OPTIMIZATION OF CHARACTERISTIC VALUE OF SEISMIC ISOLATED BRIDGES

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ABSTRACT

When establishing the characteristic value of a seismic isolation device, it is required that the seismic isolation device should work efficiently not only against the small-to-medium earthquake motions specified in the service-ability limit state design, but also against other big earthquake motions in the ultimate limit state design.

This paper proposes a practical method of quickly finding the characteristic value of a seismic isolation device which can be successfully controlled for a variety of earthquake motions to an equal degree. Furthermore, the effect of elasticity of the substructure can be expressed in terms of the natural period on non-isolated assumption. Then, an optimum value is selected for each of the 9 combinations created by combining 3 representative characteristic values of the substructure and 3 input earthquake motions in accordance with the stiffness of the ground. The result has revealed that a practical optimum characteristic value can be easily found to the extent that the displacement of the seismic isolation device does not exceed a value which can be tolerated in it's design.

KEYWORDS

Seismic base isolation; Seismic design; Optimization method; Ultimate limit state; Service ability limit state.

INTRODUCTION

The number of bridges which have been designed with a seismic isolation device used as the bearing are on the increase in the expectation that this seismic isolation device would be helpful in reducing some inertia caused by the earthquake motion. Speaking of the earthquake motion which should be generally taken into account in bridge designs, the criterion for seismic design, which is expressly provided for in the " Specifications for Highway Bridges Part V Seismic Design" (the Japan Road Association., 1990) and in the "Manual on the Design of Menshin (base-isolated) Highway Bridges" (P.R.I. Joint Research Report., 1992) that specifies the way in which those bridges are designed, is established in the following two checks:

- The first check, which corresponds with what is stipulated in the service-ability limit state design method, should be made for certain earthquake motions which more frequently occur: all structural members should be designed in such a manner that they might be stressed up to the allowable stress ;
- The second check, which corresponds to what is stipulated in the ultimate limit state design method, should be made for earthquake motions which less frequently occur: The plastic deformation of any of those members, which are stressed, is designed to be within the range of ductility, even if a plastic hinge occurs in the members.

The design earthquake which is generally used for the serviceability limit state design method is assumed to be of a return period of about 75 years, while for the ultimate limit state design method - about 400 years. Hereafter, the former earthquake will be called Design Earthquake L1, while the latter - Design Earthquake L2. Acceleration response spectra S_1 and S_2 can be expressed by means of Formulae (1) and (2) respectively :

$$S_1 = C_z \cdot C_1 \cdot C_D \cdot S_{10} \tag{1}$$

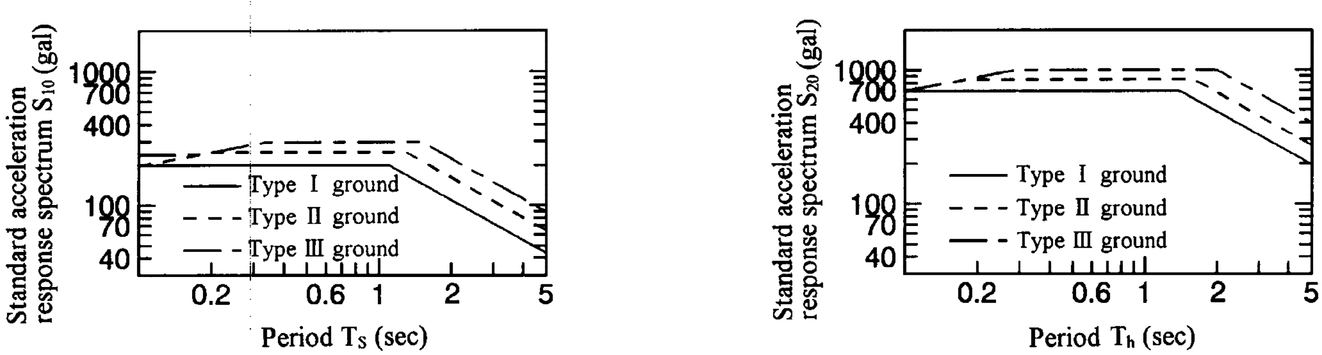
$$S_2 = C_z \cdot C_1 \cdot C_D \cdot S_{20} \tag{2}$$

Where, C_z = zone factor, C_1 = importance factor, C_D= correction factor due to damping ratio that can be obtained from the following Formula (3):

$$C_D = \frac{1.5}{40h+1} + 0.5 \tag{3}$$

Where, S_{10}= standard acceleration response spectrum of L1, S_{20}= standard acceleration response spectrum of L2. Each of those spectra is given in Fig. 1.

