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Evaluation Method of Human Injury During Earthquake Based on Seismic Response Analysis Model of Human Body

T. Hida[(1)], T. Itoi[(2)], and T. Takada[(3)]

[(1)] *Assistant Professor, Graduate School of Engineering, The University of Tokyo, hida@load.arch.t.u-tokyo.ac.jp*
[(2)] *Associate Professor, Graduate School of Engineering, The University of Tokyo, tatsuya.itoi@arch.t.u-tokyo.ac.jp*
[(3)] *Professor, Graduate School of Engineering, The University of Tokyo, takada@load.arch.t.u-tokyo.ac.jp*

Abstract

When the accident of the Fukushima Daiichi Nuclear Power Plant occurred in the 2011 off the Pacific coast of Tohoku Earthquake, the accidents were prevented from expanding by desperate efforts of the manager and operators at the site. Although immediate operations during and just after huge earthquake should not rely on human efforts, various human control operations after the earthquake and damage mitigating operations in case of accidents would be needed, as experienced at the 2011 Fukushima Daiichi NPP accident.

So many people suffered damages during massive earthquakes occurred before now. The causes of injury were not only due to overturning of furniture, but also hitting their head to the wall or falling over themselves. In the event of a huge disaster such as the earthquake directly below Tokyo or the Nankai Trough earthquake, which could occur in the near future in Japan, damage reduction and societal restoration activities by human are essential. Therefore, evaluation of whether human can perform disaster reduction and recovery activities after the earthquake is required. A seismic analysis model of human body would be useful to predict human injury during an earthquake.

In this study, shaking table tests with a human subject were conducted to develop a non-linear seismic response analysis model of a human body for evaluation of injury during an earthquake. The model is constructed based on a cart-type double inverted pendulum with feedback control system. Next, a seismic response analysis model of a human body was developed based on a cart-type double inverted pendulum with feedback controller. The model allows us to predict foot displacement and head velocity of a human. In addition, the evaluation methodology of head injury probability of human by using head injury criterion (HIC) derived from the head velocity calculated by the human model is proposed. Finally, the case studies based on a seismic response analysis model of RC super high-rise building were performed in order to show the evaluation procedure of human injury during earthquake.

Keywords: human body, shaking table test, inverted pendulum, feedback control, head injury criterion

1. Introduction

When the accident of the Fukushima Daiichi Nuclear Power Plant occurred in the 2011 off the Pacific coast of Tohoku Earthquake, the accidents were prevented from expanding by desperate efforts of the manager and operators at the site. Although immediate operations during and just after huge earthquake should not rely on human efforts, various human control operations after the earthquake and damage mitigating operations in case of accidents would be needed, as experienced at the 2011 Fukushima Daiichi NPP accident.

In the event of a huge disaster such as the earthquake directly below Tokyo or the Nankai Trough earthquake, which could occur in the near future in Japan, damage reduction and societal restoration activities by human are essential. Therefore, evaluation of whether human can perform disaster reduction and recovery activities after the earthquake is required.

There are some previous studies dealing with human behavior during an earthquake. Nachi et al. [1] investigated the human injury caused by strong shaking. Takahashi et al. [2] and Hida et al. [3] evaluated the psychological effects of seismic motion on human. Takahashi et al. [4] also investigated the influence on the human body due to overturning of furniture during earthquake. However, objectives of these studies are not to propose the methodology for evaluation of injury considering the human response to earthquake shaking.

The seismic response analysis model of a human is needed to evaluate injury due to shaking, because it is impossible to conduct an experiment dealing with falling over of human and injuries under a huge earthquake. Numerous models have been proposed to analyze the physical behavior of human body against disturbances in various fields such as automobiles, railroads, robotics, CG, biomechanics etc. (e.g. Kudoh et al. [5], Uenishi et al. [6]). In the structural engineering field, Yamamoto [7] proposed the vibration response analysis model of a human body subjected to sinusoidal sweep excitation under a standing position, based on a simple single mass system. However, the model is not aimed to evaluate the dynamic behavior of humans subjected to random and complex disturbance such as earthquake shaking.

