IMPACT FORCE OF SNOW AVALANCHE ON A MOVABLE HUMAN BODY

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Information of impact force is expected to assist in trauma severity evaluation for snow avalanche accidents. The study employed a coupled human-snow avalanche model to simulate the impact force on a movable human body in several snow avalanche conditions. The simulation results with the movable body had a smaller impact force than the fixed one, which might be due to a part of the impact energy from the snow avalanche transferring to the movement of the human body. The body motion differed in various flow conditions. It was categorized by flow depth into push, crash, and slip types, corresponding to deep, intermediate, and shallow depths. Their energy ratios were correlated with the Froude number, showing the linear relation in the push type, the independent relation in the crash type, and the exponential relation in the slip type. The empirical equation of the energy ratio for each motion type was proposed finally and expected to help assess the injury and vulnerability of snow avalanches for people in the backcountry.

Key Words : *Snow avalanche, Impact force, Coupled human-snow model*

1. INTRODUCTION

Snow avalanche is a dangerous natural hazard, causing fatalities and injuries. According to the data from Japan snow avalanche network, the overall 500 people were rushed by snow avalanches from 1991-2020. Within 30 years, 238 people died and 115 people were injured. Among the causes of death, asphyxia and trauma (external injury) accounted for 65% and 29% of fatalities, respectively[1)]. The vulnerability related to asphyxia has been proposed based on snow depth[2)]; however, the trauma vulnerability is out of discussion. Strapazzon et al indicated that climate change might affect snow and terrain properties, causing more severe trauma[3)]. Assessing the trauma severity-vulnerability relation might become a significant issue. It can be evaluated by the impact force.

Kitou et al proposed an empirical equation of the drag coefficient[4)], helping to estimate the impact force on the human body in various flow conditions. They assumed a person as a fixed cylindrical object and simulated the impact force with different flow conditions and an inclination of 15° - 60°, including the frequent snow avalanche slope of 30°-45°[5)]. However, evaluating impact force by the proposed equation might be too conservative because the fixed setting for the human body makes it suffer all the energy from snow avalanches without transferring energy into a movement of the human body.

The study aims to realize the relationship between the maximum impact force on a movable human body and the various flow conditions. The results are expected to propose an empirical equation for maximum impact force approximation. It might help evaluate the potential injury of mountain travelers and define the risk level in the backcountry and off-piste regions in the future. The article contains the following sections: Section 2 introduces the numerical model. Section 3 is the impact force comparison of fixed and movable object conditions. Section 4 discusses the impact force on the human body in various flow conditions and proposes an empirical equation for maximum impact force evaluation. Section 5 ends in conclusion.

2. NUMERICAL MODEL

The study utilizes a coupled human fluid numerical model named DRowning hUman Model (DRUM) to simulate human-snow avalanche interaction in several conditions. DRUM was developed by Ajima et al. to simulate the motion of a human body in a flow[6)]. By applying to flume experiments in which a

dummy doll is swallowed by a tsunami[6] and falls from a height to water[7], it has been confirmed that the DRUM can restore the human-body motion in the fluid well and evaluate the impact force due to the collision to fluid precisely.

DRUM is divided into fluid and solid parts. The fluid part computes the fluid motion in tracing the free surface by the advection of volume fraction with Constrained Interpolation Profile (CIP) scheme. The equations are shown in the following:

$$\frac{\partial \phi}{\partial t} + u_i \frac{\partial \phi}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{1}{\rho}\left(-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}\right) + g_i \quad (3)$$

$$\tau_{ij} = \mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \quad (4)$$

where ϕ, u, and g are fractions of the air volume, velocity, and gravity acceleration, respectively.

