A PRACTICAL DESIGN METHOD
OF THREE-LAYERED ABSORBING SYSTEM

Hisashi Konno[1], Osamu Nakano[2], Norimitsu Kishi[3], Yukio Gotoh [4], and Yoshihiro Ishikawa[5]

ABSTRACT

In order to effectively absorb and to disperse the impact force occurred due to flight and/or falling bodies, a Three-Layered Absorbing System has been developed by authors, which is composed of sand layer (top), Reinforced Concrete (RC) core slab, and Expanded Poly-Styrol (EPS) block layer (bottom). The applicability was confirmed performing many prototype impact tests by means of a falling-weight impact test method. Here, the practical design method for determining the main parameters of the system (thickness of RC core slab and EPS layer, and transmitted impact force) is developed to easily apply it in real protective structures like rock-shed structures. The design values obtained from this method are compared with the experimental results. It is seen that the proposed method can be apply to the practical design with a good agreement.

Key Words: EPS, Three-Layered Absorbing System, impact, RC core slab, transmitted impact force

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[1] Chief Researcher , Structures Division, Civil Engineering Research Institute of Hokkaido, ME
(Address: 1-3 Hiragishi, Toyohira Ward, Sapporo, 062-8602 Japan,
Tel: +81-11-841-1698, Fax: +81-11-820-2714, E-mail: 86167@ceri.go.jp)

[2] Hokkaido Development Bureau, Ph. D

[3] Professor, Department of Civil Engineering, Muroran Institute of Technology, Ph. D

[4] President, K.G. Co. Ltd.

[5] Vice-chief, Mitsubishi Chemical Foamplastic Co.Ltd.

1. INTRODUCTION

To ensure the greater safety of facilities of nuclear power plants, fuel tanks, rock-sheds or other important structures against impact loads, many theoretical and experimental studies have been reported (Mikami and Kishi 1996; Kishi et al. 1997, 1998). A great deal of effort has been made on the investigation of impact behavior and impact resistance of structures when flight and/or falling bodies applied onto the structures directly. Otherwise, it will be one of engineering approaches to attenuate the impact forces at the quasi-static level by using absorbing system. It is for the reason that the structures can be designed by customary design method if the applied loads on the structures were quasi-static level.

To absorb and to disperse the impact forces effectively, authors have developed a Three-Layered Absorbing System (hereinafter, TLAS) which is composed of 50 cm thick sand layer (top), 20 - 30 cm thick Reinforced Concrete (RC) slab (core) and 50 - 100 cm thick Expanded Poly-Styrol (EPS) block (bottom). Its practical applicability was made sure by performing prototype impact tests by means of falling-weight impact test method with the maximum 5,000 kg steel weight and 40 m falling height (Kishi et al. 1993; Nakano et al 1995; Sato et al 1995; Mikami et al. 1995).

In this paper, in order to easily apply this absorbing system in the real structures, the simple and practical estimation methods for the thickness of RC core slab and EPS bottom layer, and the transmitted impact force to the structure against flight and/or falling bodies are developed. These methods are derived mainly based on 1) the conservation rule of momentum among impact force, sand layer and RC core slab, and 2) the transmitted impact energy to the bottom layer will be perfectly spent due to the deformation of the EPS bottom layer. The applicability of the proposed methods is made sure by comparing the prototype field impact test mentioned above.

2. BASIC CONCEPT OF DESIGN METHOD

TLAS considered here is composed of 50 cm thick sand layer (top), 20 - 30 cm thick RC core slab, and 50 - 100 cm thick EPS block layer (bottom). In order to easily perform the practical design of TLAS, the basic concepts are defined based on many prototype impact tests on this type absorbing system set on the rigid foundation by means of falling-weight impact test method as shown in **Fig.1** and these are as follows:

2.1 Impact Force Subjected to Core RC Slab

(1) Based on the experimental results on weight and transmitted impact forces, P_a and P_t on both TLAS and 60 cm thick single-layered sand cushion (**Fig. 2**), it is made sure that the impact force subjected to the RC core slab of TLAS can be assumed almost the same with the weight impact force in case using the sand cushion.

(2) The impact force can be estimated by means of a conventional Hertz's contact theory considering Lame's constant for sand $\lambda = 1{,}960$ kN/m^2 which is formulated as:

$$P_a = 43.7\ W_w^{2/3}\ H^{3/5} \qquad \ldots (1)$$

in which W_w (kN) and H (m) are weight of a falling-weight and falling height of the weight, respectively.

2.2 Impact Energy to EPS Bottom Layer

(1) Impact force generated in the RC core slab is transmitted to the EPS bottom layer. Here, a 4 m square area of the TLAS can effectively respond against weight falling impact force.

