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FUNDAMENTAL STUDIES ON OPTIMUM DESIGN FOR BASE ISOLATION SYSTEM

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SUMMARY

This paper describes that optimum characteristics exist separately for three kinds of base isolation systems from a point of view of high reduction of response acceleration and moderate relative displacement due to base isolation systems. Quantitative solutions of equations of motion and energy are presented in this paper for elasto-plastic, frictional and viscous type base isolation systems with various input wave patterns which can be expected to occur at major different types of ground conditions. Comprehensive characteristics of general base isolation systems are shown and the presented data are thought to be available for designers in decision of isolation method and for basic design use.

INTRODUCTION

This paper will describe that each kind of base isolation system, i.e. elasto-plastic, frictional and viscous system, has the most desirable characteristics of the device, in order to obtain optimum base isolating function regarding responses of dynamic systems.

Authors have been studying optimum base isolation systems for electric power facilities aiming at the establishment of rational countermeasures for earthquakes (Ref. 1 and 2). Many structures in Japan, mainly buildings, have been constructed adopting base isolation systems so far. When those designs were carried out, it seemed that development of devices of isolation systems and individual case studies were precisely done according to the desired specifications and the conditions of seismicity of each construction site. On the other hand, as the lack of comprehensive studies of isolation systems, concerning selection of methods of system, expected input wave conditions, dynamic characteristics of upper structures and so on, whether the obtained designs of existing base-isolated structures are really optimal can not be examined by using the past knowledge of ours.

ANALYTICAL MODELS

Analytical models concerned in this paper consist of one mass model of upper structure with natural period of first order of the structures of 0.25 second, and base isolation devices installed under the upper structures, as shown in Figure-1. The base isolation devices are combined systems with restoring springs and energy absorbing ele-

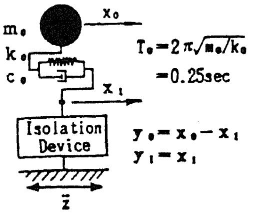


Fig.-1 Analytical Model

ments in parallel; and the energy absorbing elements are elasto-plastic, frictional and viscous systems. The restoring characteristics combined with energy absorbing elements are shown in Figure-2. In this paper, balance of energy within the dynamic systems with isolating device is concerned so as to study how to maximize the consumed energy in the absorbers. Equations of motion and energy for each systems are as shown below; and calculations for responses of the systems are executed by linear-acceleration method.

Equation of Motion

a) Elasto-Plastic Systems

$$m_0\ddot{x}_0+c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=-m_0\ddot{z}$$
$$c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=Q(x_1,t) \qquad (1)$$

$Q(x_1,t)$: Restoring Force of Total Device

b) Frictional Systems

During "Fix"

$$m_0\ddot{x}_0+c_0\dot{x}_0+k_0(x_0-x_1)=-m_0\ddot{z}$$
$$|c_0\dot{x}_0+k_0(x_0-x_1)-k_2x_1|\leqq Fr \qquad (2)$$
$$x_1=\mathrm{const.}\ ,\quad \dot{x}_1=0$$

During "Slip"

$$m_0\ddot{x}_0+c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=-m_0\ddot{z}$$
$$c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=k_2x_1+Fr\cdot\mathrm{sgn}(\dot{x}_1) \qquad (3)$$
$$|c_0\dot{x}_0+k_0(x_0-x_1)-k_2x_1|>Fr$$

k_2, Fr: As defined in Fig.-2

c) Viscous Systems

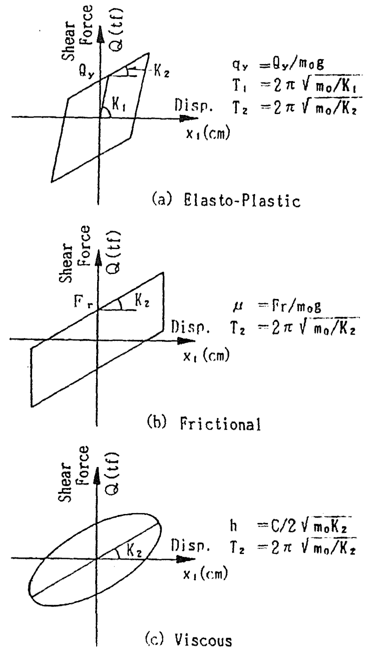
$$m_0\ddot{x}_0+c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=-m_0\ddot{z}$$
$$c_0(\dot{x}_0-\dot{x}_1)+k_0(x_0-x_1)=C\dot{x}_1+k_2x_1 \qquad (4)$$

