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Experimental Study Concerning Impact Characteristics by Collision of Weight on Sand Cushion over Steel Beam

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ABSTRACT: Sand cushion is often utilized in rockfall protection structures as a shock absorber. Impact by rockfall is considered one of the most important variable loads for protection structures. To clarify the evaluation method and the buffering effects of impact force, the series of weight impact experiment were conducted. A simple supported double steel beam was used to reproduce the behavior of structure. Experiments were carried out by the free fall of the weight to the sand tank installed at the center of simply supported double steel H beams. The impact force of the weight and transmitted force under the sand tank as well as displacements of beam and strains of the beam were measured. Dynamic characteristics of impact force, transmitted force to the steel beam and behavior of the beam were investigated. Dynamic interaction between sand and beam, shock absorbing effect of sand and also the transfer ratio of kinetic energy of rockfall to the structure were shown.

Keywords: Rockfall, Impact Force, Sand Cushion, Protection Structure

1. INTRODUCTION

Generally rockfall protection structures are classified into nets, fences, shelve, walls, embankments, and rocksheds, etc. (Fig.1 and Fig.2) [1], [2]. Rockshed is one of the safe and important protection structures when the target rockfall has the large energy. In Japan, many prestressed concrete rocksheds and reinforced concrete rocksheds have been constructed. A certain cushion material is generally installed on the roof of the rockshed for the purpose to buffer the impact force by a rockfall. Sand is mostly used as typical cushion material in Japan. Sand and a bag in which sand is filled are also used for a protection shelf or protection embankment for the same purpose. Risk is rarely remained sometimes at the protection structure for the rockfall with large energy beyond initial estimation (Fig.3) [3], [4].

Fig. 1 Rockshed and protection net

Research of this shock absorbing material has been done for years [5] However, the evaluation method of impact behavior and the absorbing effects of impact force which is transmitted to the structure through the cushion are not necessarily clarified enough. It has been clear empirically that sand cushion has a large shock absorbing effect. Therefore, the use of sand cushion material for protection structures, such as a rockshed, is considered rational against the impact force by a rockfall.

When a protection structure is designed according to the idea of a performance based design, it is necessary to clarify

Fig. 2 Embankment for rockfalls

Fig. 3 Failed rockshed by large rockfall

the ultimate state of a protection structure in which sand cushion is installed. It is also required to advance suitable use of cushion material from the point of repair and reinforcement of the existing structure. In this research, the series of impact experiments to the sand cushion on H section steel beam were conducted in order to obtain the fundamental data about the impact action for designing a structure safely and rationally. This paper reports the knowledge acquired by investigating the impact force, the absorbing effect of sand cushions, dynamic interaction between structure and cushion.

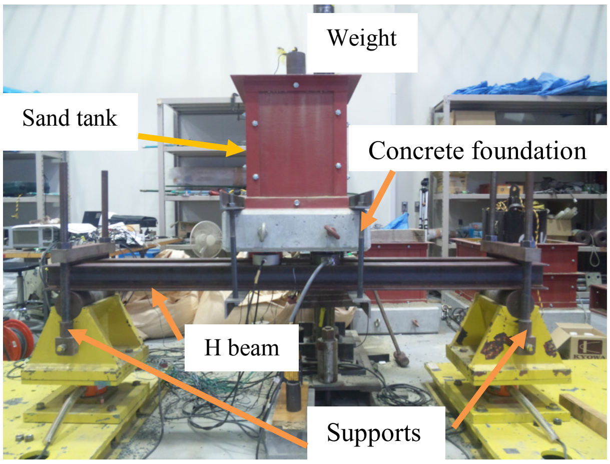


Fig. 4 Device of impact experiment

2. OUTLINE OF EXPERIMENT

2.1 Method of Experiment

Fig. 4 shows the free-fall type device for impact experiment set up at the Structure Engineering laboratory of Kanazawa University. The sand tank filled up with sand cushion material was installed in the center of two H-beams, which were simple supported locating in parallel. The size of a sand tank was 350 mm in width, 350 mm in depth and 500 mm in height. It was fixed to H beams with the angle steel beams and bolts.