(2) The wave of impact force forms sinusoidal half wave, of which the duration time T and the amplitude P_a are 30 ms and the same value evaluated from Eq.(1), respectively.

(3) Following conservation rule, an impulse due to the impact force subjected to the RC core slab is equal to a momentum of mass of the upper part of TLAS (sand cushion and RC core slab) including a falling-weight.

(4) The impact force is uniformly distributed over the area of RC core slab which is assumed as a 4 (m) square one from experimental results.

2.3 Estimation of Transmitted Impact Force

(1) Input impact energy is perfectly absorbed due to the deformation of EPS bottom layer in prescribed area mentioned above. Transmitted impact stress corresponding to the deformation is given due to the stress-strain relation of the EPS block.

(2) The effective area of EPS bottom layer behaves one-dimensionally due to the impact kinematical energy induced in the upper part of TLAS.

2.4 Estimation of Required Thickness of EPS Bottom Layer

(1) In order to assure a good deal of safety margin of TLAS against a bigger impact force than that of the given design condition, the required thickness of EPS bottom layer is specified.

(2) It is assumed that the RC core slab is locally perforated with punching shear failure, and the input impact energy is absorbed by only the deformation of local area of EPS block where corresponds to the surface area of cone of the RC core slab.

3. DESIGN OF RC CORE SLAB

In order to maintain the absorbing capacity of TLAS, it is very important to design to prevent the RC core slab from punching out due to a falling-weight. This means that a punching shear capacity of the slab is demanded to be bigger than the impact force subjected to the slab. In this paper, the shear capacity of RC core slab is evaluated assuming that the slab is punched out in circular area having the same diameter with the falling-weight as shown in **Fig. 3**, in which usually the scale of 1.0 m in diameter is assumed. Then, the capacity is easily evaluated by using the ultimate concrete strength and rebar shear strength. Assuming double reinforced concrete slab in two orthogonal directions with rebar ratio p, the required effective thickness of RC slab d (m) against the maximum impact force P_a (kN) given by Eq. (1) is obtained introducing a safety factor γ(= 1.1) as follows:

$$d = \frac{\gamma P_a}{D(\pi \tau_{cu} + 8 p \tau_{su})} \qquad \dots (2)$$

in which, D (m) is diameter of a falling weight, τ_{cu} (kN/m^2) and τ_{su} (kN/m^2) are the ultimate shear strength of concrete and rebar, respectively. In this paper, $\tau_{cu} = \sigma_{cu}/10$ is assumed from experimental results and $\tau_{su} = \sigma_{su}/\sqrt{3}$ are defined based on von Mises yield criterion, in which σ_{cu} (kN/m^2) and σ_{su} (kN/m^2) are compressive strength of concrete and tensile strength of rebar, respectively. **Table. 1** shows the numerical examples for an effective slab thickness d and a design slab thickness h_c (m) considering cover concrete for various falling-weights under the conditions of: a weight falling height H = 30 m; D = 1.0 m; σ_{cu} = 20,600 kN/m^2; σ_{su} = 402,000 kN/m^2; and p = 0.01.

4. DETERMINATION OF TRANSMITTED IMPACT FORCE

Following the aforementioned basic concept, the impact force subjected to the RC core slab is assumed forming the wave as shown in **Fig. 4** and can be formulated as:

$$P = P_a \sin \frac{\pi}{T} t \qquad (0 \le t \le T) \qquad \dots(3)$$

where T is assumed as T = 30 ms based on the results of prototype impact test, and P_a is the maximum impact force given by Eq. (1).

The velocity V of the effective area of the upper part of TLAS (sand cushion and RC core slab) including a falling-weight can be obtained using a conservation rule that a impulse equals to a change of momentum on the TLAS, and can be represented as:

$$V = \frac{1}{M} \int_0^T P \, dt \qquad \dots (4)$$

in which M is total mass of the effective area of the upper part of TLAS and a falling-weight.

The velocity V can be easily given substituting Eq. (3) into Eq. (4). Then, the impact energy E_w input to the upper part of TLAS is formulated using the velocity V as:

$$E_w = \frac{M V^2}{2} = \frac{2 g T^2 P_a^2}{\pi^2 W} \qquad \dots (5)$$

in which g is an acceleration of gravity and W (kN) is a total weight of the effective area of the upper part of TLAS and a falling-weight.

Considering the duration time of impact force T and density for each material composing the TLAS, the impact energy E_w (kJ) can be represented as:

$$E_w = \frac{P_a^{\ 2}}{559.5\ (141.1 + 392\ h_c + W_w)} \qquad \dots (6)$$

in which h_c (m) is a thickness of RC core slab.