k_2, C : As defined in Fig.-2

Equation of Energy

$$\underbrace{\int_0^t m_0\ddot{x}_0\dot{x}_0dt}_{E_1}+\underbrace{\sum\int_0^t c_i\dot{y}_i\dot{y}_idt}_{E_2}+\underbrace{\sum\int_0^t k_iy_i\dot{y}_idt}_{E_3}+\underbrace{\int_0^t Q(x_1,t)\dot{x}_1dt}_{E_4}=\underbrace{-\int_0^t m_0\ddot{z}\dot{x}_0dt}_{IE} \qquad (5)$$

E_1: Energy of Motion
E_2: Absorbed Energy due to Upper Structure
E_3: Elastic Energy of Restoring Spring
E_4: Absorbed Energy due to Absorbing Element
IE: Input Energy



Q_y : Yielding Shear Force
q_y : Non-dimensional Shear Foece
K_1, K_2 : Restoring Stiffness
F_r : Frictional Force
μ : Coefficient of Friction
C : Coefficient of Damping (Isolation Device)
h : Equivalent Damping Factor

Fig.-2 Characteristics of Three Kinds of Isolation System

RESPONSE ANALYSES

<u>Input Acceleration Waves</u> Input acceleration waves used in this study are three kinds of waves for representative three kinds of ground synthesized by spectrum fitting method. When input waves were synthesized, real phase characteristics of three observed waves were used, referring standard spectra which appear in the Japanese conventional design code for road bridges as shown in Figure-3. As the real observed waves, Kaihoku Bridge TR 1978, El Centro NS 1940 and Hosojima 1968 are selected for Group 1, 2/3 and 4 ground, respectively. The synthesized input waves are as

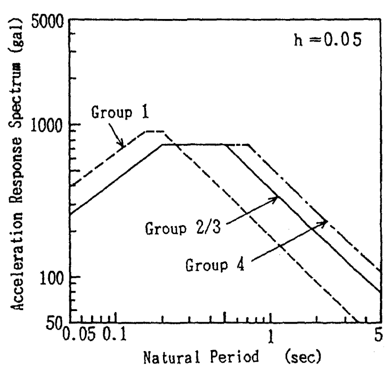


Fig.-3 Acceleration Response Spectrum

shown in Figure-4.

Results of Analyses Responses of upper structures are shown in Figure-5 to 7: in (a) to (c) series, selected characteristics of each energy absorbing element are non-dimensional shear force q_y, coefficient of friction μ and equivalent damping factor h, respectively; in (c) series Energy Absorption Ratio is defined as [E_4] divided by [IE]; and in (d) series the characteristics is selected as T_2 defined in Figure-2.

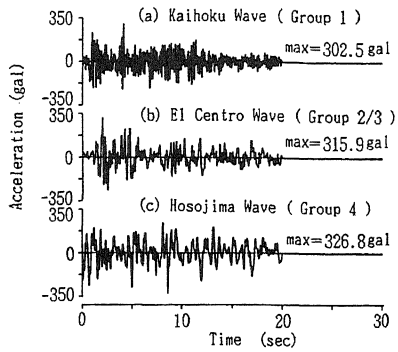


Fig.-4 Synthesized Input Wave

a) Elasto-plastic Systems Figure-5(a) and (b) show relations of q_y vs. maximum response acceleration and displacement in case of T_1=1.0 second and T_2=2.0 seconds. Maximum response acceleration curves show that minimum value appears at q_y is nearly 0.04 for every input waves. Maximum relative displacement is almost constant in the region of q_y is larger than 0.04 for every input waves.