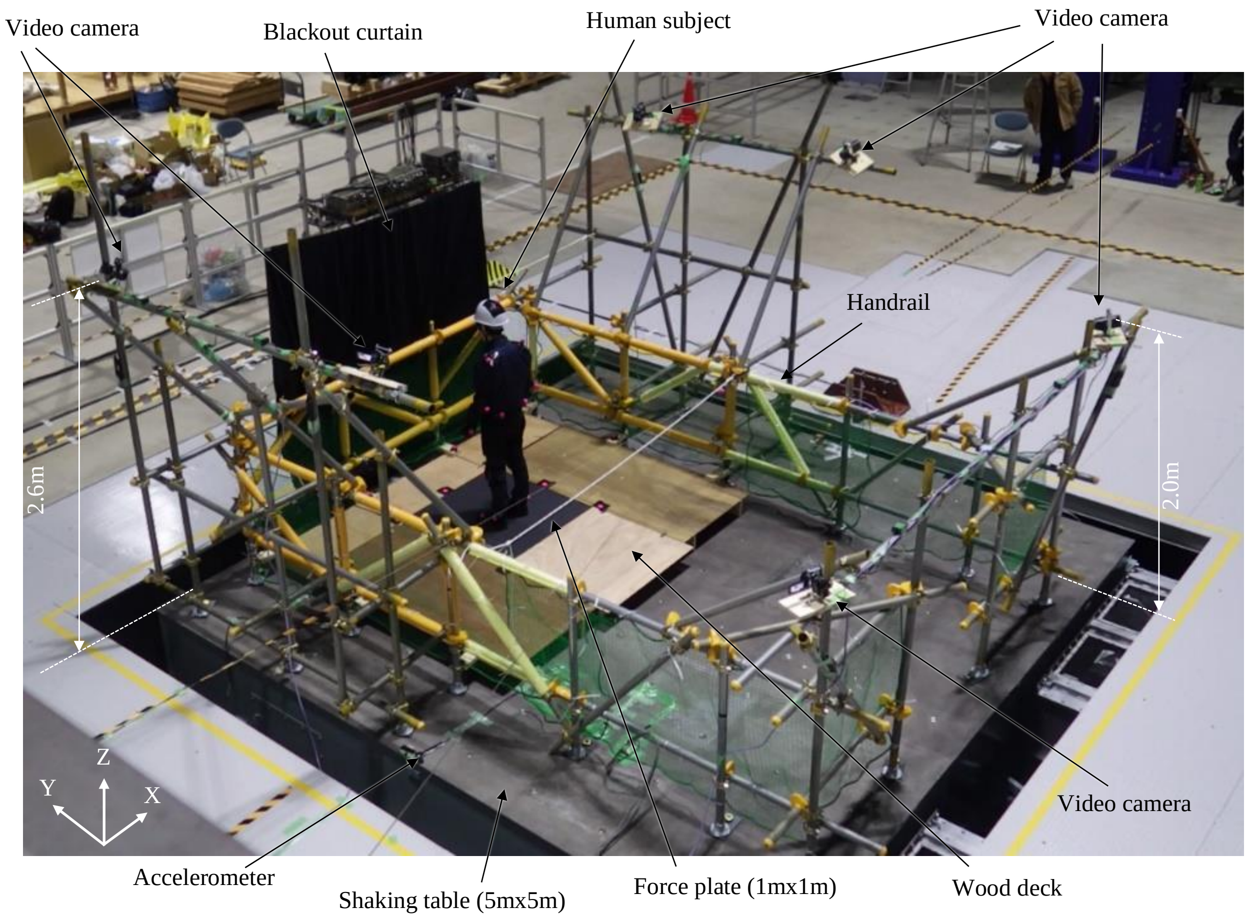
In this study, the shaking table tests with human subject were conducted to develop the non-linear seismic response analysis model of a human body for evaluation of injury during an earthquake. The model was developed based on the cart-type double inverted pendulum model with feedback system. The model allows us to estimate the foot displacement and head velocity of the human. Then, the evaluation methodology of the probability of human injury by using the head injury criterion (HIC) derived from the head velocity calculated by the human model was proposed. Finally, the case studies based on the seismic response analyses of RC super high-rise building were performed in order to demonstrate the procedure of evaluation of human injury during earthquake.

2. Outline of shaking table test

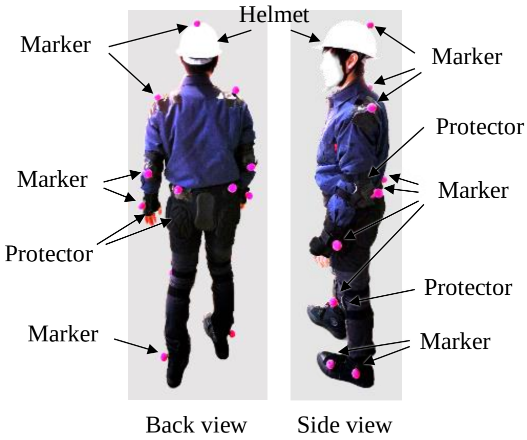
Figure 1(a) illustrates the setup of shaking table test [8]-[10]. The size of the shaking table is 5 m x 5 m. Two directional horizontal excitations were applied to the human subject. The human subject was made to stand on a force plate. Six video cameras (1920x1080, 60 fps) were set on the handrail constructed on the shaking table.

The human subject (male, 24 years old, 169 cm, 57 kg) is shown in figure 1(b). The subject was put on a helmet and protectors for safety. In order to measure the behavior of each body parts of the subject by using 3D motion capture system, markers colored in pink were attached on each position of the subject. The displacement waveform of each markers attached to the human subject were obtained by using 3D motion capture system (DIPP-Motion V/3D [11]). The subject was instructed to take the balance by swinging his own body or stepping, not to grab the handrail as much as possible, not to squat down, and to maintain the standing posture during the excitation. A force plate was set on the shaking table to measure the displacement of center of pressure (CoP [12]) applying on the floor by the human subject. The plate was made by honeycomb panel supported vertically by four load cells.

