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Evaluation of Human Damage During Earthquake in Nuclear Power Plant Using Physics Engine

Hiroki Yamatani[1], Takenori Hida[2]

[1]Graduate Student, Ibaraki University, Ibaraki, Japan (24nm839a@vc.ibaraki.ac.jp)
[2] Assoc. Prof., Ibaraki University, Ibaraki, Japan (takenori.hida.mn75@vc.ibaraki.ac.jp)

INTRODUCTION

Many human damages occurred during past Earthquakes. If the severe accident occurred in a nuclear power plant, the operators and workers need to make the damage not to spread. Therefore, human damages must be prevented in a nuclear power plant. It is reported that the fluorescent lights and ceiling panels dropped at the central control room in a nuclear power plant during a past Earthquake. These dropping objects can cause severe human damages. The knowledges on human tolerance against earthquake shaking and indoor damages are limited. Therefore, it is important to clarify the severity of human damages in the event of a massive Earthquake.

Masatsuki and Midorikawa (2015) used a physics engine to simulate indoor damage during an earthquake. However, dropping objects such as ceiling panels and lighting were not considered. Therefore, the severity of indoor damage was underestimated. Injuries to humans due to collisions between scattered objects and humans in the room were not considered.

Kawaguchi et al (2021). clarified the relationship between the drop height of the ceiling panel and the maximum impact load on the human head. However, the relationship was examined only in the vertical direction. In the central control room, the severity of human injury could be varied depending on standing position of the operator during the earthquake.

In this study, the indoor damage of central control room during an earthquake is simulated based on the seismic response analyses using physics engine. In the analyses, the dropping objects and the human behaviour are considered. The dependencies between the severity of human injury and the standing position of human are investigated.

EARTHQUAKE SIMULATION

In this study, we reproduced indoor damage and human damage using a physics engine to investigate human injury severity during an earthquake shaking. The model of the central control room is shown in Figure 1. It is 6 m wide, 6 m deep, and 3.5 m high to the upper floor slab. The desk, chair, display monitor, and control panel are each modelled as a rigid body. The physical parameters of each object are listed in Table 1. Mass, width, depth, height, static and dynamic friction were set based on the previous studies (Masatsuki et al. 2015). For the chair, the friction coefficient was set low to reproduce the behaviour of the chairs with casters.

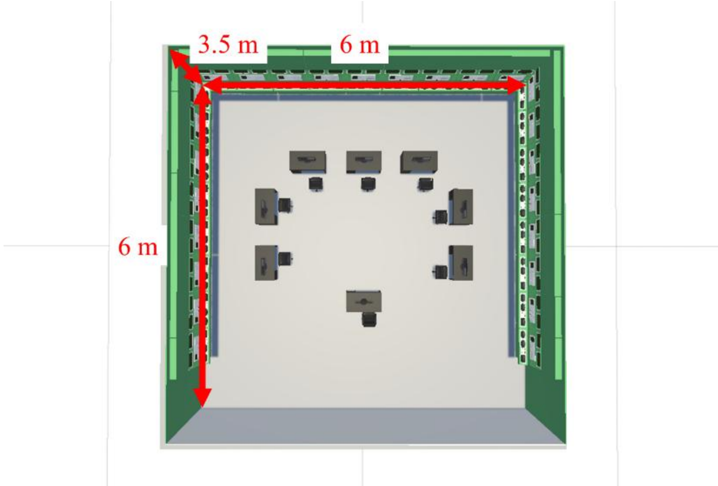

Figure 1. Central control room model.

Table 1: Physical parameters of each object.

Object	Mass [kg]	Width [m]	Depth [m]	Height [m]	Static friction	Dynamic friction
Desk	40.0	1.20	0.70	0.70	0.33	0.30
Chair	5.0	0.52	0.43	0.85	1.0×10^{-4}	1.0×10^{-4}
Display monitor	6.40	0.60	0.18	0.43	0.33	0.30
Control panel	-	1.26	0.60	2.80	-	-

Figure 2 illustrates the ceiling model of the central control room. The suspended ceiling consisting of a lightweight steel frame, fluorescent lights, and slits were installed. A clearance of 0.3 m was provided between the lightweight steel frame and the wall. A collider component was attached to each object to reproduce the collision.