There are 3 kinds of standard acceleration spectrum which vary according to the stiffness of the ground.



a) standard acceleration response spectrum of L1

b) standard acceleration response spectrum of L2

Fig. 1. Standard acceleration response spectrum of input earthquake motion

A model of the structural system of a base isolated bridge consisting of the equivalent linear spring constant and the equivalent damping ratio has been proposed. Considering that the equivalent damping ratio of the seismic isolation device can be the optimal one only when it reaches a maximum, a method was proposed for determining the optimum characteristic value of those seismic isolation devices in response to the design earthquake, to which careful consideration had been given (Ijima K.. *et al.*., 1993).

However, the value of stiffness and the damping ratio vary according to each of those earthquakes: L1 and L2, because most seismic isolation devices have a non-linear restoring force. It is clear that establishment of the characteristic value of a seismic isolation device according to one of the design earthquakes, so as to allow the natural period and damping coefficient of the bridge structure to be optimized, does not always lead to the optimization of the ones of the other. The selection of a characteristic value for base isolation that is equally effective for both Design Earthquakes L1 and L2 at the same time is a requirement. This is the value, at which the best base isolation is obtained, corresponds to what has been already said in the criterion for seismic design which is made in two steps of checking.

OPTIMIZATION METHOD

Requirements for optimization

Seismic design is to reduce inertial forces. Let the objective function z be equal to Formula (4) so that this function can be used for assessment. In this case, z is a smaller one of the rates of reduction z_1 and z_2. Optimization for reduction in inertial force is accomplished when the objective function z has a maximum.

$$z = \min(z_1, z_2) \rightarrow \max \tag{4}$$

$$z_1 = \left(1 - \frac{A_h}{A_{ha}}\right) \tag{5}$$

$$z_2 = \left(1 - \frac{A_{hc}}{A_{hca}}\right) \tag{6}$$

Where, the objective function z is used for assessment of reduction in inertial force, z_1 is the rate of reduction in inertial force in response to Design Earthquake L1, while z_2 is the rate of reduction in inertial force in response to Design Earthquake L2. And A_h is the acceleration of the superstructure of a base-isolated bridge, which is caused by L1, while A_{ha} is allowable value the acceleration of the superstructure which depends upon a assessment of the design ultimate strength of the substructure by the service ability limit state design method. Further, A_{hc} is the acceleration of the superstructure which is caused by L2. Finally, A_{hca} is an allowable value of the acceleration of the superstructure which depends upon a assessment of the design ultimate strength of the substructure by the ultimate limit state design method.

Formula (8) is obtained using a hypothesis about the relationship between input energy and energy dissipation given in Formula (7).

$$A_{he} = \frac{A_{hc}}{\sqrt{2\mu - 1}} \tag{7}$$

when if $A_{he} \cdot M = P_a$

$$A_{hca} = \frac{P_a}{M}\sqrt{2\mu - 1} \tag{8}$$

Where, A_{he}= acceleration with special attention paid to the elasto-plasticity of the substructure; A_{hc}= acceleration obtained on the assumption that the stiffness of the substructure would be elastic, μ= allowable ductility ratio computed using Formula (9); P_a = design ultimate horizontal strength of the pier column which can be computed using Formula (10); δ_u= ultimate displacement; δ_y= yield displacement; α = safety coefficient, has a constant of 1.5:

$$\mu = 1 + \frac{\delta_u - \delta_y}{\alpha \bullet \delta_y} \tag{9}$$

$$P_a = P_y + \frac{P_u - P_y}{\alpha} \tag{10}$$

Where, P_y= yield horizontal strength of the pier column; and P_u= ultimate horizontal strength.