After each excitation, a questionnaire on condition and mental burden was conducted, and attention was paid to assure safety of the subjects. In addition, after obtaining the approval of the ethics committee of the University of Tokyo, the objective of this experiments and safety measures were explained to the subject in advance and we gained consent from the subject.



a) Shaking table



b) Human subject

Figure 1 Shaking table Test [8]-[10]

The strong motion records shown in Table 1 were used for the excitation. The records were observed on the vicinity of operation floor of a reactor building of nuclear power plants during the 2011 off the Pacific Coast of Tohoku Earthquake and Niigata-ken Chuetsu-oki Earthquake in 2007 occurred in Japan [13], [14].

Table 1 Input motion

Name	Earthquake name	Observation site	Amp. factor
Case 1	The Niigataken Chuetsu-oki Earthquake in 2007	Kashiwazaki-Kariwa Nuclear Power Plant, 3rd floor of Unit 7 reactor building	0.50
Case 2			0.70
Case 3			1.00
Case 4	The 2011 off the Pacific coast of Tohoku Earthquake	Fukushima Daiichi Nuclear Power Plant, 6th floor of Unit 6 reactor building	0.50
Case 5			0.85
Case 6			1.00
Case 7		Fukushima Daiichi Nuclear Power Plant, seismically isolation building	1.00

Figure 2 and 3 respectively show the acceleration waveform and acceleration response spectrum of each input motion. In order to restage the situation at the actual earthquake occurrence as much as possible, the order of the input motion was made random, and excitation was carried out without telling the subject the names of the input motions. In this study, the experimental result in the case 3 and 6 are mainly investigated.

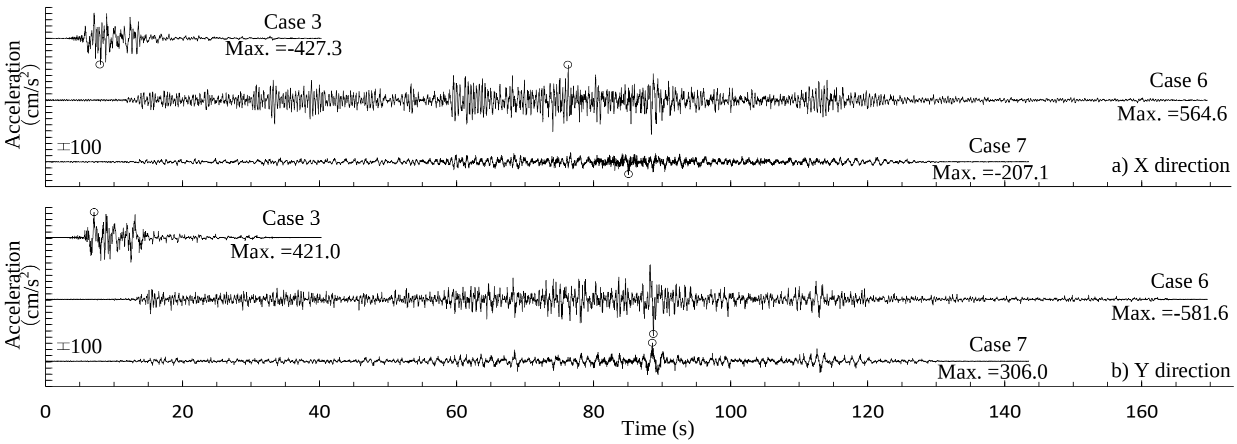


Figure 2 Acceleration Time History of Input Motion [13], [14]

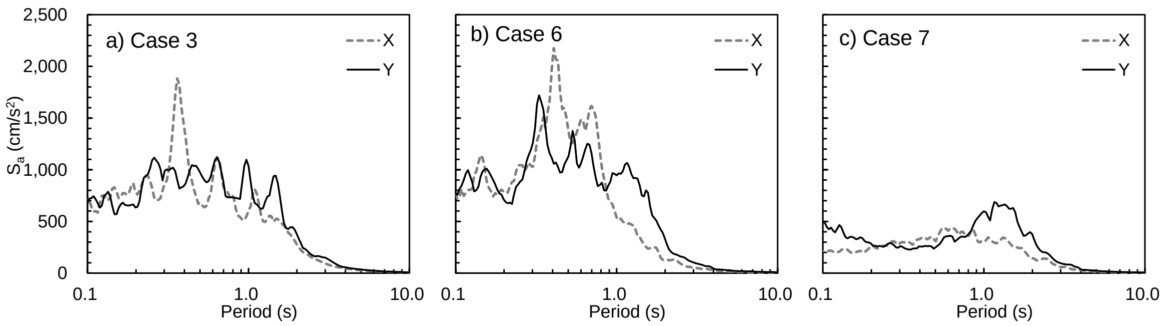


Figure 3 Acceleration Response Spectrum of Input Motion (h =5%) [13], [14]

3 Seismic analysis model of human body

Figure 4 illustrates the seismic response analysis model of the human body based on a cart-type double inverted pendulum with feedback control system [8]-[10].