Based on the prescribed concept of the procedure, the impact energy E_w estimated above will be perfectly spent due to the deformation of the EPS bottom layer. Here, it is assumed that the effective area of EPS layer will behave one-dimensionally due to weight falling. The stress-strain (σ - ε) relation of the EPS layer is tri-linearly modeled based on the results obtained from the static loading test with 10 cm/min loading speed (**Fig. 5**). In this paper, the maximum design strain of EPS layer is limited to 0.55 to ensure an absorbing capacity of the TLAS and to keep some safety margin. Letting the impact energy E_w obtained by Eq. (6) be equal to the strain energy spent in the EPS layer, the transmitted impact force P_t (kN) to the structure can be obtained replacing stress into force considering an effective area of the EPS layer (4×4 m) as follows:

$$P_t = 262.7 \sqrt{\frac{E_w}{h_e}} \qquad (0 \le \varepsilon \le 0.05) \qquad \dots (7)$$

$$= 83.1 \sqrt{(388.1 + \frac{E_w}{h_e})} \qquad (0.05 \le \varepsilon \le 0.55) \qquad \dots (8)$$

5. REQUIRED THICKNESS OF EPS BOTTOM LAYER

The design strain of the EPS layer is limited to 0.55 mentioned above. Then the required thickness of the EPS bottom layer h_e can be obtained considering the area *A'* subjected due to shear cone formed in the RC core slab. Here, the *A'* is defined as a rectangular area for simplicity:

$$A' = (D + 2\,h_c)^{\,2} \qquad \dots (9)$$

Assuming that a diameter of falling-weight D = 1 m and its falling height H = 30 m, numerical examples on required thickness of the EPS bottom layer for various falling weights are listed in **Table 2**.

6. VERIFICATION OF PROPOSED DESIGN PROCEDURE

In order to make sure the practical applicability of the TLAS developed by authors, many prototype field impact tests were performed by means of falling-weight impact test method. Here, to verify the proposed design method of the TLAS, the weight and transmitted impact forces P_a and P_t estimated based on the method are compared to the experimental results. **Figure 6** shows the comparison in cases of: (1) W_w = 19.6 kN, h_c = 0.2 m, and h_e = 0.5 m; (2) W_w = 29.4 kN, h_c = 0.2 m, and h_e = 0.5 m / 0.75 m; (3) W_w = 49 kN, h_c = 0.2 m, and h_e = 0.5 m / 1.0 m; and (4) W_w = 49 kN, h_c = 0.3 m, and h_e = 0.75 m.

From these figures, it is seen that the impact forces estimated applying the proposed design method correspond to the experimental results with a good agreement.

7. CONCLUSIONS

In order to ensure the great safety of the important structures such as rock-shed structures and/or nuclear power plants, mitigating the impact force occurred due to flight and/or falling bodies to the quasi-static level by using absorbing system is one of engineering approaches. Here, a Three-Layered Absorbing System (TLAS) was developed to effectively absorb and to widely disperse the impact force, and its practical applicability was confirmed performing many prototype falling-weight impact tests with the maximum 49 kN steel weight. The system is composed of 50 cm thick sand layer (top), 20 ~ 30 cm thick Reinforced Concrete (RC) core slab, and 50 ~ 100 cm thick Expanded Poly-Styrol (EPS) bottom layer. In this paper, in order to easily apply the TLAS in the practical facilities, a design method for the system is formulated. An applicability of the proposed design method is made sure comparing with the experimental results with a good agreement.

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Table 1 Numerical examples on design slab thickness

Falling weight	W_w (kN)	19.6	29.4	49.0
Impact force	P_a (kN)	2,450	3,210	4,510
Effective slab height	d (m)	0.11	0.14	0.20
Design slab thickness	h_c (m)	0.15	0.20	0.25

(H = 30 m, D = 1m, σ_{cu} = 20,600 kN/m^2 , σ_{su} = 402,000 kN/m^2 , p = 0.01)

Table 2 Numerical examples for required thickness of EPS layer

Falling weight	W_w (kN)	19.6	29.4	49.0	
Impact force	P_a (kN)	2,450	3,210	4,510	
Thick. of RC slab	h_c (m)	0.20	0.20	0.20	0.30
Reqrd. Thick. of EPS	h_e (m)	0.29	0.48	0.88	0.58

(H = 30 m, D = 1m)

