plate which extends to leeward from the edge. However, according to my observations in the fields and the wind tunnel experiments, it is extremely fragile and always breaks down after **growing several centimeters long at the maximum.**

Respond: Thank you very much for your time and valuable comments. The cornice growth on the mountain ridge and causes snow avalanches has been observed by Eckerstorfer et al. (2013b), Vogel et al. (2012), and Hancock et al. (2020). From the previous observation results, cornice growth experiences multiple times of collapses and extends. At each time of growth, it may break down after a few centimeters of growth. This phenomenon is also observed in our experiment. Due to the limited field observation, it is tough to observe the particle moving around a real cornice on the mountain ridge. However, understanding the mechanism of snow cornice formation is still essential for avalanche prediction and simulation. Therefore, we carried out a wind tunnel experiment to observe the particle movement surrounding a small cornice we produced, for no matter in the field or in the wind tunnel, the particle moving and sticking laws are the same.

It never grows to the much larger one, such as, we find on the crest of a ridge along a mountain slope and occasionally causes the avalanche release.

Reply: Thanks for pointing this out. This is due to the involved dimensions and timescales which are way smaller/shorter in the ring wind tunnel. However, the size of crest of a ridge is a long-term result by multiple growth events, not in one precipitation event. In our experiments, the cornice can grow to more than 10 cm, which is almost the size of the base.

The authors need to make clear at the outset that the authors are looking at completely different phenomena. Even though it is allowed to say this miniature as "cornice" as well in a broad sense, the following numerous points should be taken into consideration before the publication.

Reply: Thanks for your suggestions. Although there are differences to real natural conditions, we are looking at snow particles that are transported by wind across a ridge while a fraction of the particles deposit on the lee edge resulting in horizontal and vertical snow slab (cornice) growth. As we mentioned above, no matter in the field or in the wind tunnel, the particle moving and sticking law are the same.

In all, we will revise the manuscript according to your suggestions. The following are the point-to-point responses:

Specific comments

Line 14: After "and snow cornice", Seligman et al. (1936) should be put as the reference.

Reply: We agree with this and will add it in the revised manuscript.

Line 29: "mechanical mechanism" sounds redundant and unnatural, although grammatically correct. I suppose only "mechanism" is fine.

Reply: Here, we emphasize the mechanism of the mechanics by carrying out the static force analysis on the single particle which deposits on the edge of a cornice. Therefore, we used "mechanical mechanism".

Line 53 to 54: 4 m/s is the wind speed at the center of wind tunnel? If the authors would like to analyze the experimental output physically, the friction velocity u_* should be used in the manuscript instead. Furthermore, the threshold wind speed needs to be specified.

Reply: Thanks for your suggestions. The thickness of the boundary layer in this ring wind tunnel is very thin (~2 cm), and the wind speed inside the wind tunnel can be considered as uniformly distributed on the cross-section. Therefore, we used the center wind speed instead of friction velocity in the manuscript. We will mention this in Section 2 of the revised manuscript: "The wind speed inside the wind tunnel is nearly uniform with a very thin (~2 cm) boundary layer.".

Figure 1: 0.125 m on the side view corresponds to the height of snow on the floor?

Reply: Thank you for pointing this out. This value represents the height of the ridge model made of snow. The height was measured from the lower floor. We added description in line 56: "A ridge model with a fixed size (height 0.125 m, total length 0.4 m, flat surface length 0.1 m) is built with compacted snow before each experiment, and its side view is shown in Fig. 1."

Line 118: "190 collision particles": Are these particles with the snow surface? Such careful explanations are lacking overall. Please check the manuscript again by standing at the place of the readers.

Reply: Thank you for pointing this out. These 190 collision particles are moving particles in the air, and they also interact with the surface. This sentence will be revised to: "By maintaining the wind speed in the experiment at a constant (4 m/s), the study analyzed 190 collision particles as they interacted with the snow surface, including particles that rebounded, impacted, or deposited on the snow, using an image post-processing method."

Figure 4 (b): Although it is described that the size of points shows the particle diameter, no explanation are found in the figure caption. Further, the corresponding specific size should be added as well.

Reply: Thank you for pointing it out. We have re-plotted this figure and used color variation to represent the size difference. The explanation are added in the figure caption: "Impact velocity and impact angle of different sizes (deeper color represents for larger size) of snow particles on edge (in blue points) and surface (in red points)."