Human body is modelled by two rigid bars. The upper bar corresponds to upper body, whereas the lower bar corresponds to lower body. Movement of the CoP due to weight shift and foot stepping of human could be considered by cart moving. Hip torque of human could be considered by a torque applied on a hinge between upper and lower bars.

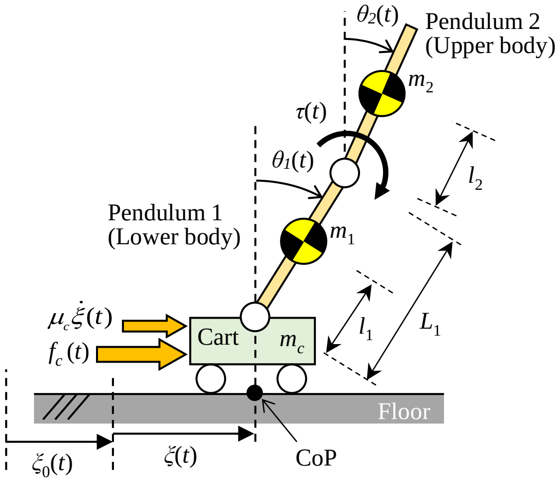


Figure 4 Seismic Analysis Model of Human Body Based on Cart-type Double Inverted Pendulum [8]-[10]

The equation of motions of the model are given as follows [15].

$$d_1\left\{\ddot{\xi}(t)+\ddot{\xi}_0(t)\right\}+d_2\ddot{\theta}_1(t)\cos\theta_1(t)+d_3\ddot{\theta}_2(t)\cos\theta_2(t)+\mu_c\dot{\xi}(t)=d_2\dot{\theta}_1^2(t)\sin\theta_1(t)+d_3\dot{\theta}_2^2(t)\sin\theta_2(t)+f_c(t) \quad (1)$$

$$d_2\cos\theta_1(t)\left\{\ddot{\xi}(t)+\ddot{\xi}_0(t)\right\}+d_4\ddot{\theta}_1(t)+d_5\cos\left\{\theta_1(t)-\theta_2(t)\right\}\ddot{\theta}_2(t)=d_7\sin\theta_1(t)-d_5\dot{\theta}_2^2(t)\sin\left\{\theta_1(t)-\theta_2(t)\right\}-\tau(t) \quad (2)$$

$$d_3\cos\theta_2(t)\left\{\ddot{\xi}(t)+\ddot{\xi}_0(t)\right\}+d_5\cos\left\{\theta_1(t)-\theta_2(t)\right\}\ddot{\theta}_1(t)+d_6\ddot{\theta}_2(t)=d_5\dot{\theta}_1^2(t)\sin\left\{\theta_1(t)-\theta_2(t)\right\}+d_8\sin\theta_2(t)+\tau(t) \quad (3)$$

Where, $\theta_1(t)$ and $\theta_2(t)$ are angles with respect to the vertical line of the lower pendulum and the upper pendulum at time t, $\xi(t)$ is the horizontal relative displacement between the cart and the floor, $\xi_0(t)$ is the horizontal absolute displacement of the floor. $f_c(t)$ is horizontal force applied on the cart, and $\tau(t)$ denotes torque applied on the hinge between lower and upper pendulum. μ_c is the damping coefficient of the cart.

Note that d_1 to d_8 in the above equations are expressed by the following equations.

$$\begin{array}{lll} d_1=m_1+m_2+m_c & d_2=m_1l_1+m_2L_1 & d_3=m_2l_2 \\ d_4=J_1+m_1l_1^2+m_2L_1^2 & d_5=m_2l_2L_1 & d_6=J_2+m_2l_2^2 \\ d_7=\left(m_1l_1+m_2L_1\right)g & d_8=m_2l_2g & \end{array} \quad (4)$$

Where, m_1, m_2 and mc are the masses of lower pendulum, upper pendulum and cart, respectively. J_1 and J_2 are the moment of inertia of lower bar and upper bar. l_1 and l_2 are the height from the lower end to the center of mass of the lower pendulum and the upper pendulum. L_1 is the total length of lower pendulum.

Fig. 5 shows a block diagram of the analysis model. $\mathbf{x}(t)$ is the state vector descrived as:

$$\mathbf{x}(t)=\left[\xi(t)\quad\theta_1(t)\quad\theta_2(t)\quad\dot{\xi}(t)\quad\dot{\theta}_1(t)\quad\dot{\theta}_2(t)\right]^T. \quad (5)$$

The differences between the reference vector $\mathbf{r}$ and the state vector $\mathbf{x}(t)$ is delayed for a short time which corresponds to reaction time of human, and input to the cart-type double inverted pendulum via two controllers. Considering the dead time L, the control force $f_c(t)$ applied to the cart and of the control torque $\tau(t)$ applied to the hip are expressed by the following equations.