Figure-5(c) is relation of q_y vs. energy absorption ratio, showing that maximum values exist almost at the same position as minimum response acceleration as shown in Figure-5(a) in the region of q_y= 0.02 - 0.04. Those results mentioned above suggest that optimum design using elasto-plastic method can be made if the parameter q_y is appropriately selected, and the appropriate q_y value increases slightly as the ground comes to be softer. Figure-5(d) is relation of T_2 vs. response acceleration, maximum and residual relative displacements, in which q_y is selected as almost optimal value of 0.04 using synthesized El Centro wave. This figure shows that maximum relative displacement has minimum value at T_2 is 2.0 seconds, and that response acceleration decreases simply as T_2 becomes larger.

As stated above, both response acceleration and relative displacement can be moderately designed in actuality, if T_2 is selected to be 2.0 seconds which is currently adopted in many base isolated buildings in the world.

b) Frictional Systems Figure-6(a) and (b) show relations of μ vs. maximum response acceleration and displacement in case of T_2 = 2.0 seconds. Maximum response acceleration curves show that minimum value appears at μ is 0.04 to 0.08 for each input waves. And, each minimum value is almost one quarter compared with non-isolated value which is the same ratio of elasto-plastic and viscous systems. Maximum relative displacement can be decreased as μ comes to be larger, which means that relative displacement can be controlled as low as a desired value in frictional systems if μ is selected adequately.

Figure-6(c) is relation between μ and energy absorption ratio, showing that maximum value exist almost at the same position as minimum response acceleration as shown in Figure-6(a) in the region of μ = 0.04 to 0.08. Figure-6(d) is relation of T_2 vs. response acceleration, maximum and residual relative displacements, in which μ is selected as almost optimal value of 0.06, using synthesizes El Centro wave. This figure shows that maximum relative displacement is almost constant in the region that T_2 is over 1.0 second, and that response acceleration decreases in simple manner as T_2 becomes larger.

As stated above, both response acceleration and relative displacement can be designed in ideal, if T_2 is selected to be 1.5 to 2.0 seconds and μ is selected to be 0.04 to 0.08. But μ value of 0.08 to 0.12, which is able to be obtained easily in real friction devices, is considered to offers effective base isolation function.

c) Viscous Systems Figure-7(a) and (b) show relations of h vs. maximum response acceleration and displacement in case of T_2 = 2.0 seconds. Maximum response acceleration curves show that they are almost constant in the region that h is larger than 0.2, which means that response accelerations are not keenly affected by the parameter of h in that region. Maximum relative displacement is slightly decreasing in the region that h is larger than approximately 0.2.

Figure-7(c) shows that energy absorption ratio is simply increasing as h comes to be larger within h is under 1.0 region. Figure-7(d), which is drawn under the condition of h=0.2, shows that maximum relative displacement increases as h comes to be larger. No residual displacement can be seen after shaking in viscous systems as expected.

Legend

Isolated	Non-Isolated
○ Kaihoku Wave	——— Kaihoku Wave
△ El Centro Wave	- - - - El Centro Wave
□ Hosojima Wave	········ Hosojima Wave

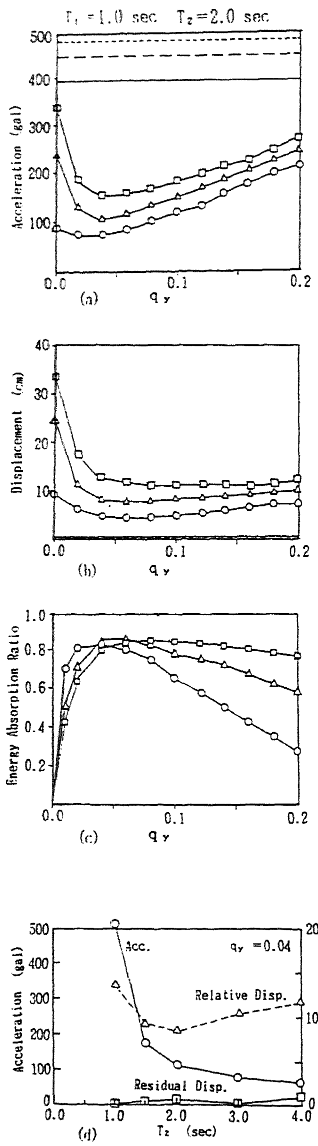


Fig.-5 Results of Analyses
(Elasto-Plastic)