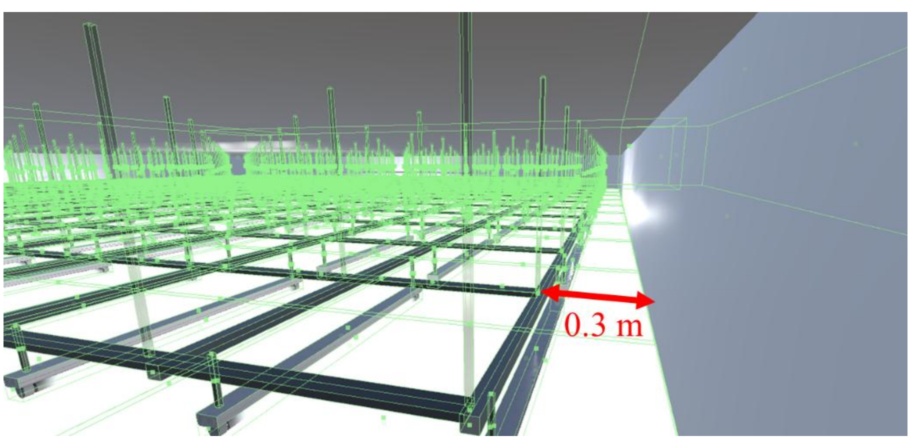

Figure 2. Ceiling model.

The ceiling configuration is shown in Figure 3. The upper frames are suspended from the slab of the upper floor by bolts. The joints between the upper floor slab and the bolts were modelled as a pin joint. The joints between the upper flames and the bolts were also modelled as a pin joint. The upper frames are attached to the lower frames by rigid joints. The fluorescent lights are suspended from the lower frame by bolts. The joints between the lower frames and the bolts and between the fluorescent lamps and the bolts are pin joints. The joints between the fluorescent lamps and the bolts are disengaged when an external force of 80 N or more is applied to the fluorescent lamp. There are slits under the fluorescent lamp when it is struck by an impact. The slit was made of gypsum board, which is commonly used as a common ceiling board, with a size of 910 × 910 × 12.5 mm and a weight of 8.1 kg.

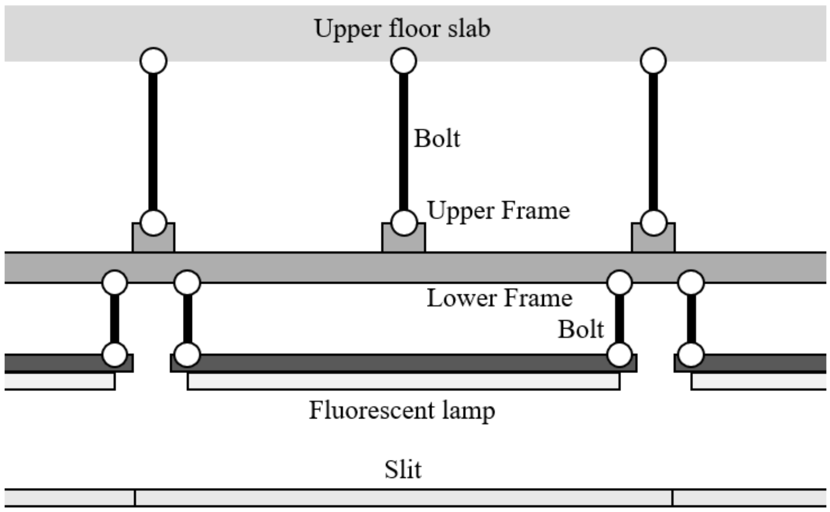

Figure 3. Ceiling configuration.

In the seismic simulation, the strong motion record was input to the upper and lower slab, walls, and control panels. Figure 4 shows the displacement time history of input motion used in this simulation. In this study, the amplitudes of the NS and EW components of the strong motion records observed at the Kashiwazaki-Kariwa Nuclear Power Plant during the 2007 Niigata-ken Chuetsu-oki earthquake. The amplitude of the input motion was multiplied by 2.5.