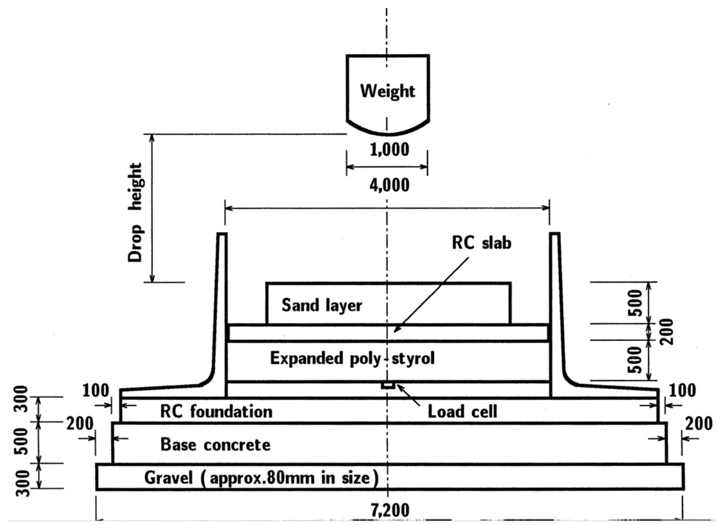
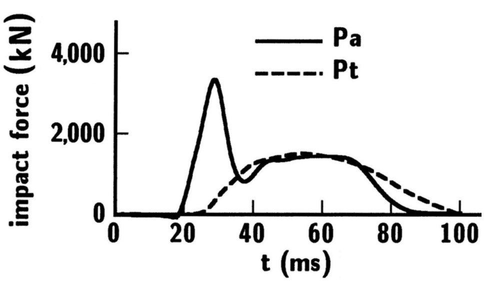
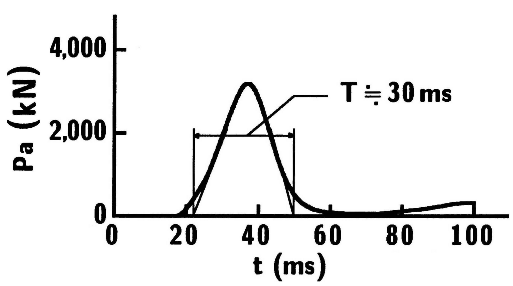


Figure 1 General view of prototype impact test on TLAS



(a) TLAS



(b) 0.6 m thick single-layered sand cushion

Figure 2 Comparison of impact forces obtained using two absorbing systems (falling-weight W_w = 29.4 kN, falling height H = 30 m)