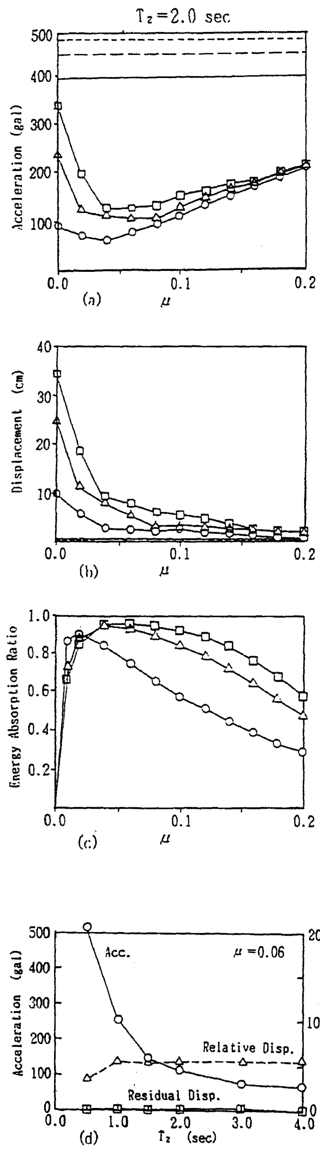


Fig.-6 Results of Analyses
(Frictional)

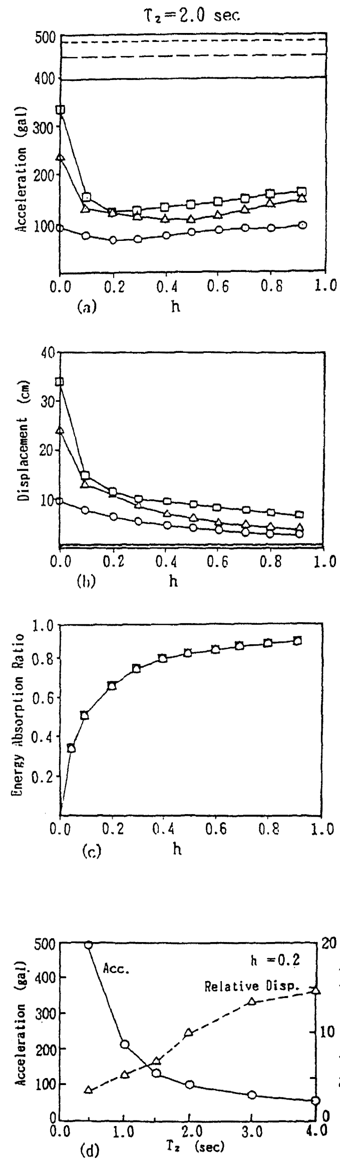


Fig.-7 Results of Analyses
(Viscous)

Considering both response acceleration and relative displacement, it is suggested that h=0.1 to 0.2 and T_2= 1.5 to 2.0 seconds are preferable to keep effective function of base isolation.

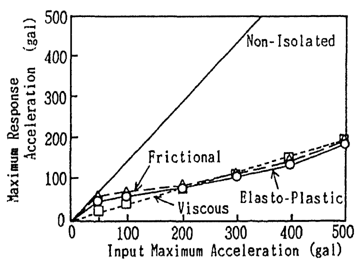
COMPARISON OF RESPONSES AMONG THREE ISOLATION SYSTEMS

Comparing study of response characteristics by three kinds of base isolation systems have been carried out based on the results by response analyses. In these analyses, the same natural period for each systems were used, and parameters of energy absorbing devices were selected as thought to be optimum value in each method. The parameters adopted in the analyses were as follows: T_1=1.0 second, T_2=2.0 seconds and q_y=0.04 for elasto-plastic system; T_2=2.0 seconds and μ=0.06 for frictional system; and T_2=2.0 seconds and h=0.2 for viscous system, respectively. Analyzing model is as shown in Figure-1, and input wave is synthesized El Centro which is the same as mentioned above.