Incompressibility is assumed both for air and snow[4]. In the same way as Marker and Cell (MAC) scheme, pressure P is determined by solving a Poisson equation derived from Eqn (2). Density ρ and viscosity μ are given by $\rho=\rho_{air}\phi+\rho_{snow}(1-\phi)$ and $\mu=\mu_{air}\phi+\mu_{snow}(1-\phi)$, respectively. While the uniform density and viscosity are assumed for the air (ρ_{air} = 1.3 kg/m^3, μ_{air} = 19.4·10^{-6} Pa·s), to consider the snow properties, the snow is assumed as a Bingham fluid model, which has been widely used for snow avalanche simulation [4,8]. The density of snow ρ_{snow} is assumed to be 350 kg/m^3. Its viscosity μ_{snow} is modeled with the following equation.

$$\mu(\dot{\gamma}) = \mu_0 + \frac{\tau_Y}{\dot{\gamma}} = \mu_0 + \frac{c + p\tan\varphi}{\dot{\gamma}} \quad (5)$$

$$\dot{\gamma} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \quad (6)$$

where μ, τ_Y, μ_0, c, φ, and $\dot{\gamma}$ represent dynamic viscosity, yield shear stress, viscosity coefficient after yield, cohesion, internal friction angle, and shear strain rate, respectively. Based on an actual accident that occurred in Mt. Nasu[4], Japan, the dry snow is assumed and the snow properties observed/expected in the accident are set: c = 10N, φ = 15°, μ_0 = 0.0Pa·s.

A link segment model is used to compute human motion. A human body consist of rigid segments linked by joints (**Fig. 1**). Motion of each segment is described by

$$M_s \frac{\partial v_i}{\partial t} = F_{i,s|Fluid} + \sum_{m\ on\ s} F_{i,s|m} - M_s g_i \quad (7)$$

$$I_i \frac{\partial \omega_i}{\partial t} + \varepsilon_{ijk}\omega_i(I_j\omega_j) = T_{i,s|Fluid} + \sum_{m\ on\ s}(\varepsilon_{ijk} r_{i,sj} F_{j,s|m} + T_{i,s|m}) \quad (8)$$

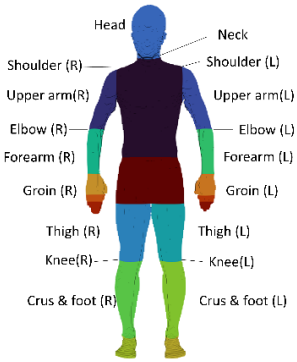

Fig. 1 The rigid body segment in the solid part of DRUM

$$F_{i,s|fluid} = \iiint \left(-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}\right)\phi_s dxdydz \quad (9)$$

where M_s, I, v, ω, r, T, and F are the mass, moment of inertia, translation, angular velocity, displacement, torque, and force of s-th segment. The fluid force is estimated by integrating the pressure P and fictional stress τ surrounding the human body (Eqn. 9). ϕ_s is volume ratio of the segment of human body. The impact force on the whole body is the sum of the forces on each segment.

To trace a rapid translation of a human body swiped by a snow avalanche without unaffordable computational load, translating Eulerian grids is used in this study[9]. At each time step, a Cartesian computational mesh is moved without a rotation and recentered around the gravity center of the human body. This transformation corresponds to the change of the coordinate system.

$$x_i \rightarrow x_i + \int_0^t U_i(\tau)d\tau \quad (10)$$

where $U(\tau)$ is the velocity of the gravity center of a human body.

3. EFFECT OF THE HUMAN BODY'S MOVABILITY ON IMPACT FORCE

The numerical simulation of snow mass crashing into a cylindrical obstacle in Kitou et al. is selected as a simple validation case. The study only compares the results of maximum impact force when the slope angle is 45°.

The simulation assumes that the snow avalanche flow moves with the velocity of κ and the height of H. A human body stands on the terrain with slope θ and faces in the direction of the snow avalanche. In the study, the initial depth and velocity are 1m and 5.7m/s. Except for the two settings, the parameter set is same as Kitou. The mesh size is 5cm, chosen based on mesh convergence test results.