Table 1 Properties of used cushions

Type	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Effective particle size D_{50} (mm)	Uniformity coefficient C_u	Coefficient of curvature C_c
Sand	0.2	0.34	0.61	0.49	3.10	0.95
Gravel	4.0	5.5	6.5	6.1	1.63	1.16

The used H-beams were H-100x100x6x8 (mm). The span lengths of beams were 1.3 m, 1.8 m, 2.8 m and 3.8 m. The used weight is a steel cylinder with a diameter of 80 mm and a mass of 7.233 kg, and the tip form is spherical. Two kinds of shock absorbing materials accordingly one kind of sand and one kind of gravel were used. The characteristic values of sand and gravel are shown in Table 1. The used gravel and sand were crushed stone and loose sand with grain size ranges as shown in Fig. 5. The sand tank was covered by a thickness of 0.5 m in both cases.

Table 2 shows the list of all experiments carried out. The falling heights of the weight were seven kinds respectively 0.5 m,0.75 m, 1.0 m, 1.25 m, 1.5 m, 1.75 m and 2.0 m. 3 times impact experiments were carried out on each condition.

2.2 Measurement Items and Measurement Method

Measurement devices include an accelerometer (Kyowa Electronic Instruments Co., Ltd., AS-100HA), load cell (Kyowa Electronic Instruments Co., Ltd., LUK-1TBS), laser displacement meter (Keyence Corporation, LB300) and strain gauge (Tokyo Sokki Kenkyujo Co.,Ltd., FLA-10-11-3-LT) as shown in Fig. 6.

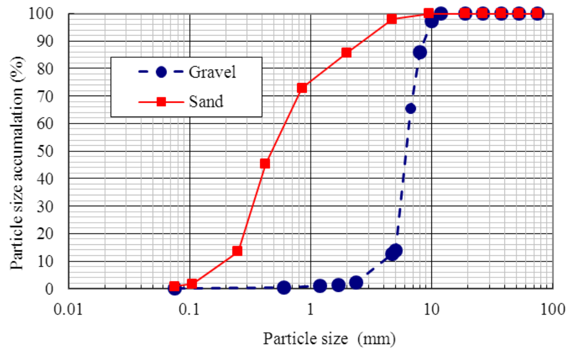


Fig. 5 Particle size accumulation curve

Table 2 List of impact experiments

Cushion	Span length of beam (m)	Falling heights of weight (m)
Sand	1.3	0.50,0.75,1.00,1.25,1.50,1.75,2.00
	1.8	0.50,0.75,1.00,1.25,1.50,1.75,2.00
	2.8	0.50,0.75,1.00,1.25,1.5,01.75,2.00
	3.8	0.50,0.75,1.00,1.25,1.50,1.75,2.00
Gravel	1.3	0.50,0.75,1.00,1.25,1.50,1.75,2.00
	1.8	0.50,0.75,1.00,1.25,1.50,1.75,2.00
	2.8	0.50,0.75,1.00,1.25,1.50,1.75,2.00
	3.8	0.50,0.75,1.00,1.25,1.50,1.75,2.00

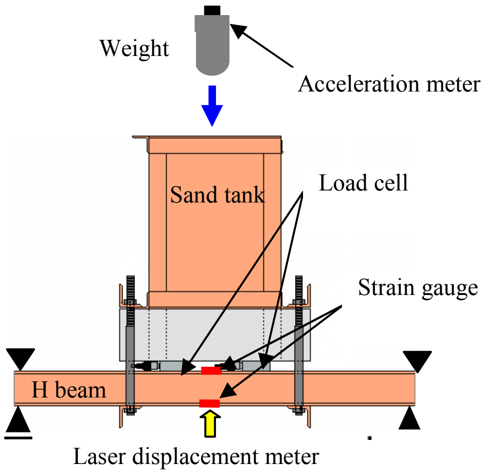


Fig. 6 Measurement devices and their locations

Concretely, the accelerometer was installed at the center of the weight to measure its acceleration. The laser displacement meter was used to measure deflection of the steel beams. The transmitted force of the sand tank to H-beams was determined through the load cells placed between the tank bottom and the beams. The strain gauges mentioned above were stuck to measure axial direction strain at the top and bottom flange of the central section of H-beam.