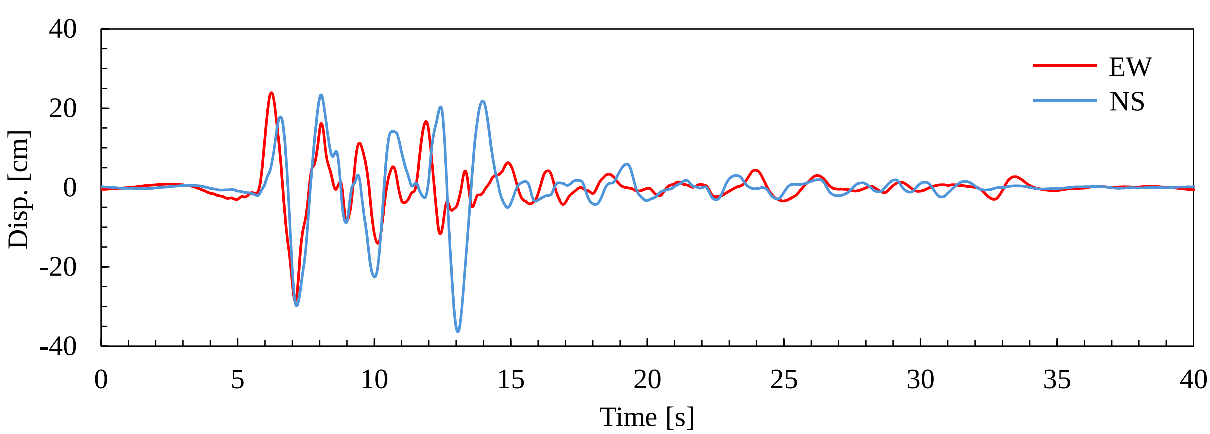

Figure 4. Displacement time history of input motion.

The simulation results are shown in Figure 5. At 7.62 s, some fluorescent light and ceiling panels in the corner dropped. At 8.12 s, several ceiling panels at the right and left ends dropped. At 8.52 s, dropped ceiling panels collided with a display monitor, a desk, and a chair. At 11.70 s, dropped ceiling panels overlapped. 76% of ceiling panels dropped.