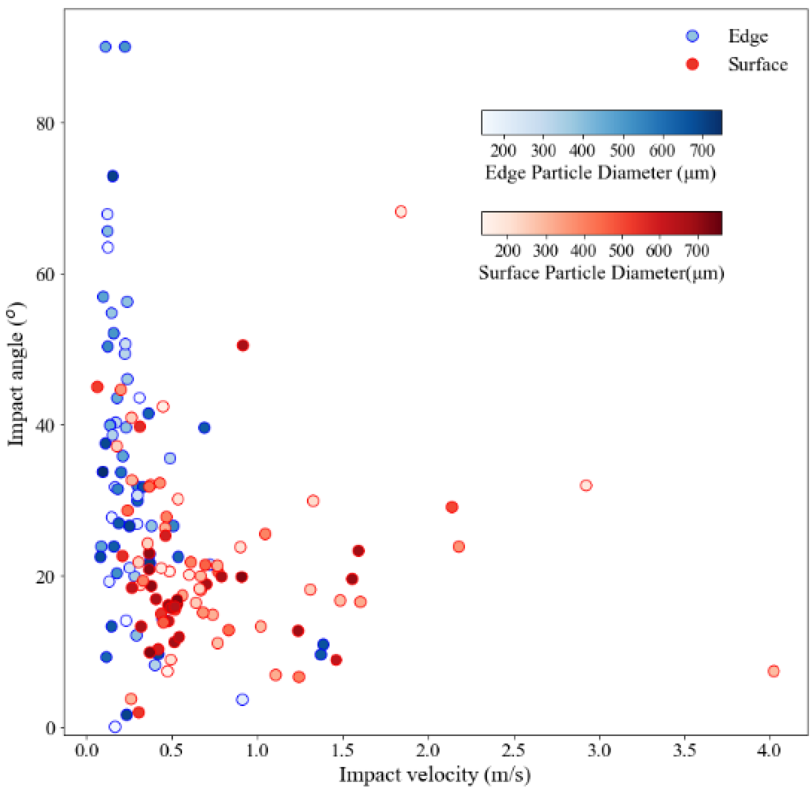

Fig. 4(b) Impact velocity and impact angle of different sizes (deeper color represents for larger size) of snow particles on edge (in blue points) and surface (in red points).

Line 137: Although Stokes number: *St* is introduced, no explanations about the parameters are shown. Probably, ρp is particle density, *d* is particle diameter, *U* is wind speed, *m* is kinematic viscosity and *L* is the characteristic length scale. Specify each value you used, particularly *L*. It looks the difference of St between the surface and the edge is caused by the particle diameter only. If it is the case, I am wondering it is needed to take the trouble to introduce *St*. As you see, *St* is a dimensionless number that characterizes the behavior of particles suspended in a fluid flow. It represents the ratio of the particle's inertial forces to the viscous forces exerted by the fluid. When *St* is much smaller than one, the particle closely follows the fluid flow, whereas *St* is much larger than one particle's inertia dominates, and it is less affected by the fluid flow, tending to maintain its original trajectory. On the other hand, at $St \approx 1$ the particle behavior lies between these extremes, showing partial coupling with the fluid flow. In this case, both 1.8 and 3.1 are close to one and the difference is quite small; correspond to the third case together. Consequently, I have to say the discussions here are almost meaningless.

Reply: We agree with this and will add a notation for all variables existing in this manuscript. The discussion on the Stokes number will be deleted from the revised manuscript.

NOTATION

Symbol	Definition and units
A	Constant [=3.18×10^{-7}]
A_p	Projected area of one particle [m^2]
D	Diameter of particle [m]
d_e	Particle equivalent diameter [m]