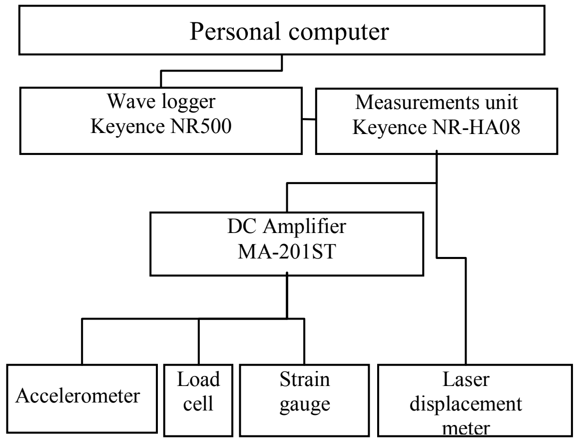


Fig. 7 Measurement system

Fig. 7 shows the measurement system of this experiment. The output obtained from each measuring instrument was measured at intervals of the sampling of 100 μs (sampling frequency: 10 kHz) and recorded by PC.

3. RESULTS OF EXPERIMENT

3.1 Dynamic behavior of impact experiment

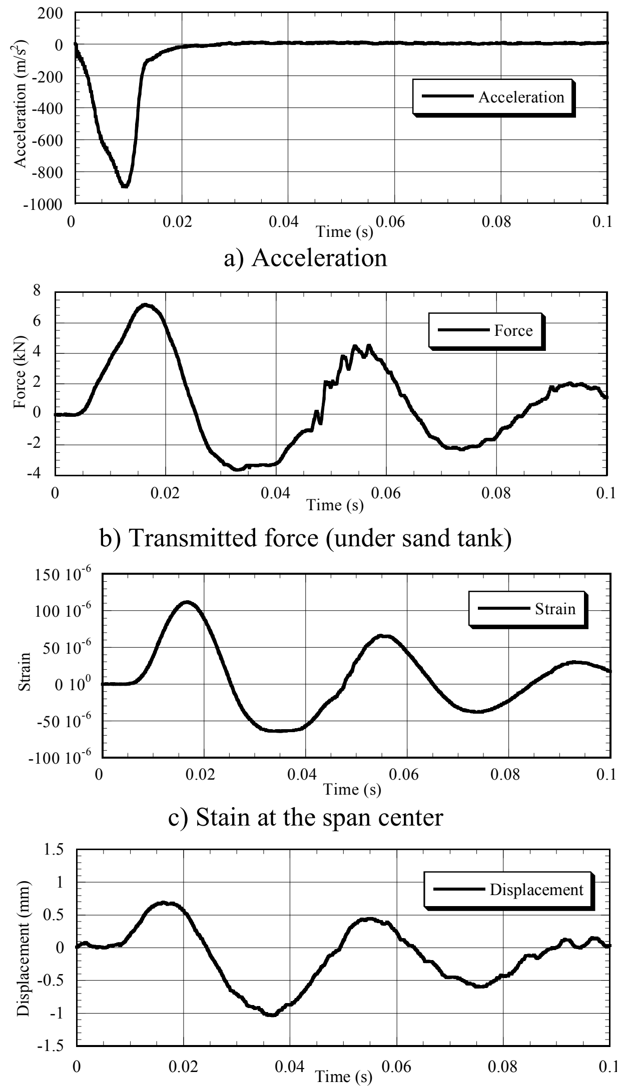
Fig. 8 shows the time history of measured data for the case 1.8m in span length, and 2.0 m in falling height for sand cushion.

The acceleration of the falling weight reached the peak at approximately 0.01 s after having collision into the sand cushion and became zero at 0.02 s. The transmitted force measured under the sand tank appeared at 0.005 s, reached its peak at 0.016 s and became zero at 0.025 s. The damped oscillation of the transmitted force was described afterward. Strain and displacement appeared at 0.01 s, also reached their peaks at approximately 0.016 s and became zero at 0.025 s. The similar damped oscillations were shown afterward in both time histories.

Generally, the dynamic behavior of structure under hard impact load is complicated. Hard impact herein means that the magnitude of impulse force is large and duration of impact is very short. Meanwhile, it is also known that the response of structure under relatively soft impact load is mostly quasi-static. Those beams used in this study have large mass at the center of span center. The impact load, furthermore, occurred due to the collision of the weight to the cushion is relatively smooth because of the shock absorbing effect of the cushion material. In that case, it can be assumed that the response of the beam was quasi-static.