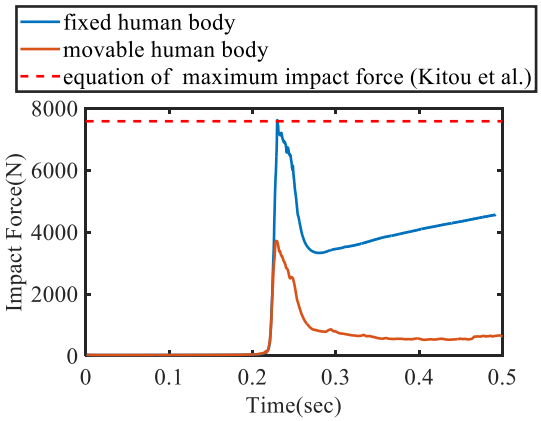

Fig. 2 The impact force on the whole human body of the fixed and movable human body

Fig. 2 shows the impact force on a fixed human within 0.5 sec. The peak impact force on the whole body of the numerical model is in good agreement with the equation proposed by Kitou et al. In addition to the results of a fixed human body, the impact of a movable one is shown in the red line in **Fig. 2**. Comparing the impact force in the two human body conditions, a smaller impact force can apparently be observed on a movable human body. The peak impact force is about half that on a fixed body. The mobility properties enable the human body to change its posture when the flow comes forward. Because part of the energy from the snow avalanche becomes the momentum of the human body, it helpfully decreases the impact force on the human body.

4. IMPACT FORCE ON HUMAN BODY

As mentioned in Section 3, the maximum impact force may be quite smaller when the human body is movable. To understand the relation of maximum impact force on the human body and snow avalanche conditions, a series of human-snow avalanche interaction simulations in various terrain slopes, flow velocity, and avalanche depth are conducted. In the preceding study[10], to generate a hazard map, the runout of snow avalanches has been simulated for over 100 potential source areas in Mt. Nasu. In this study, the target of velocity, flow depth, and slope angle are determined to include the range observed in the runout simulation. The flow conditions for simulation are in the range of κ = 1, 3, 5, 7.5, 15 m/s and H = 0.5, 1, 2, 4 m. To consider the terrain angle of runout and relases, the slope angle θ is set as 25°, 30°, and 45°. The flow condition of κ = 15 m/s has additional depths of H = 8, 10, and 12m. The mesh size is 5cm.

The study focus on the scenario of a climber suffering a snow avalanche attack. When standing on a slope, the human body is parallel to the gravity axis.

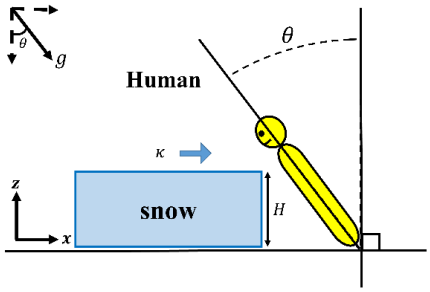

Fig. 3 The initial setting of the model

Table 1 The human body motion and its corresponding flow condition when θ=45°. The green, yellow, and orange colors represent slip, crash, and push motion types, respectively.

θ = 45°		Depth(m)						
		0.5	1	2	4	8	10	12
Velocity(m/s)	15	Slip	Crash	Push	Push	Push	Push	Push
	7.5	Slip	Crash	Push	Push			
	5	Slip	Crash	Push	Push			
	3	Slip	Crash	Push	Push			
	1	Slip	Slip	Push	Push			

Due to this reason, the initial set of the human body has an inclined angle with a vertical line of the terrain **(Fig. 3)**.

(1) Motion in various conditions

Through a series of simulations in various flow conditions, it is suggested that the human body motion during and after a first collision with the front edge of an avalanche is categorized into three types. In this work, the three types are named "push", "crash" and "slip" types after the posture of the human body. As the cases of θ=45° in **Table 1**, the categorization seems to depend on the relationship between avalanche flow depth H and height of human-body (h_{body}=168cm), independently from velocity. A similar tendency is seen at other slope angles.

When the flow depth exceeds the human height($H>h_{body}$), it is categorized as push-type motion. The avalanche front hits a whole body from feet to head almost simultaneously. After the collision, a part of the avalanche flows over a head because the avalanche is thicker than the human height. The human body remains in a standing posture and is swept away as if surrounded by the avalanche (**Fig. 4**). Maximum impact force on the human body is observed during the first hit by the avalanche front. As shown in **Fig. 5**, impact force increases rapidly once the flow front hits the human, then decreases immediately.