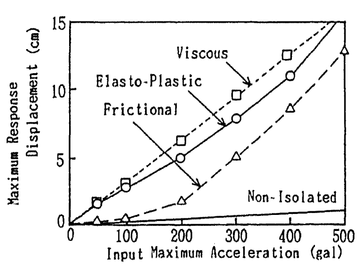
Figure-8(a) shows response acceleration waves of the upper structures. It is notable that response accelerations wave of elasto-plastic and viscous systems contain almost no component of high frequency which appears in the input wave, and that, in the friction system, strong acceleration part is restrained within a certain maximum value about 70 gals in this case and higher frequency component can be seen in the acceleration wave. As shown in Figure-8(b), in the frictional system "slip and fix" phenomenon appears alternatively, while in the elasto-plastic and viscous system displacement wave show continuous curves.

Relations between the maximum response value and the maximum input acceleration are shown in Figure-9(a) and (b). The results described in these figures can be explained by using hysteresis loop model(as shown in Figure-2) of displacement vs. resistant force for each damper as follows:i.e. in elasto-plastic system the loop has optimum area only when the input acceleration is moderate such as 100 - 300 gals in which both K_1 and K_2 regions are used effectively; in the frictional system the loop has no area under input acceleration of about 100 gals and works more effectively with stronger input acceleration; and in the viscous system the loop has sufficient enough area from weak to strong input acceleration.

Figure-10 is response spectrum of response acceleration waves as shown in Figure-8(a). Compared with non-isolated case, elasto-plastic and viscous

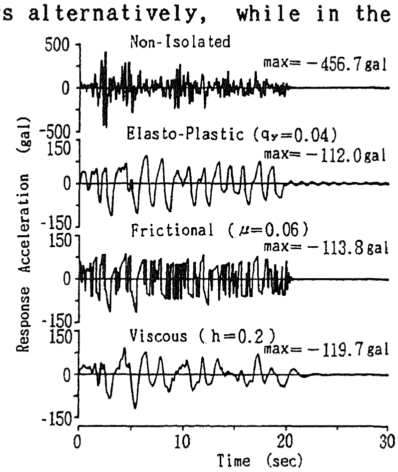


(a) Maximum Response Acceleration

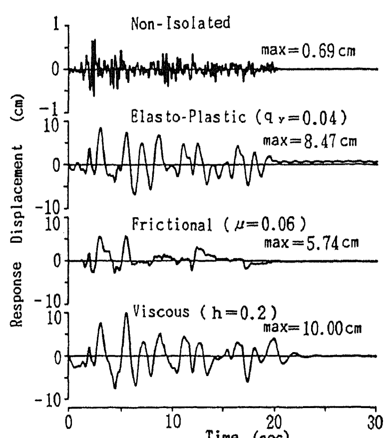


(b) Maximum Response Displacement

Fig.-9 Input Maximum Acceleration vs. Maximum Response



(a) Response Acceleration



(b) Response Displacement

Fig.-8 Response Waves

systems show very low responses in the region of short period though showing higher response in the long period region than non-isolated. In the frictional system, the response is higher than those of elasto-plastic and frictional, but it has no keen peak at the restricted band.

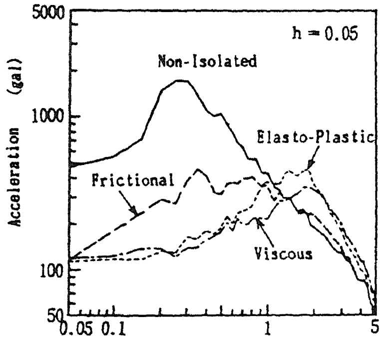


Fig.-10 Acceleration Response Spectrum

CONCLUSION

Response characteristics of three kinds of isolation systems have been studied from the point of view that they are compared impartially as far as possible. Those characteristics have been made clear in order to select the method of isolation system and to decide some values of parameters of the devices for a particular requirement of facilities or structures at an installation site. More detailed consideration must be done when the final design is carried out, but those data presented herein are available to comprehend the fundamental principle of general base isolation systems.

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