Fig. 9 shows the deflection curve and the bending moment diagram of the simple beam under two static concentrated loads. Equivalent static forces can be determined according to the deflection and the strain resulted from bending moment under this assumption. Here, P_s and P_d are equivalent forces by the strain and the deflection.

Fig. 10 shows time histories of the impact force, transmitted force and equivalent forces by strain and deflection for four cases, namely span length L=1.8m and 3.8 m for sand cushion and gravel cushion. The falling height H is 2.0 m for any case. The impact force P_a is smaller than the other forces for sand cushion with span length L=1.8 m. In this



a) Acceleration

b) Transmitted force (under sand tank)

c) Stain at the span center

d) Deflection at the span center

Fig. 8 Time histories of measured data (Sand, span length1.8m, falling height 2.0m)

case, the maximum of force is large in the order of the transmitted force P_t, the strain equivalent force P_s and the deflection equivalent force P_d. Meanwhile, such sand cushion on the longest span length L=3.8 m, the impact force P_a is larger than the other forces. The shape of the first

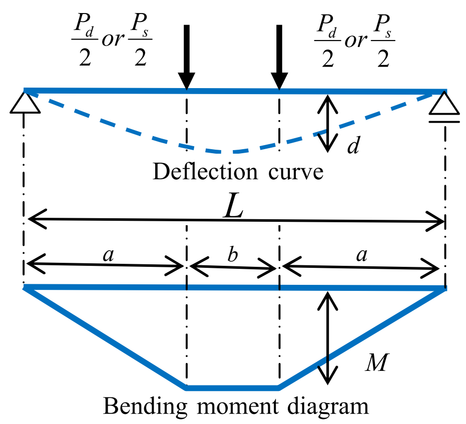
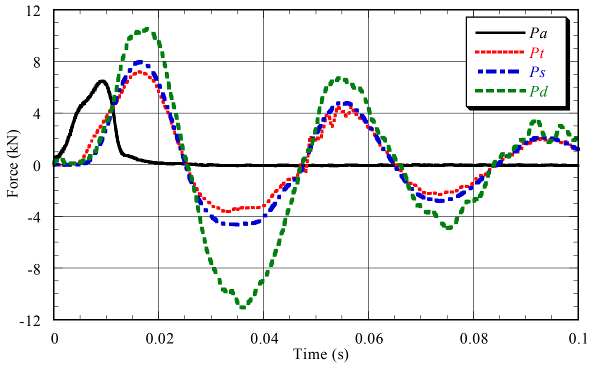
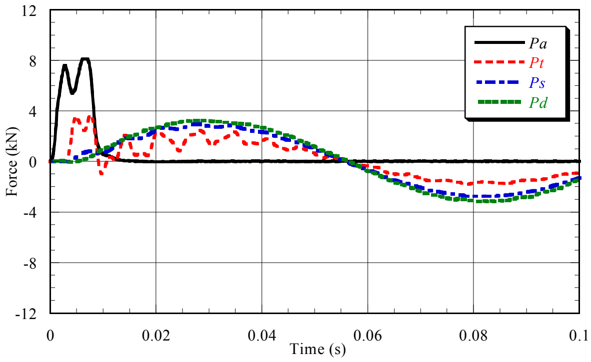


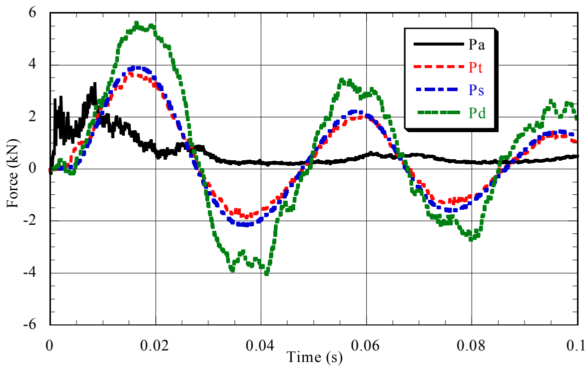
Fig. 9 Deflection and bending moment of the beam under equivalent static forces P_d and P_s