The crash type is observed when the avalanche depth is shallower than the human body height ($H<h_{body}$) and deeper than the crotch height ($H\geq$1m). After the avalanche front firstly hits to the lower body, the human body is thrown in the above of snow avalanche in being the upper body down. Then, the

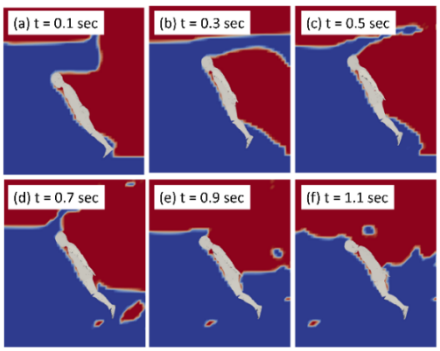

Fig. 4 The motion of push type ($\theta = 45^{o}$, κ =15m/s and H =2m as an example.)

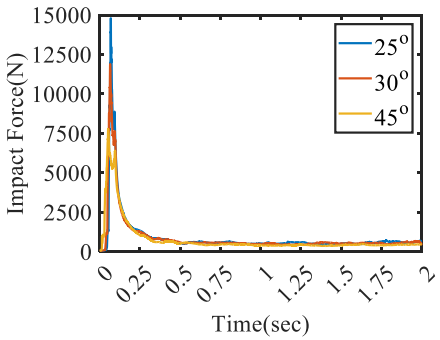

Fig. 5 The impact force on the human body of push type. (κ=15m/s and H =2m as an example)

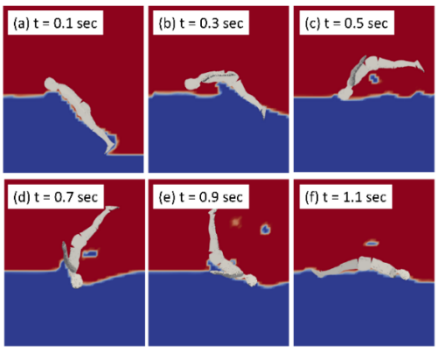

Fig. 6 The motion of crash-type ($\theta = 45^{o}$, κ =15m/s and H =1m as an example.)

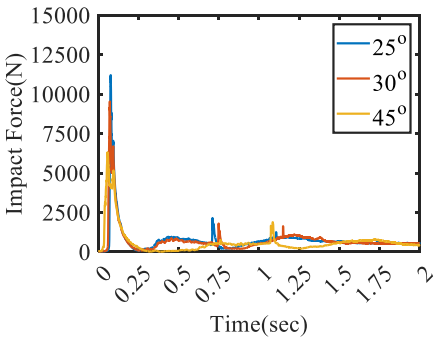

Fig. 7 The impact force on the human body of crash-type (κ=15m/s and H =1m as an example)

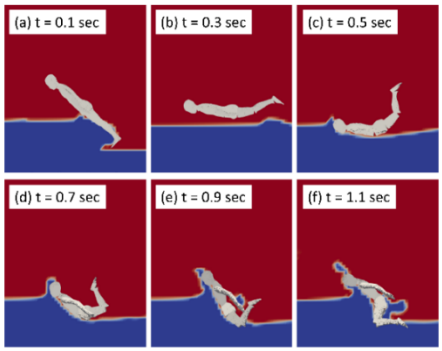

Fig. 8 The motion of slip-type ($\theta = 45^{o}$, κ=15m/s and H =0.5m as an example.)

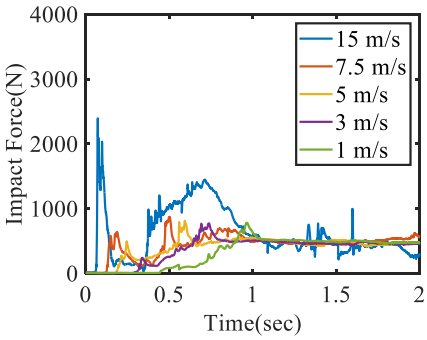

Fig. 9 The impact force on the human body of slip type (θ= 45° and H =0.5m as an example)

body falls on the upper surface of avalanche and is suffered by the 2nd collision (**Fig. 6**). As shown in **Fig. 7**, commonly, the impact force in the 2nd collision is smaller than that in the 1st collistion, the plot of the impact force is similar to the push type.