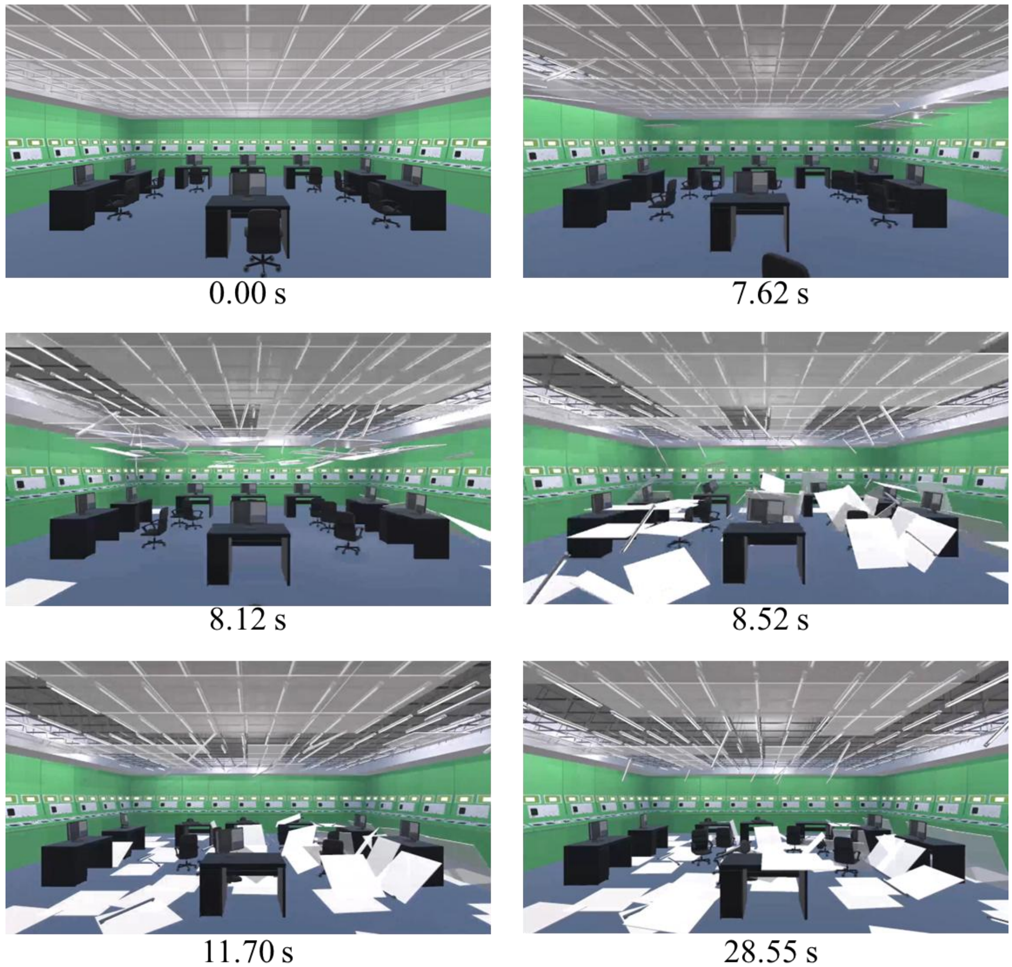

Figure 5. Simulation results of earthquake excitation

For human injury severity evaluation, the seismic response analysis model of the human body proposed by Sato (2024) et al. is used in order to reproduce the human behaviour during the earthquake.

Figure 4 shows the human model. The displacements obtained from the seismic response analysis model were input to the head, hip, and foot. It is set that the human model falls when the head collides with another object. The limits of hip joint angles were set at 90 degrees forward, 30 degrees backward, and 60 degrees to the left and right in order to reproduce the falling motion.

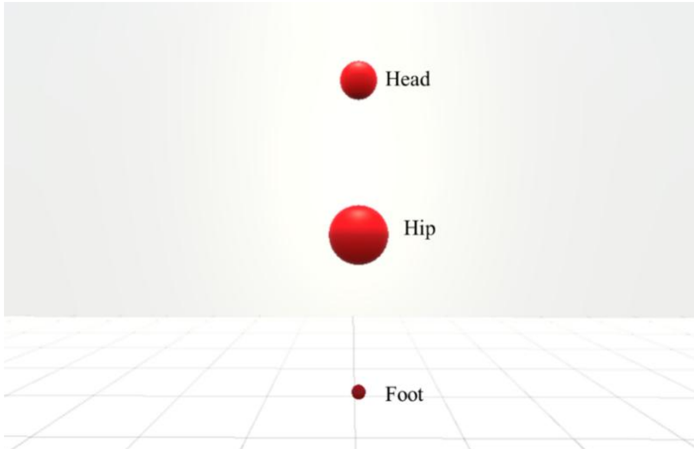

Figure 6. Human model.

In this study, two cases of earthquake simulations were performed. In case 1, the human model is placed in the center of the room. In case 2, the human model is placed near the wall on the right side. By comparing the injury severity between Case 1 and Case 2, we investigate where it is safer to be in the central control room during an earthquake.

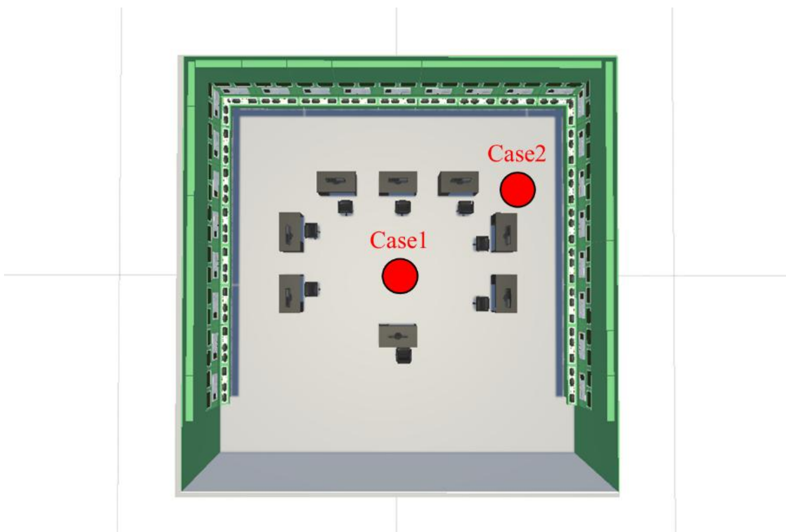

Figure 7. The plan of central control room.