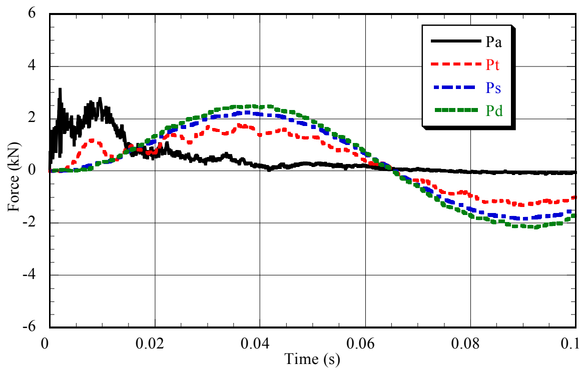
a) Sand (L = 1.8 m, H = 2.0 m)



b) Sand (L = 3.8 m, H = 2.0 m)



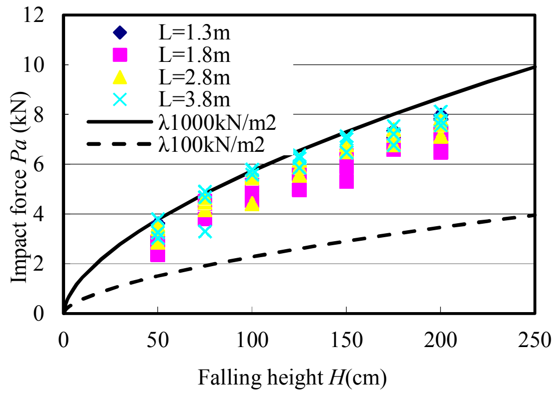
c) Gravel (L = 1.8 m, H = 2.0 m)



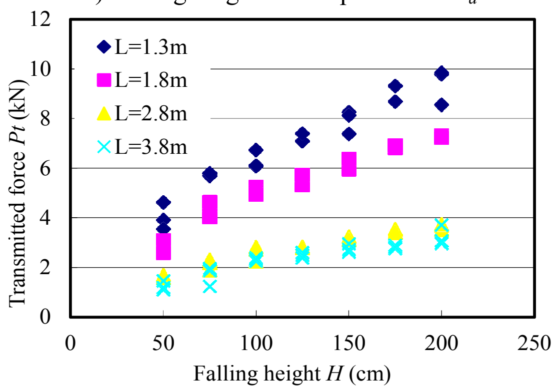
d) Gravel (L = 3.8 m, H = 2.0 m)

Fig. 10 Impact force, transmitted force and equivalent forces by strain and deflection

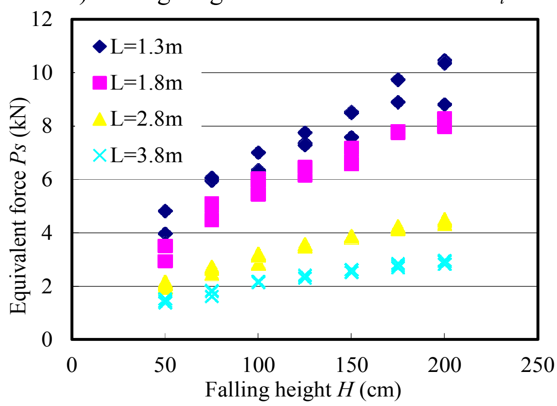
wave of the transmitted force P_t is similar to the impact force P_a. However, the wave shape of P_t afterward is similar to the shapes of the equivalent forces P_s and P_d. The wave periods of these forces with span length L=3.8 m are double longer than those periods with the span length L=1.8 m. For the gravel, similar tendencies are observed. However, maximum values of forces are smaller than those



a) Falling height and impact force P_a



b) Falling height and transmitted force P_t



c) Falling height and equivalent force P_s

Fig. 11 Relationship between falling height and various maximum forces for sand

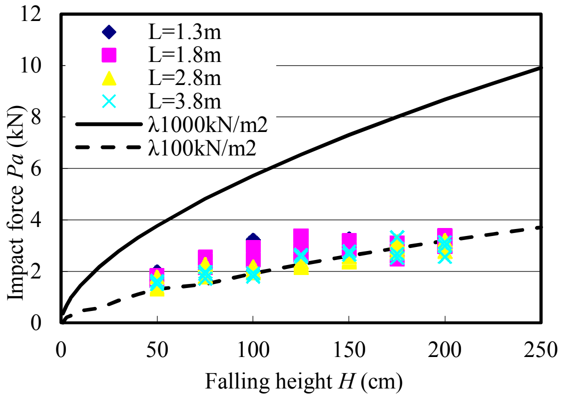
values in sand. It becomes clear that the gravel has stronger shock absorbing ability than sand has and the large flexibility of the beam itself also contributes to the cushioning role for impact.