dt	Time interval [s]
E	Electric field [V/m]
v_p	Particle velocity [m s^{-1}]
v_{px}	Particle velocity component in x direction [m s^{-1}]
v_{py}	Particle velocity component in y direction [m s^{-1}]
v_{imv}	Vertical impact velocity of particle [m s^{-1}]
$E_{i/j}$	Yong's modulus of particle *i/j*
F_b	Bond cohesion force [N]
F_c	Cohesion force [N]
F_e	Electricity force [N]
F_f	Maximum static frictional force [N]
F_g	Gravity force [N]
F_s	Supporting force [N]
q_i	Charge on particle [C]
M_x	Torque of elastic/plastic force [Nm]
n	Radius of particle contact surface [m]
$R_{i/j}$	Contact radius of particle i/j [m]
T	Air temperature [°C]
t	Current time [s]
Δt	Time step [s]
Δl	Horizontal growth length [m]
δ	Compression displacement [m]
δ_{max}	Maximum compression displacement on particle [m]
$\dot{\delta}$	Displacement rate [m/s]
θ_p	Particle moving angle [°]
θ_{im}	Particle impact angle [°]
θ	Cornice angle [°]
$\mu_{i/j}$	Poisson's ratios of particle i/j
μ_f	Friction coefficient of ice surface
ρ_p	Particle density [kg/m^3]
σ	Elastic/plastic force per unit length [N]
α	Angle between direction of gravity and cohesion [°]

Figures 5 and 7: Generally, the number of particles you analyzed is extremely small. If the authors would like to induce concrete and statistically significant conclusions, at least more than 300 particles data for edge and surface each should be corrected and examined.

Figure 7: Authors are looking at the impact velocity and the angle separately. I suppose the combination of two factors for the particles on edge and surface reveals interesting findings,

supposing the enough data exists.

Reply: Thanks for your suggestions. We have increased 383 surface particles and 121 edge particles. The p-values of both surface and edge particles are higher than 0.05 (not significant), which represents that the sample number satisfies the analysis results. The updated Figure 5 and Figure 7 are shown below.

In the updated Fig. 5, the size distribution of particles follows the same trend as the previous one, with the same distribution function but different parameters. We will revise lines 134 - 137 to: "For all particles adhering to the cornice surface, their size distribution follows the log-normal distribution function $\theta \sim N(\mu = 5.94, \theta = 0.36)$. For particles adhering at the edge, their size distribution follows the log-normal distribution $\theta \sim N(\mu = 5.76, \theta = 0.43)$. And for particles adhering on the surface, their size distribution follows the log-normal distribution function $\theta \sim N(\mu = 5.74, \theta = 0.47)$."

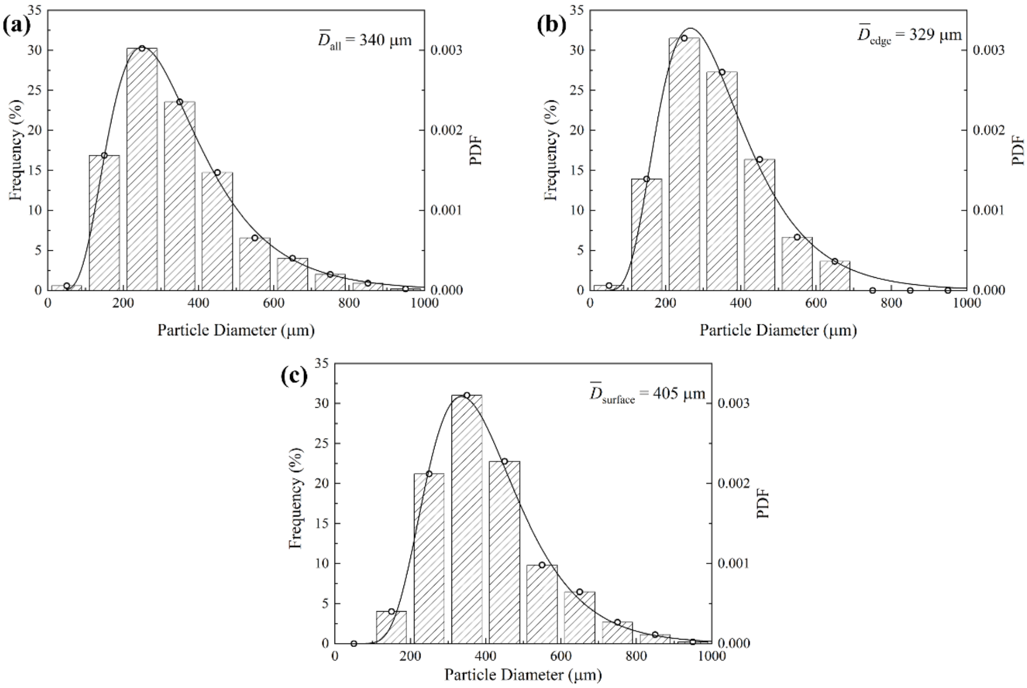

Figure 5. Size distribution of particles at different positions. (a) All particles. (b) Adhesion particles at the edge. (c) Adhesion particles on the surface. The grey shadow represents the existence frequency of particles with different sizes.