Figure 8 shows the simulation results of Case 1. At 8.24s, a dropping ceiling board collided with the head of the human model. At 8.54s, the human model was slightly tilted. At 9.07s, the human model fell to the floor. After that, the human model did not collide with anything and maintained its posture until the end of the excitation.

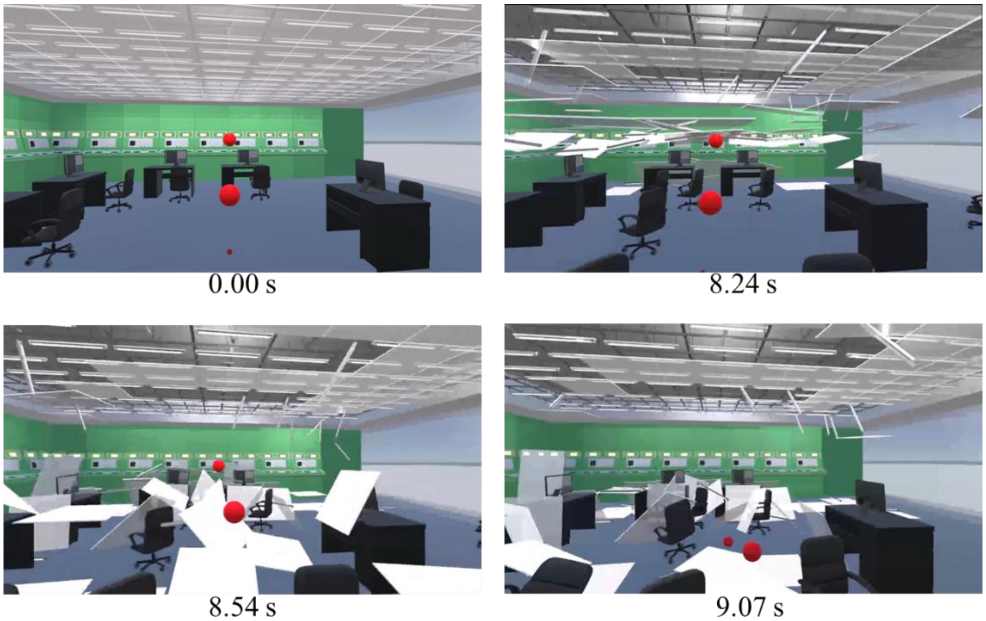

Figure 8. Simulation results of Case 1.

Figure 9 shows the simulation results of Case 2. At 7.81s, the falling ceiling panel collided with the head of the human model. At 8.22s, upper body of the human was greatly inclined. At 8.56s, the head of the human model fell to the floor and collided with the dropping ceiling board. 10.80s, the human model lay on the floor and maintained its posture without colliding with anything. As a result, the head of the human model collided with the ceiling panel twice in Case 2.