The slip type is observed when the avalanche depth is shallow than the crotch height ($H < 1$ m). Although the human-body changes its position during in same way as the crash-type as shown in **Fig. 8**, the impact force in the 1st collision becomes to be comparable to the impact in 2nd collision. This is because the 2nd impact force still is contributed by the impact due to falling from the initial standing posture while the 1st impact is weakened due to decreasing the projection area of the avalanche front.

(2) Impact force in various conditions

The maximum impact force on the human body in various conditions when the slope is 25°, 30°, and 45° are shown in **Fig. 10-12**. The maximum impact force is larger when larger initial velocity and deeper depth. However, the larger maximum impact force appears in the smaller slope angle. **Fig. 13** is the snapshot of human-snow interaction at maximum impact force. At the moment, the projection area and the front velocity are nearly identical at these angles. The only difference is the normal and tangent velocity components along the human body. A larger slope angle increases the inclination of the human body from vertical, reducing the velocity component normal to the human body. This explains why smaller maximum impact forces occur at larger angles.

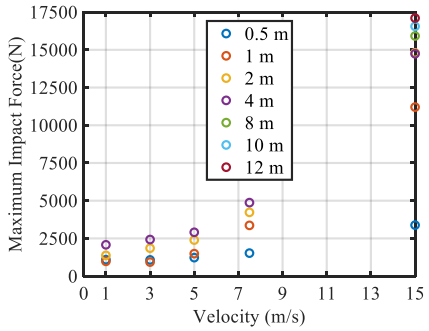

Fig. 10 Maximum impact force on the human body when θ = 25°

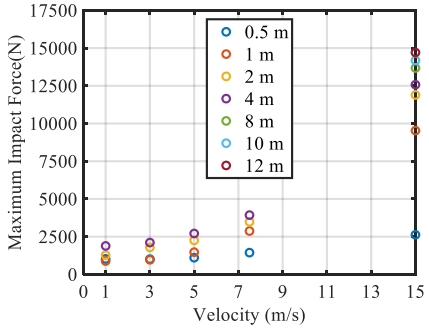

Fig. 11 Maximum impact force on the human body when θ = 35°

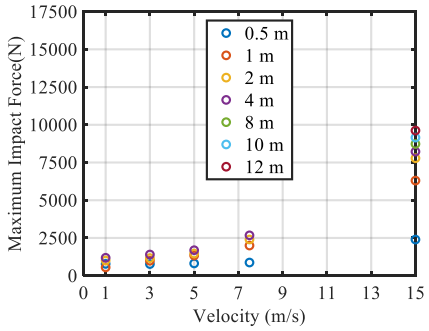

Fig. 12 Maximum impact force on the human body when θ = 45°

Fig. 13 The snapshot of human posture and flow surface at maximum impact force in the angle of 25° - 45°.

(3) The empirical coefficient λ

The relation between maximum impact force and initial condition is considered in the energy concept because the human body is movable. The following is the assumption:

A. The total energy is conservative.
B. After snow mass crashes into the human body, part of the energy becomes energy for movement.
C. The snow mass replaces the space originally occupied by the human body each timestep.

The equation with the above assumption is described as Eqn (11) and (12).

$$(\frac{1}{2}m\kappa^2 + mgH^*) \cdot \lambda = F_{max} \cdot \Delta s \tag{11}$$

$$m = \rho \cdot A \cdot \Delta s \tag{12}$$

where m, ρ, g, Δs, A, κ, F_{max}, and λ represent snow mass element, snow density, gravity, movement of the human, projection area of the human body, the initial velocity of snow mass, the maximum impact force on the human body, and the energy ratio. The function of H^* and A are shown in Eqn (13) and (14).

$$H^* = \frac{H}{\cos\theta} \tag{13}$$

The width function of the human body is determined based on the human body data. Due to an angle between the zenith angle of the human body and the orthogonal line of ground(see **Fig. 3**), the projection area is suggested to be set as Eqn (14).

$$A = \begin{cases} \int_0^{\frac{H}{\cos\theta}} dW & \left(0.5 < \frac{H}{\cos\theta} \le L\right) \\ \int_0^{L} dW & \left(\frac{H}{\cos\theta} > L \; or \; H \le 0.5\, m\right) \end{cases} \tag{14}$$

where L and W are human height and width function of the human body.