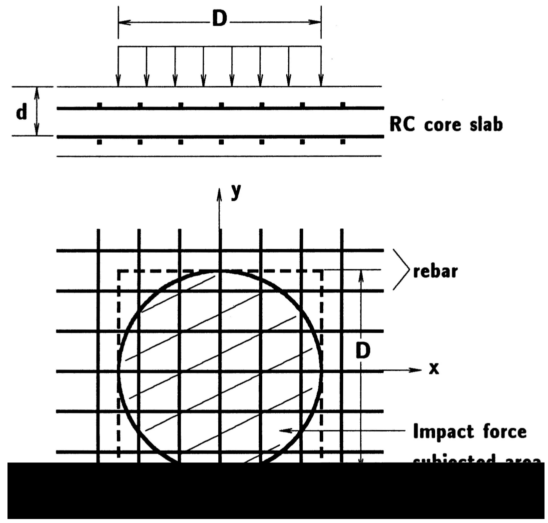


Figure 3 Impact force surcharged area onto RC core slab

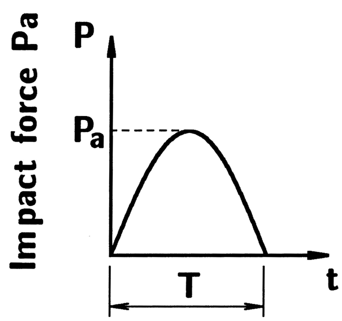


Figure 4 Assumed impact force wave onto RC core slab

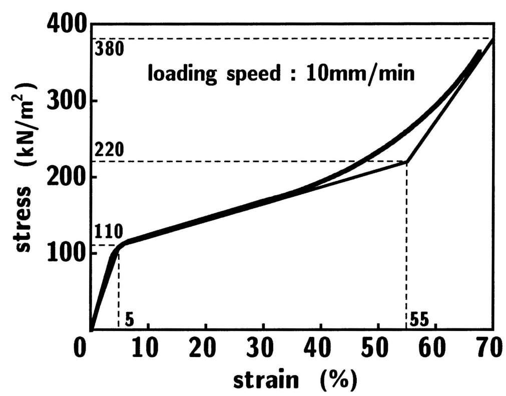
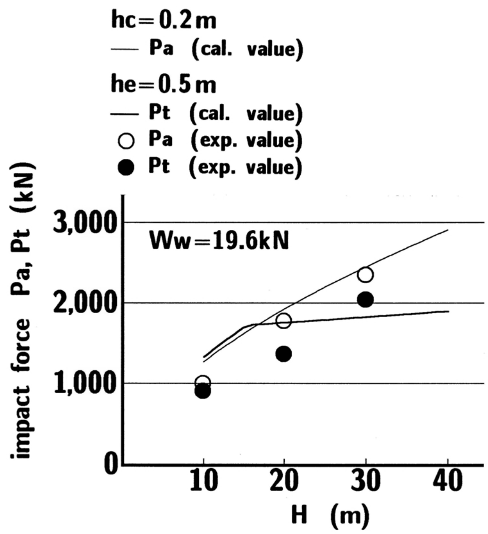
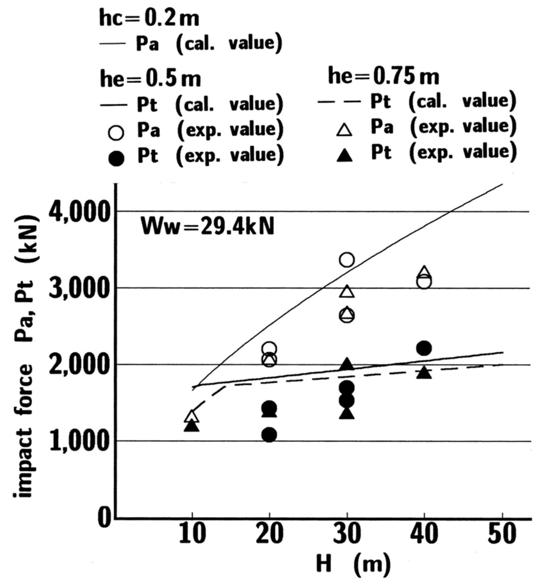


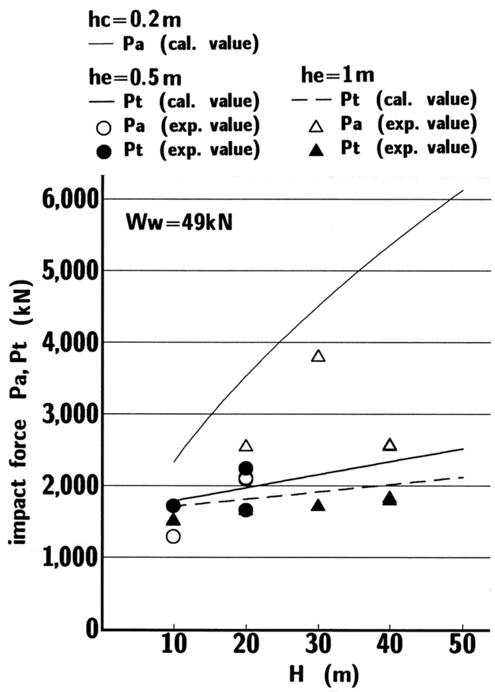
Figure 5 Stress-strain relation of EPS layer



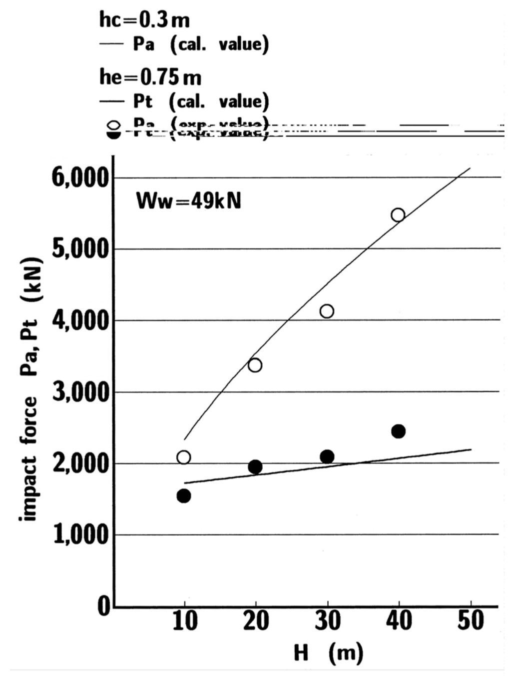
(a) Case of W_w = 19.6 kN and h_c = 0.2 m



(b) Case of W_w = 29.4 kN and h_c = 0.2 m



(c) Case of W_w = 49 kN and h_c = 0.2 m



(d) Case of W_w = 49 kN and h_c = 0.3 m

Figure 6 Comparison between proposed impact forces and experimental results