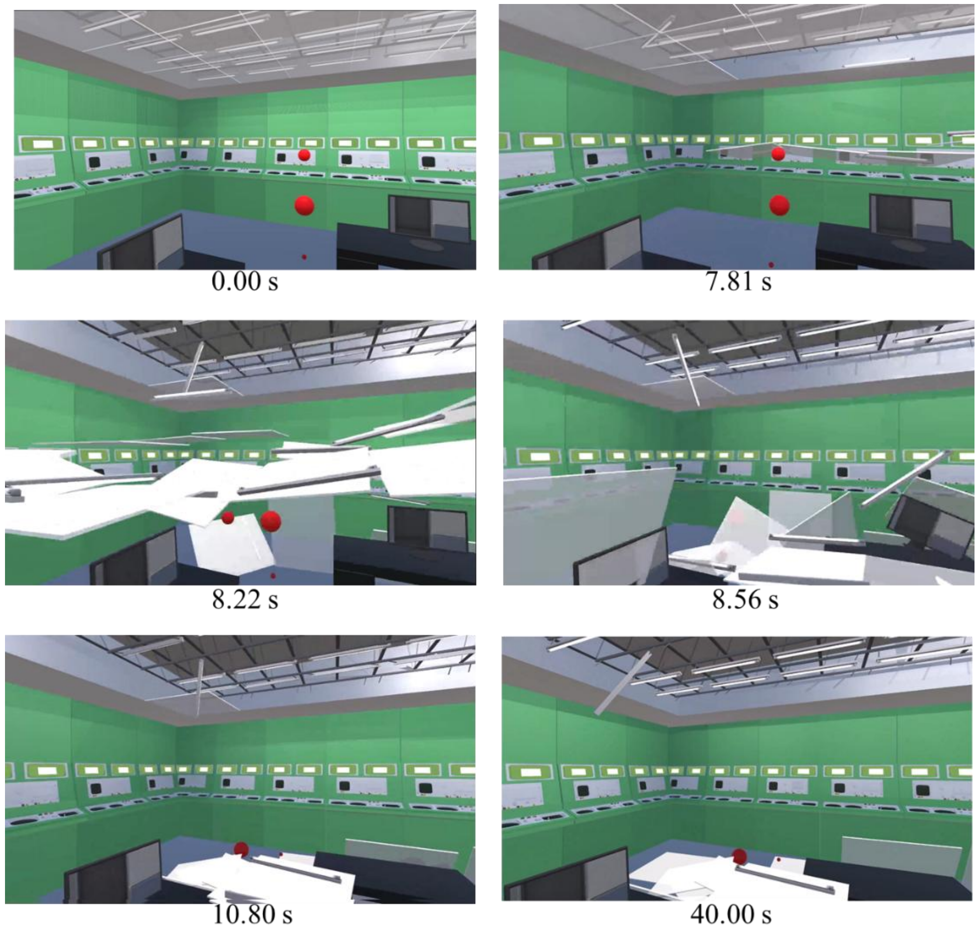

Figure 9. Simulation results of Case 2.

INJURY EVALUATION

Previous study (Kawaguchi et al., 2021) assessed injuries based on the impact force when the human head that collide with the ceiling panel and the threshold for linear fracture of the skull proposed by Nahum et al. If the impact force is less than 2000 N, headache or dizziness can occur. Impact forces exceeding 2000 N can cause linear fractures and concussions, which can be life-threatening. The impact force is evaluated using the relationship between the drop height of the ceiling panel and the maximum impact load obtained by Kawaguchi et al. Figure 10 shows the relationship between drop height and impact velocity or maximum impact load. In this figure, the standard deviations are also indicated by error bars. In the previous study, impact loads were measured with a load cell installed under the human head model. Since the ceiling board used in the earthquake simulation in this study has the same physical parameters as the gypsum board used in the previous study, the impact load can be determined by dropping height of the ceiling panel.

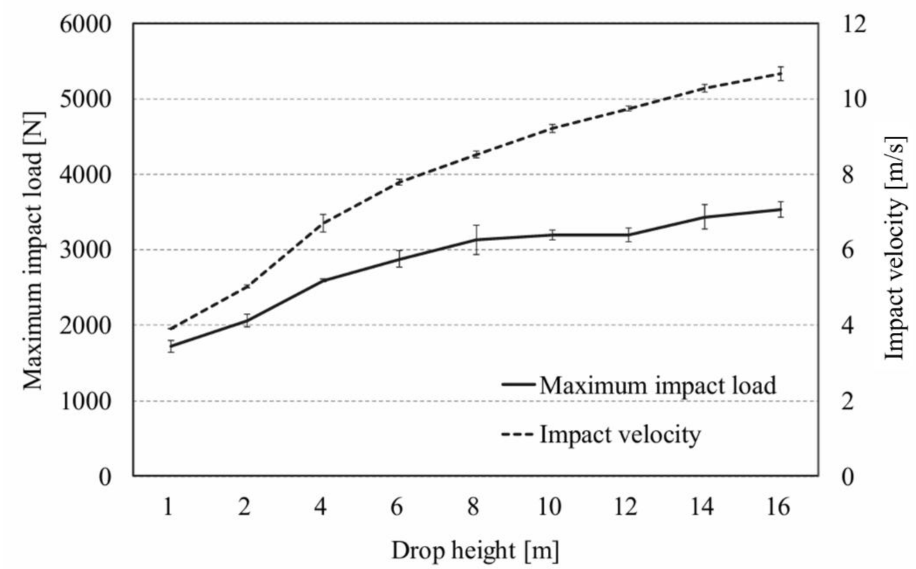

Figure 10. Relation between impact velocity, Maximum impact load and drop height with indication of standard deviation (GB-t12.5)