$$f_c(t) = -\mathbf{K}_{fc}\mathbf{x}(t-L) \tag{6}$$

$$\tau(t) = -\mathbf{K}_{\tau}\mathbf{x}(t-L) \tag{7}$$

Where, $\mathbf{K}_{fc}$ and $\mathbf{K}_{\tau}$ are the feedback gain described by the following equations.

$$\mathbf{K}_{fc} = \begin{bmatrix} k_{f\xi} & k_{f\theta_1} & k_{f\theta_2} & k_{f\dot{\xi}} & k_{f\dot{\theta}_1} & k_{f\dot{\theta}_2} \end{bmatrix} \tag{8}$$

$$\mathbf{K}_{\tau} = \begin{bmatrix} k_{\tau\xi} & k_{\tau\theta_1} & k_{\tau\theta_2} & k_{\tau\dot{\xi}} & k_{\tau\dot{\theta}_1} & k_{\tau\dot{\theta}_2} \end{bmatrix} \tag{9}$$

Where, $k_{f\xi}$, $k_{f\theta 1}$, $k_{f\theta 2}$, $k_{f\dot{\xi}}$, $k_{f\dot{\theta}_1}$, and $k_{f\dot{\theta}_2}$ are the feedback gains of f_c, multiplied to the state variables (the horizontal relative displacement between the cart and the floor, the angles of the lower and upper pendulum, the horizontal relative velocity of the cart, and the angular velocity of the lower and upper pendulum). Similarly, $k_{\tau\xi}$, $k_{\tau\theta 1}$, $k_{\tau\theta 2}$, $k_{\tau\dot{\xi}}$, $k_{\tau\dot{\theta}_1}$, and $k_{\tau\dot{\theta}_2}$ denote the feedback gains of τ, multiplied to the state variables, respectively. In this study, the analyses are performed using MATLAB and Simulink [16].

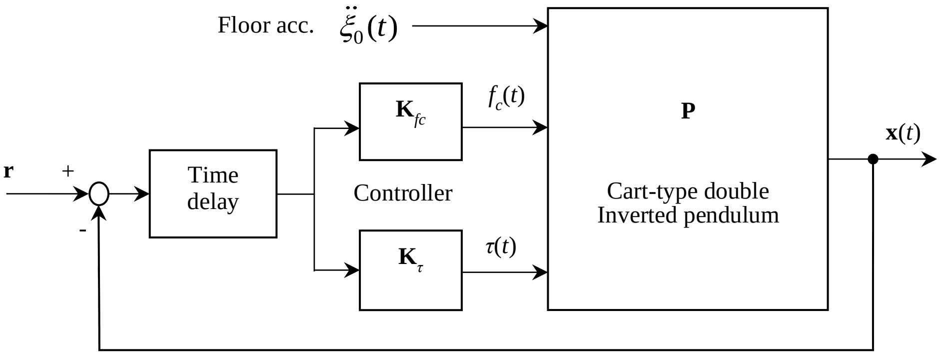


Figure 5 Block Diagram of Seismic Analysis Model of Human Body

4 Analytical result of seismic response analysis model of human body

In this study, the behavior in the Y direction, the backward and forward direction of the human subject, is dealt with. Table 2 shows the parameters of the inverted pendulum. The length and weight of the pendulum were set based on the height and weight of the human subject of the shaking table test. The moment of inertia J_1 and J_2 were calculated from the height of the human subject's center of mass of body segments and the mass distribution. The dead time L was set to 0.1 sec.

Table 2 Parameter of Cart-type Double Inverted Pendulum Model

m_1 (kg)	m_2 (kg)	m_c (kg)	L_1 (m)	L_2 (m)	l_1 (m)	l_2 (m)	J_1 (kgm^2)	J_2 (kgm^2)	μ_c (Ns/m)	L (s)	g (m/s^2)
16.7	38.6	1.68	0.82	0.785	0.453	0.301	5.55	3.5	10000	0.1	9.8

Table 3 shows the feedback gains. After finding the optimum feedback gain with a linear quadratic regulator (LQR), the feedback gains were adjusted so that the analytical result corresponds to the behavior of the test subject in case 3 of the shaking table test.

Table 3 Feedback Gain

$k_{f\xi}$ (N/m)	$k_{f\theta 1}$ (N/rad)	$k_{f\theta 2}$ (N/rad)	$k_{f\dot{\xi}}$ (Ns/m)	$k_{f\dot{\theta} 1}$ (Ns/rad)	$k_{f\dot{\theta} 2}$ (Ns/rad)
175	-39700	-24000	-12900	-12300	-4530
$k_{\tau\xi}$ (N)	$k_{\tau\theta 1}$ (Nm/rad)	$k_{\tau\theta 2}$ (Nm/rad)	$k_{\tau\dot{\xi}}$ (Ns)	$k_{\tau\dot{\theta} 1}$ (Nms/rad)	$k_{\tau\dot{\theta} 2}$ (Nms/rad)
-12.8	-66.5	186	-14.3	-22.6	24.8