3.2 Maximum impact force

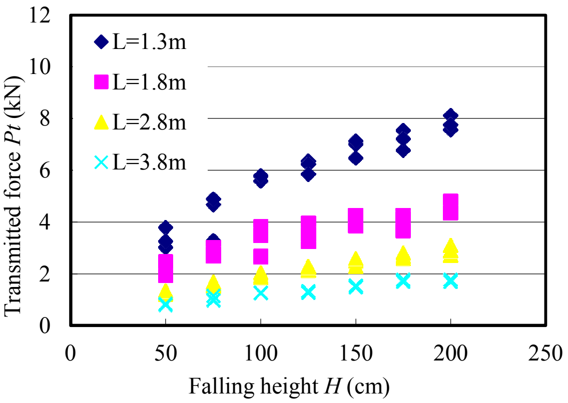
Fig. 11 shows the relationship between the falling height and various maximum impact forces for sand. In Fig. 11(a), linear estimated by the design formula for the impact load due to rock fall are shown. The formula was drawn from the elastic contact theory and widely used in Japan. This design formula is expressed as the following equation [1].

$$P = 2.108(mg)^{2/3}\lambda^{2/5}H^{3/5} \quad (1)$$

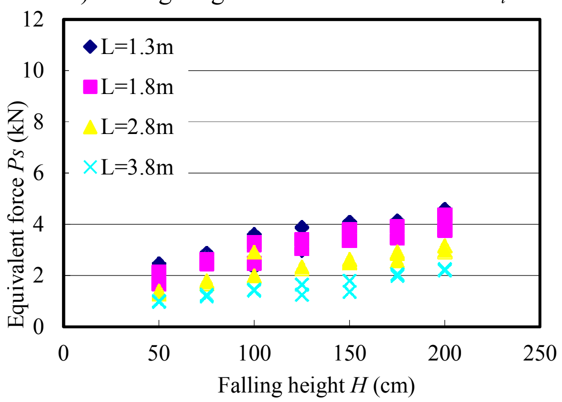
In this equation, m is the mass of a falling rock (ton), H is the height of a rock fall (m), λ is the Lame coefficient of



a) Falling height and impact force P_a



b) Falling height and transmitted force P_t



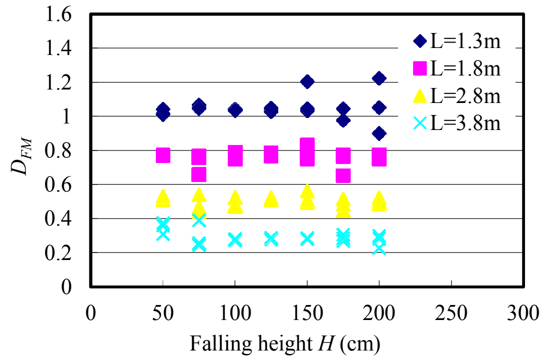
c) Falling height and equivalent force P_s

Fig. 12 Relationship between falling height and various maximum forces for gravel

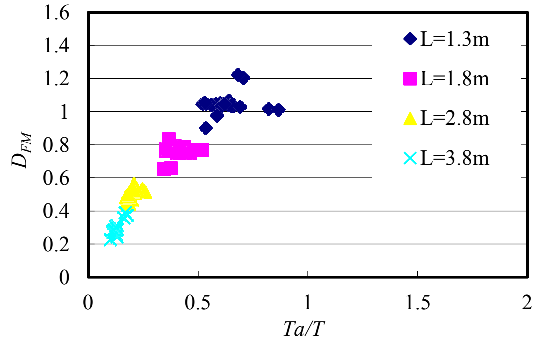
cushion material (kN/m^2) and g is the gravity acceleration (m/s^2).

There is no significant difference among span length L concerning the impact force P_a. The upper limit of the impact force is expressed as (1) λ=1000kN/m^2. Concerning the transmitted force P_t, it is understood that the span length get large, the force becomes small. Mostly similar tendencies are also observed for the strain equivalent force P_s, which is slightly larger than the transmitted force P_t.