In order to evaluate the impact force, the relationship between the drop height of the ceiling panel and the maximum impact load shown in Figure 10 is used. It is necessary to determine the drop height of the ceiling panel in Case 1 and Case 2. Table 2 shows a summary of the collisions in Case 1 and Case 2. In Case 1, the ceiling panel collided with the head at 8.24 s. The vertical coordinate of the head at this moment was 1.529 m. The initial vertical coordinate of the ceiling panel was 2.8 m. Thus the dropping distance of the ceiling panel in Case 1 was 1.271 m. In Case 2, two collisions occurred at 7.84 s and 8.56 s. The dropping distance of the ceiling panel at the first collision were 1.529 m. At the second collision, the vertical coordinate of the head was 0.277 m, since the human model had been fallen by the first collision. Therefore, the dropping distance of the ceiling panel was 2.523 m.

Table 2: Summary of Cases1 and Case2 collisions

	Time of collision [s]	Vertical coordinates of the head [m]	Drop distance height [m]
Case1	8.24	1.529	1.271
Case2	7.81	1.529	1.271
	8.56	0.277	2.523

Figure 11 shows the maximum impact loads in Case 1 and Case 2. The maximum impact load for the Case 1 and the first collision in Case 2 was 1800 N, which was lower than 2000 N. In the second collision in Case 2, the maximum impact load was 2032 N, which exceeded 2000 N. Therefore, there is a risk of linear skull fractures and concussions. The results indicate that a collision between a human head in fallen position and a dropping ceiling panel can result in death.

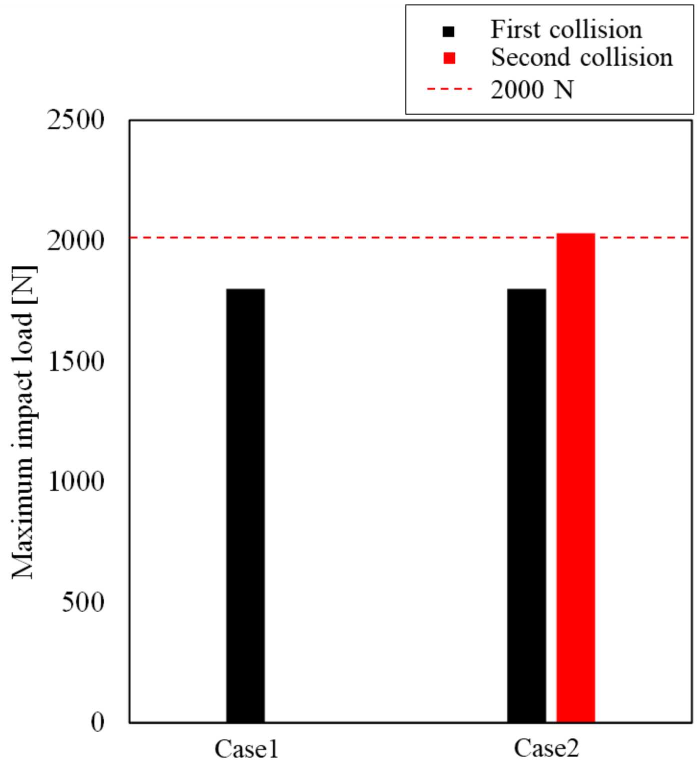

Figure 11. Maximum impact loads for Case 1 and Case 2

CONCLUSION

In order to investigate injury of the operator of a nuclear power plant during an earthquake, the central control room model was constructed using a physics engine. The ceiling panel of the central control room model dropped due to seismic motion. The human injury was assessed by using the human model. In the case where the human model was placed in the center of the room, the human model did not suffer the fatal injury. In the case where the human model was placed near the wall, the human model suffered the fatal injury. This is because that the human model fell due to the first collision with the ceiling panel, and the second collision with the ceiling panel occurred while the human model was in fallen position. As a result, the maximum impact load became large.

By reproducing a room with a physics engine in the way shown in this study, seismic damage of human can be evaluated. This could provide useful information when considering measures to reduce human casualties during an earthquake.

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