Figure 6 shows the time history waveforms of the horizontal relative velocity and the relative displacement of human's head with respect to the floor, the horizontal relative displacement of the CoP, and the shaking table acceleration. In the experiment, each waveform was input twice. The figure shows both test results and analysis results. Although the CoP displacement waveform of the analysis model does not show any high frequency components contained in the experimental results, amplitude and phase of the CoP displacement evaluated by the human model roughly correspond with the experimental results. The phase of the head displacement in the analysis corresponds well with the experimental results. In the experiment, the subject's head displacement was slightly shifted to the forward side because the subject was slightly inclined forward. This tendency was particularly remarkable in Case 6. Although the maximum head displacement obtained by the analysis was slightly underestimated, the phase of the head displacement waveform evaluated by the analyses correspond well with the experimental results. The head velocity of the analysis model reproduced the experimental results very well in both amplitude and phase. These shows that the proposed analysis model is appropriate.

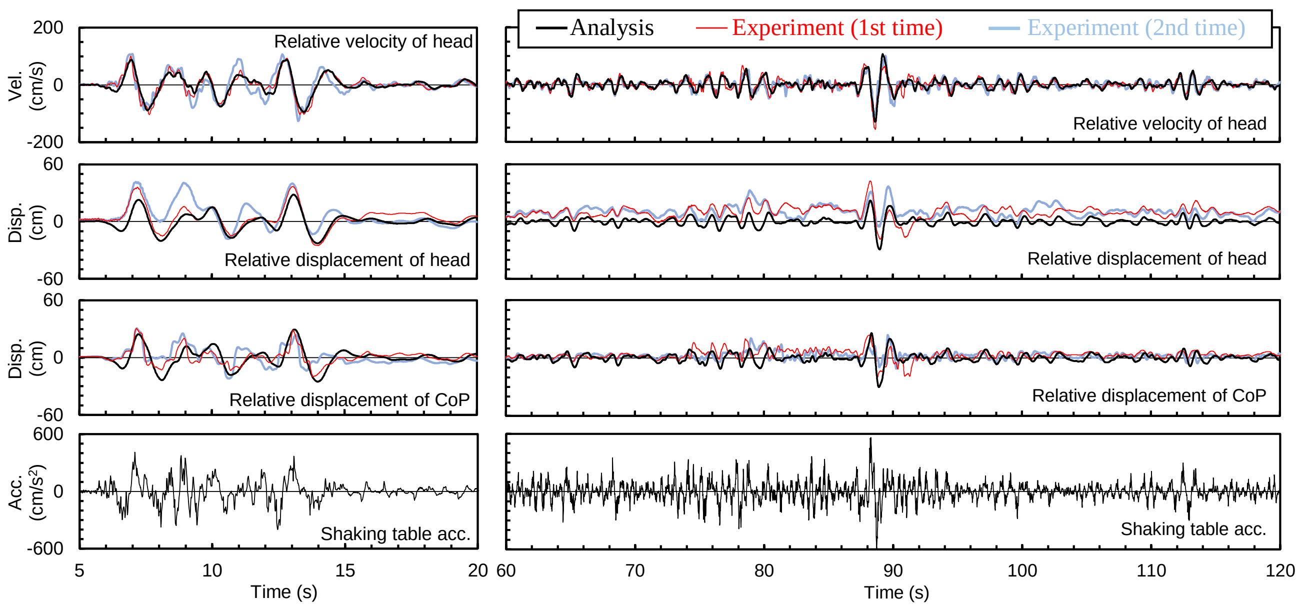


Figure 6 Time History Waveforms of Human Motion and Shaking Table Acceleration

5 Evaluation of human injury by using HIC

The maximum value of horizontal relative displacement of head is related to the possibility of collision to object, and the maximum displacement of CoP is related to an increased risk of falling over in narrow floor or stairs. Furthermore, humans can suffer severe damage if they hit their head to object such as wall and furniture. Considering those facts, we evaluated the possibility of human injury based on maximum displacement of head and CoP, and Head Injury Criterion (HIC) developed by National Highway Traffic Safety Administration [17]. HIC is defined by the following equation.

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{\max} \tag{10}$$

Where, a (t) is the acceleration of the head at the time of hitting to an object, t_1 and t_2 denote integration interval, t_2-t_1 was set to 15 msec. "max" denotes to select the integration interval to maximize HIC.

We assumed that the amplitude of acceleration acting on the head is constant during hitting time Δt. Furthermore, by using the relative velocity of the head with respect to the object right before the hitting, V_0, and the coefficient of restitution between the head and the object, e, we get the following equation.

$$HIC = (t_2 - t_1) \left\{ \frac{1+e}{g\Delta t} V_0 \right\}^{2.5} \tag{11}$$

The coefficient of restitution, e, and hitting time, Δt, were set based on previous research [18]. In this study, we assume that human hit his head against rigid plane at maximum velocity of head during earthquake. Note that these assumptions can lead overestimation of human injury.

HIC values which reach 50% probability of injury levels are showed in table 4 [19]. The table also shows the relationship between head velocities (V_0) and HICs derived by equation (11) [20].