In the updated Fig. 7, the impact velocity of edge particles follows the exponential distribution function $y = 4.3 + 30e^{-0.9 v_{imp}}$, with values mainly concentrated at below 1.5 m/s. While the impact velocity of surface particles follows the Gaussian distribution function $y = -2.8 + \frac{79}{3.4\sqrt{\pi/2}} e^{-2((v_{imp}-2.9)/3.4)^2}$, with values mainly concentrated at ~3 m/s. The impact angle of surface particles follows the Exponential distribution function $y = -0.8 + 80.6e^{-0.1 v_{imp}}$, with values mainly concentrated below 17°. While the impact angle of edge particles follows the Gaussian distribution function $y = 7.1 + \frac{448.8}{45.7\sqrt{\pi/2}} e^{-2((v_{imp}-18.1)/45.7)^2}$, with values distributed more uniformly in range. The average value of impact angle of surface particles is 13°, which is consistent with the previous experimental results of Nishimura (2000), as is shown in the red dash in Fig. 7(b).

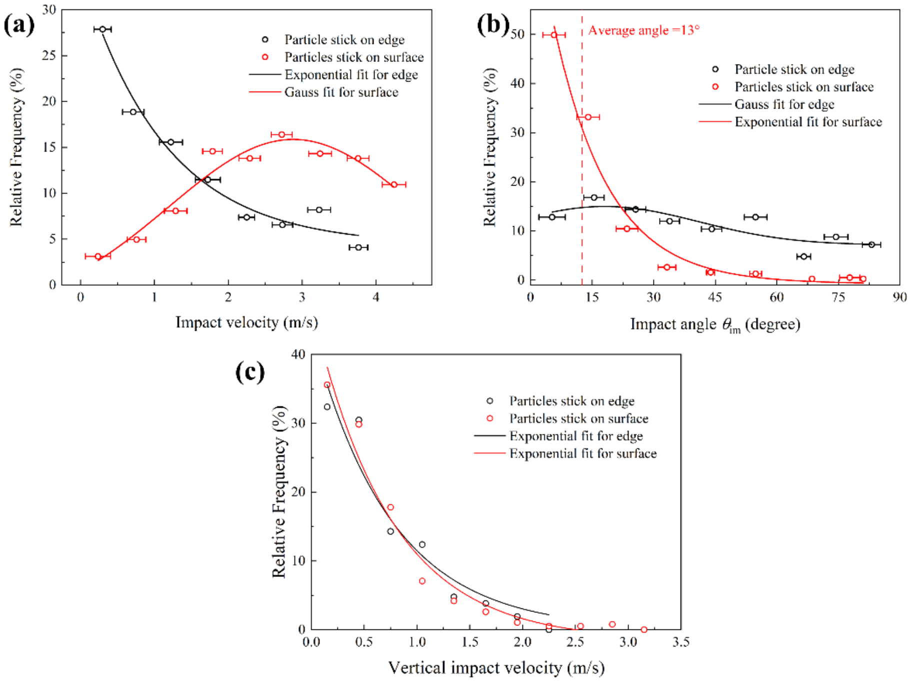

Figure 7. Relative frequencies of (a) PAV, (b) PAA, and (c) vertical impact velocity of particles on edge and surface.

Furthermore, we combined the impact velocity and angle by analyzing the vertical impact velocity ($v_{imv}=v_{im}\sin\theta_{im}$) in Fig. 7 (c). Both surface particles and edge particles follow the exponential distribution, with surface particles $y = 0.5e^{-v_{imp}/0.7}$, and edge particles $y = 0.4e^{-v_{imp}/0.8}$. The relative frequency exponentially decreases with the increasing vertical impact velocity, this is due to the fact that particles with lower vertical impact velocity have relatively lower coefficient of restitution. The vertical impact velocity distributions of surface particles and edge particles are in same trend, although the impact velocity and impact angle distributions of edge particles and surface particles are different. It indicates that particle adhesion to the surface is mainly determined by the vertical velocity, and the differences in impact velocity and angle distributions between surface and edge is due to the topographic changes. It can be inferred from Fig. 7(c) that the threshold vertical impact velocity for surface particles (~3.25 m/s) is higher than that of the edge particles (~2 m/s). This is because cornice edge is a fragile structure, particles with relatively higher impact energy will induce the edge break off.