Furthermore, Fig. 12 shows the relationship between the falling height and various maximum impact forces for gravel. There is also insignificant difference among span length L concerning the impact force P_a as observed in the case of sand. The lower limit of the impact force is expressed as (1) λ=100kN/m^2. It is observed that the tendencies of collision results on gravel are similar to results on sand, excepting P_s is smaller than P_t.



(a) Falling height and dynamic multiplication factor D_{FM}



(b) Relationship between T_a/T and dynamic multiplication factor D_{FM} (T_a: duration of impact force, T: the first natural period of beam)

Fig. 13 Dynamic multiplication factor by impact (sand)

3.3 Dynamic multiplication and energy transfer

It is generally required to rationally and safely estimate the impact load for the practical design of protection structure. Some experimental results and discussions are shown in this section concerning dynamic multiplication and energy transfer from the falling weight to the beam.

Fig, 13 shows the results concerning the dynamic multiplication for sand. Fig 13 (a) shows the relationship between the falling height H the dynamic multiplication factor. The dynamic multiplication factor is generally expressed as the following equation.

$$D_{MF} = \frac{R_{dyn}}{R_{st}} \tag{2}$$

In this equation, R_{st} is the response of the structure when the maximum dynamic force acts statically and R_{dyn} is the dynamic response of the structure. In this case, strain is used for the response of structure. It is clear that there is no particular relationship between the falling height H and the dynamic multiplication factor D_{MF} and this relationship is mostly constant. The dynamic multiplication factor D_{MF} becomes small if the span length L of the beam becomes large. Because the longer span beam has the longer first natural period T for mostly constant duration of impact force T_a. Fig 13(b) shows the Relationship between

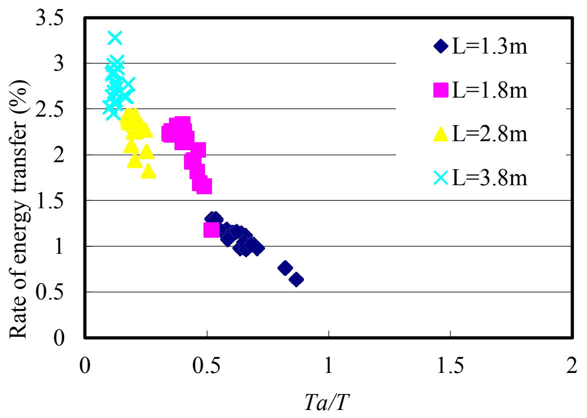


Fig. 14 Relationship between T_a/T and rate of energy transfer to beam from falling weight (sand)

T_a/T and the dynamic multiplication factor D_{MF}. It is clearly recognized that there is a proportional relationship between T_a/T and the dynamic multiplication factor D_{MF}.

Fig. 14 shows the relationship between T_a/T and the rate of energy transfer to beam from falling weight for sand. The energy transfer is the transferred energy from the potential energy of the weight mgH to the beam. It has become clear that the rate of energy transfer becomes small when the ratio T_a/T becomes large. The rate of energy transfer R_E^{tr} is important to design the member and structure under the impact. It can be considered that one of important characteristics of shock absorbing cushion is expressed by this rate of energy transfer.

We are doing further investigation concerning detailed formulation of this effect and application to design.

4. CONCLUSION

In this research, series of impact experiments to the sand cushion on steel H-section beam were conducted in order to obtain the fundamental data about the impact action. Obtained results in this research are summarized as follows.

1) The dynamic behaviors of steel H-beam with cushion under impact were concretely shown including characteristic of the impact force. The concept and actual data concerning the equivalent force were introduced and shown.
2) The impact force P_a obtained by the acceleration of the weight is mostly equal depending only falling height H using both sand and gravel cushion.
3) The transmitted force at the bottom of cushion P_t becomes small when the span length L becomes large because of the effect of dynamic flexibility of the beam. The force in gravel cushion is smaller than in sand cushion.
4) The magnitude of equivalent force P_s or P_s also depends on the span length as like that of the transmitted force P_t.
5) The dynamic multiplication factor D_{MF} has particular relationship with the natural period of the beam T and no relation with the falling height H.
6) The rate of energy transfer to the beam from falling weight R_E^{tr} was concretely shown. It has been shown that there is relationship between R_E^{tr} and the natural period of the beam T.

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