Table 4 HIC and Head Velocity Correspond to Injury Level [19], [20]

Injury (p=50%)	HIC	Head velocity (cm/s)
Minor (head injury without disturbance of consciousness)	331	205
Moderate (skull fracture)	593	259
Critical (cerebral contusion)	1848	408
Fatal (death)	2175	435

6 Case study based on seismic analysis model of RC super high-rise building

In this chapter, seismic response analyses of an RC super high-rise building are performed in order to evaluate the human injury during earthquake. Figure 7 illustrates the analysis model [21]. This model is a multi-mass shear model, and the restoring force characteristics of each layer are degrading trilinear models. The damping model is of the tangent stiffness-proportional damping, and the damping ratio h was set to 0.03 for the first-order natural frequency. This model is expressed by the following equations [21].

$$T_1 = 0.02 \times 3N \tag{12}$$

$$\frac{m_n}{A_0} = -0.31 z_n + 1.55 \quad (z_n \geq 0.25) \tag{13}$$

$$\frac{m_n}{A_0} = 25.4z_n^2 - 13.3z_n + 3.21 \quad (z_n < 0.25) \tag{14}$$

$$\gamma_{\beta u1} = -3.91z_n^2 + 3.74z_n + 0.86 \tag{15}$$

$$\gamma_1 = (4.54z_n + 5.48) \times 10^{-4} \tag{16}$$

$$\gamma_2 = (-6.02z_n^3 - 2.61z_n^2 + 7.36z_n + 6.01) \times 10^{-3} \tag{17}$$

$$C_B = \frac{\alpha}{T_1} \tag{18}$$

Where T_1 is the natural period of 1st mode [s], N is the floor number of the building, m_n is the mass of the n th floor [ton], A_0 is the floor area [m^2], z_n is the normalized height of the n th floor, $\gamma\beta_{u1}$ is the inter-story drift angle of the participation function β_{u1} in the first-order mode, γ_1 and γ_2 are the inter-story drift angles at the crack and the yield strength, and C_B is the base shear coefficient. The floor height was set to 3 [m], the floor area A_0 was set to 900 [m^2], the coefficient α = 0.166, and the third stiffness is 0.1 times the initial stiffness [21]. In this study, we use a 30-story (T_1 = 1.8 [s]) building model.

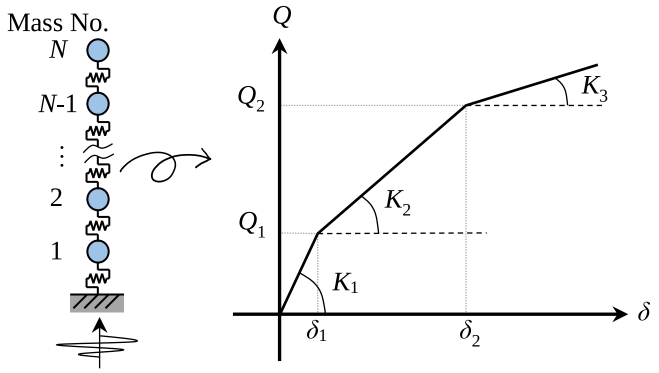


Figure 7 Analysis model of RC super high-rise building

The seismic waveforms of El Centro 1940 NS [22] with a maximum velocity of 50 [cm/s] and BCJ Lv. 2 provided by the building center of Japan [23] are used for the input wave. In this study, analyses were performed by using SNAP Ver. 7 [24]. After the analyses of building, the acceleration wave forms of each floor were input to the seismic analysis model of human boy. Then the maximum responses of the human were investigated.

The height distribution of peak floor acceleration (PFA), peak floor velocity (PFV), and peak inter-story drift angle (PIDA) of the building are shown in fig. 8 and 9. These graphs also show the height distributions of the displacement of CoP and head, and the head velocity of human. the floor response acceleration tends to be larger in the lower and upper floors in each case. On the other hand, the floor response velocity increases from the lower floor to the higher floor. In both cases, the inter-story drift angle is less than 1/100 [rad] on all floors.

Ito et al. [20] conducted an interview survey with operators at the Kashiwazaki-Kariwa Nuclear Power Plant to investigate the action difficulty of operator during the shaking of the 2007 Niigata-ken Chuetsu-oki Earthquake. In addition, the strong motion records observed near the central control room of the nuclear power plant during the earthquake were input to the seismic response analysis model of the human body and obtained the maximum displacements of the CoP. Then, the maximum CoP displacements were compared with the results of the interview survey about action difficulty of the human. As a result, it has been revealed that it is difficult for the operator to act on his own will when the maximum displacement of CoP exceeds about 40 cm.

It can be seen from figures 8 and 9 that the higher the floor, the larger the human responses. The CoP displacement exceeds 40 cm on almost all floors in both cases. This suggests that the action during the earthquakes would be extremely difficult. Particularly, the maximum displacement of CoP on the top floor is about 160 [cm] when BCJ Lv. 2 is input, and humans are greatly tossed about by shaking. If the floor area was too small to keep the standing posture, the risk of falling increases. In addition, the maximum displacement of the head is also large similarly to the maximum displacement of the CoP, especially on a high floor, and the risk of the head colliding against an obstacle, e.g., wall or furniture, is increased. Furthermore, the maximum relative velocity of the head exceeds moderate injury level on the top floor. This suggests that if the head of human collides against an obstacle, the human can suffer severe injury.