We will add the above discussion into the revised manuscript.

Further, here, authors set focus on saltating particles only. How do you estimate the contribution of the **creep particles**?

Reply: Thanks for pointing it out. The samples we analyzed also include the creep particles (rolling over the surface). We concluded four adhering patterns of snow particles, and one of them is creep. The creep particles contribute ~13.6% of the particles (using the number ratio) that stick on the cornice, which has been mentioned in lines 147-148.

Figure 8: Please make the figure clearer. Though many parameters are introduced, it is hard to recognize what they mean and indicate, such as, a. In addition, preferably, make the right and left sides reverse to align with Figures 4 and 6.

Reply: Thanks for your suggestions. To address the concerns raised, we will add a variable table to clearly define and explain the parameters as we mentioned above. Moreover, Fig. 8 has been adjusted by reversing the right and left sides to align with the structure of Fig. 4 and 6.

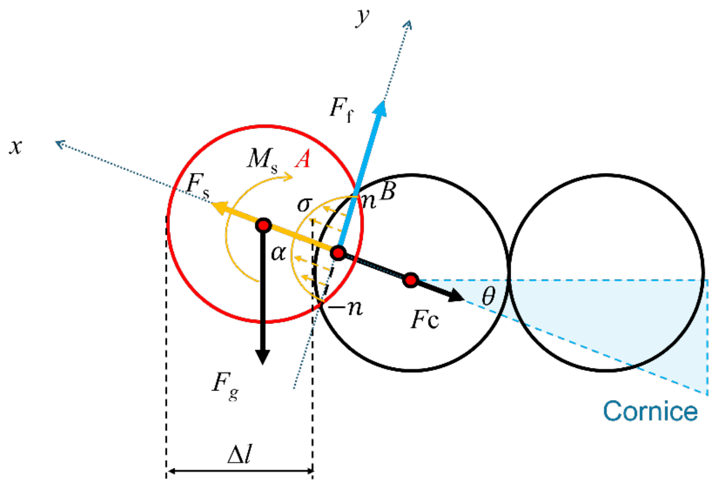

Fig. 8 Schematic diagram of force analysis of particles adhering on the edge

Line 190-191: In fact, the wind speed near the surface is getting smaller. However, you cannot neglect the wind shear stress acting there.

Reply: Thank you for this suggestion. There are two methods of calculating the drag force on a particle. First method calculates the drag force with the relative velocity between the particle and the flow:

$$F_d = 18\pi D^2 C_D (u - u_p)^2$$

where u_p is the particle velocity, u is the air wind speed, C_D is the drag coefficient, and D is the particle diameter.

The second method calculates the drag force with the surface shear stress [N/m^2]:

$$F_d = \tau A$$

where A [m^2] is the wind-affected surface area of a particle.

The shear stress ($\tau = \rho u_*^2$) is small due to the sudden sharp decrease of the friction velocity at the edge (calculated by numerical CFD simulation, not published yet), as is shown in the Fig. S1.

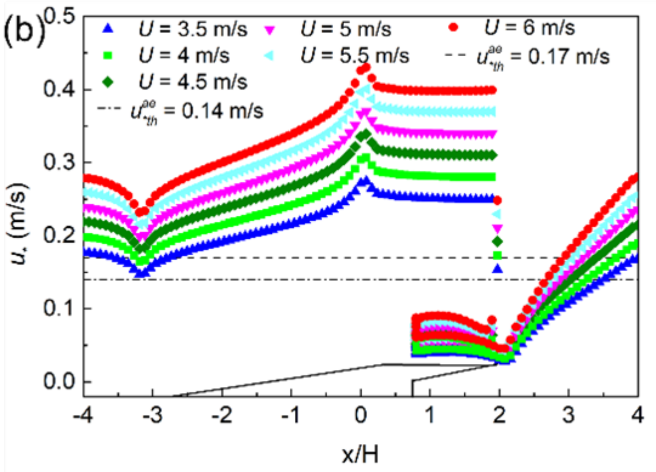

Figure S1. Friction velocity along the snow model in different wind conditions.

The drag force of a snow particle with mean diameter calculated by the second method is about 10^{-10} N according to our simulation results, which is much smaller than the gravity F_g (10^{-8} N). Therefore, the results from these two calculation methods are almost same: The drag force on the particle that sticks on a cornice edge can therefore be ignored when carrying out static force analysis.