When the initial depth is less than 0.5m, the human body moves in the slip type. The maximum impact force occurs when the human body falls on the flow surface after slipping. The projection area is the whole body at the moment of human-snow contact. Thus, an extra limitation is added.

The energy is summarized as Eqn (15).

$$\lambda = \frac{F_{max}}{(gH^* + \frac{1}{2}\kappa^2)\rho A} \tag{15}$$

$$\mathrm{Fr} = \frac{\kappa}{\sqrt{gH}} \tag{16}$$

Fig. 14-16 shows the relation of the whole body between the energy ratio and Froude number (Eqn 16) in various motion types. The trend is different in motion types. The energy ratio of the push type has a linear relation to Froude number. The energy is larger as the Froude number is larger. In contrast, the energy ratio of the slip type has an exponential relation with Froude number. The larger energy ratio appears when Froude number is smaller. It means that the human body might suffer almost the same energy as the initial condition when shallow flow. For the energy ratio of crash type, a clear dependency on Froude number is not found. It might be due to the transition type between slip and push type. The empirical equation of energy ratio is shown in **Table 2**.

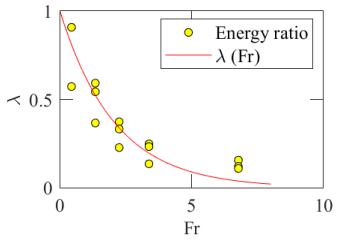

Fig. 14 The relation of energy ratio and Froude number (Slip type)

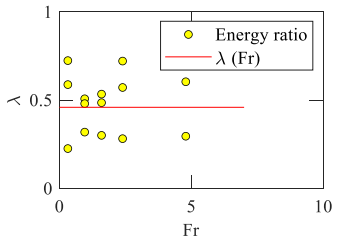

Fig. 15 The relation of energy ratio and Froude number (Crash type)

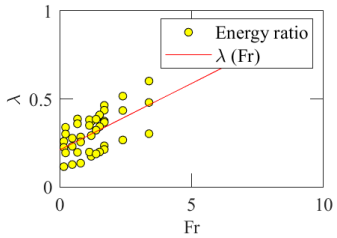

Fig. 16 The relation of energy ratio and Froude number (Push type)

Table 2 The function of energy ratio

	Type	Function
Whole body	Slip type	$\lambda(\mathrm{Fr}) = 1.01\exp(-0.48\mathrm{Fr})$
	Crash type	$\lambda(\mathrm{Fr}) = 0.46$
	Push type	$\lambda(\mathrm{Fr}) = 0.08\mathrm{Fr} + 0.21$

5. CONCLUSION

The study simulated a series of human-snow avalanche interaction cases in various conditions of velocity, depth, slope angle, and mobility of the human body. The impact force on the movable human body was much smaller than the fixed conditions. It proved that the overestimation of the impact force might happen when the human body was set as a fixed obstacle.

The maximum impact force on the human body reasonably appeared in fast and deep flow conditions. The mild slope led to a larger impact force due to the larger normal velocity. The relation between maximum impact force and initial condition was evaluated through energy consideration. The empirical equation of energy ratio for the three motion types was proposed and had different trends. The push motion type had a linear relation to the Froude number. The exponential relation could be observed in the slip type. The independent relation was shown in crash type due to the transition between push and slip types.

The study assumed a simple situation that a human body stands on a constant slope without any obstacles. Because a collision with a tree or rock in actual terrain may increase impact force, the impact force evaluated in this work may be underestimated and the consideration of the collision to obstacles remains to be a future work. The present model can simulate a large deformation of the avalanche surface by modeling the avalanche as the Bingham flow. The advantage may enable to project whether the human body is swallowed inside of avalanche or not and evaluate the possibility of asphyxia in future work.

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