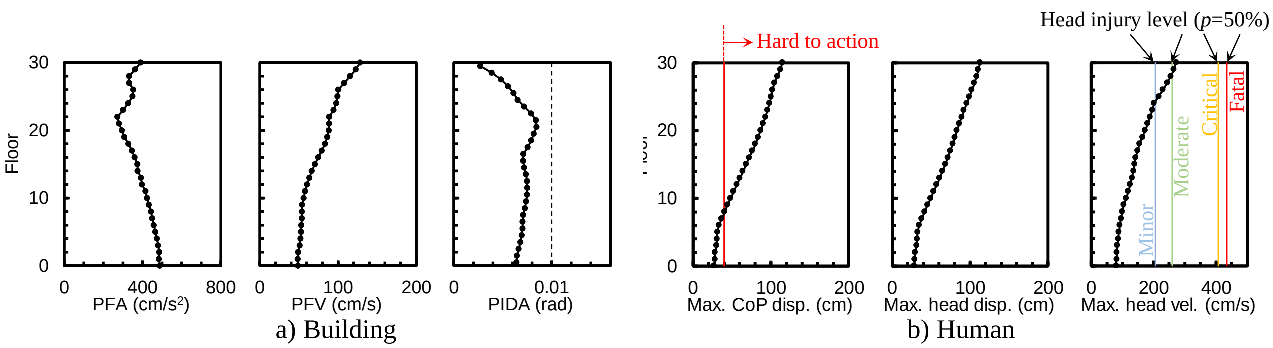


Figure 8 Height distributions of maximum responses of building and human (El Centro NS)

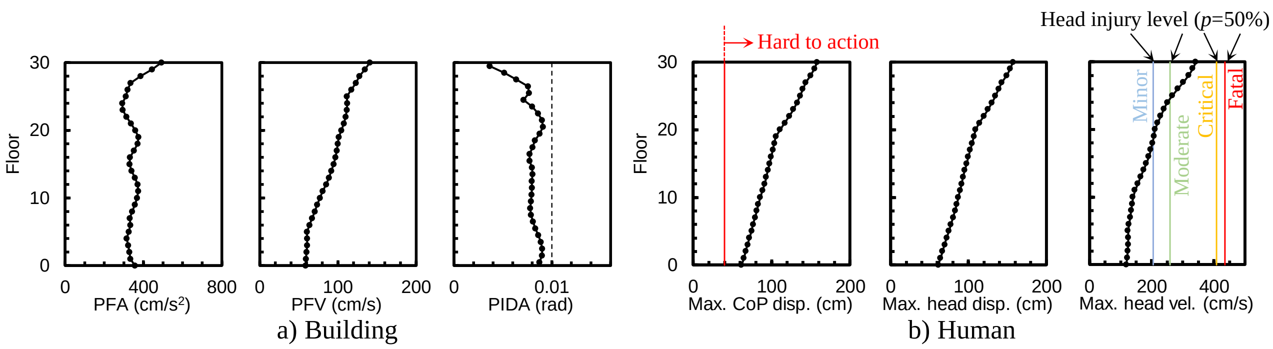


Figure 9 Height distributions of maximum responses of building and human (BCJ Lv. 2)

As mentioned above, even though the maximum inter-story drift angles of the building were less than 1/100 rad on all floors in all cases, the possibility of human injury was extremely high, especially on the upper floors. This suggests that merely confirming that the inter-story drift angle was less than the design criteria may not be enough as an earthquake safety evaluation of the building.

The seismic response analysis model of the human body constructed in this study evaluates the behavior of only one subject in the shaking table test. Thus, the model could not evaluate the variation of behavior caused by the individual differences. It is also important to note that the seismic response of the human body shown in this chapter includes the result that exceed the input level of the shaking table test. Therefore, it is necessary to verify the validity of the analysis results when an extremely large amplitude shaking is input by collecting further shaking table test data and information on injuries during an actual earthquake. Although there are future issues, the possibility of human injury is evaluated using the nonlinear seismic response analysis model of the human body proposed in this study. It is expected to contribute to the construction of a building design method to reduce human damage as well as the structural safety of the building.

7. Conclusion

In this study, we conducted the shaking table tests, and constructed a seismic response analysis model of human body by using a cart-type double inverted pendulum with feedback control system. We also proposed a method to evaluate the possibility of human injury during an earthquake based on the analysis results. Then, the seismic response analyses of RC super high-rise building were performed in order to calculate the risk of human injury in the building. As a result, it was suggested that even if the building did not suffer severe damage, humans in the building can suffer severe injury due to collisions against a furniture or wall.

Evaluation of variations in behavior due to individual differences and examination of the validity of the analysis results when extremely large amplitudes are input to a human are topics for future work.

8. Acknowledgements

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