Line 191: According to your data, particle speed is quite low (nearly 0.5 m/s), thus, the compression deformation due to the collision is unlikely.

Reply: Based on the previous experimental studies (Wang et al., 2020), there are two kinds of deformation when snow particles contact collision happens: Plastic deformation and brittle failure, which is mainly determined on the loading rate (which refers to the relative moving speed of snow particles here). When the loading rate is relatively low, the snow particles will undergo continuous plastic deformation. During the collision process, the particles will be compressed and deformed, transforming from their original dendritic shape into irregular polygonal structures. When the loading rate is relatively high, it will lead particle sudden fracture and brittle failure. For particle speed with moving speed of 0.5 m/s, the particle will undergo continuous plastic deformation.

For clarity, we will add the sentences before introducing the maximum compression displacement of particle in Section 3.2: "During contact collision, snow particles will be compressed and deformed, which will undergo plastic deformation and brittle failure (Wang et al., 2020)".

Line 216: Authors say that the sintering time is much longer than the collision time in the manuscript at lines 26-27 and exclude the mechanism to create the wedged-shaped form. I do not understand why it appeared again. It looks contradictory statements. Furthermore, the static electric forces have been observed in the specific cases so far, and not always.

Reply: Thank you for pointing out the unclear point in the manuscript. I understand the concern about the seemingly contradictory statements regarding the role of sintering in the formation of snow cornices. I would like to clarify that in lines 26-27, it was stated that the sintering time is much longer than the collision time when a particle impacts the cornice surface. This means that on the timescale of particle sintering, the drifting snow aerodynamic process dominates the redistribution of snow particles and the patterns of snow cornices. However, the intention was not to imply that the sintering force is unimportant in maintaining the shape of snow cornice. Rather, the point is that during the initial stage of cornice formation, the drifting snow aerodynamic process is the primary driver of the distribution of snow particles. After these particles are deposited on the edge, the sintering force then dominates the main place in keeping the particle stationary, thus shaping and preserving the cornice structure.

To be clear, sentences in lines 26-27 will be deleted, and add "In which, F_b is the sintering force, which can be calculated as the product of the ice tensile strength and the area of the contact surface (Szabo and Schneebeli, 2007), $\sigma_{tensile} n^2 \pi$. Sintering happens after the particle deposit and dominates the main place in keeping the particle stationary, thus shaping and preserving the cornice structure." in Section 3.2 of the new version of manuscript.

Although authors tried to introduce all the conceivable forces which may act between particles on edge, time scales are not always consistent. Furthermore, all the discussions are qualitative from beginning to end and no quantitative estimates, which is enough to keep the thin plate growing, are shown. To say the least, quantitative approval of their idea, based on the snow and environmental data obtained in the experiment, is essential to make the manuscript reasonable and worthwhile.

Reply: As response above, during snow particle transportation, deposition and erosion on surface always happens when particle is in stationary state. Although sintering has longer time compared to particle collision process, the sintering effects starts from the beginning of particle deposit on the surface/edge of the cornice. Thus, the sintering force should also be considered, especially in this static mechanical analysis.

The size of snow particles follows a distribution function, and different sized particles are subjected to varying values of particle forces. Therefore, we have presented the order of magnitude instead of the exact values of each force. This allows us to analyze which forces are dominant and which forces can be neglected.

In the new version of manuscript, we will revise the discussion on mechanical force analysis. We also added the comparison of dendritic particle and round particle. We found that the ratio of cohesion force to gravity determines the shape of snow cornice. Due to the fact that the cohesion force for dendritic particle is 1.44 times of that value for spherical particle, indicating that the dendritic particle is more prone to stick on the edge. This theoretical analysis explained our experimental phenomenon. Moreover, it can also be used to explain the phenomenon in experiment that particles with smaller size and lower impact velocity are more prone to adhere on edge.

Reference:

Enliang Wang, Xiang Fu, Hongwei Han, Xingchao Liu, Yao Xiao, Yupeng Leng, Study on the mechanical properties of compacted snow under uniaxial compression and analysis of influencing factors, Cold Regions Science and Technology, Volume 182, 2021, 103215, ISSN 0165-232X, https://doi.org/10.1016/j.coldregions.2020.103215.