A graph which indicate the relationship between base isolation characteristic values and value of the objective function can be drawn. By making some reference to this graph and the graph which indicate the displacement of seismic isolation device, designers can select the optimal characteristic value of the seismic isolation device. Characteristic value of the seismic isolation device has to be selected considering comparison between optimization for reduction in inertial force and displacement of a seismic isolation device. When the displacement becomes too large, the width required to reduce shear strains put on the rubber portion of the seismic isolation device to a level that can be tolerated will become too large in comparison with the original one required to support vertical loads. Furthermore, it will become necessary to widen the top of the bridge pier on which the girders rest in order to secure a wider bearing area. Special attention shall be paid to the creation of enough room for positioning two adjoining bridge girders apart and for setting expansion joints at the edge of the slab. Thus, it is very difficult to specify this allowable displacement of seismic isolators on a specific basis because of much of the complexity inherent in each bridge system.

Bridge Model and Generalized Indicators of the substructure

The bridge model which is used at this searching procedure is shown in Fig. 2.
Optimal characteristic values of seismic isolation devices vary with characteristics of substructures such as pier columns and foundations, and with periodic characteristics of input earthquake motions. So, generalized indicators is used to represent the characteristics of the substructure of a bridge.

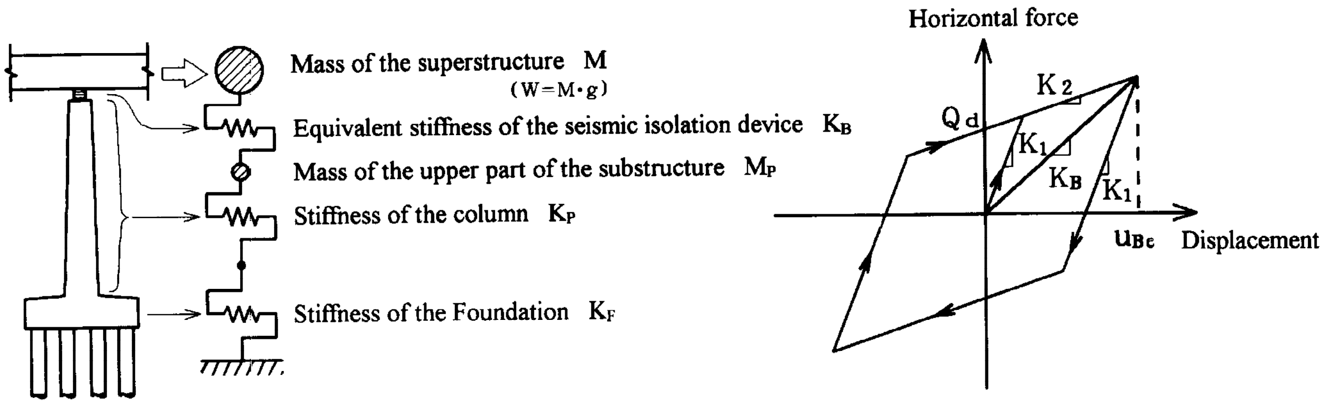
The equivalent stiffness is considered to be one of the most influential indicators of the substructure. The generalized indicator of a substructure can be expressed using Formulae (11) and (12).

$$T_N = \sqrt{\frac{M}{K_N}} \tag{11}$$

$$K_N = \frac{1}{\dfrac{1}{K_p} + \dfrac{1}{K_F}} \tag{12}$$

Where, T_N= natural period of a bridge model with no seismic isolation device, M= mass of the superstructure, K_N= stiffness of the substructure, K_P= stiffness of the column, K_F= stiffness of the foundation.

When the pier is about 10m; 20m; and 30m in height, the value of Indicator T_N will be equal to 0.54 sec; 0.78 sec; and 1.03 sec respectively.



Hysteresis loop of seismic isolation device

Fig. 2. Model

OPTIMAL VALUE-SEARCHING

By setting several representative values of the indicator of the substructure, a graph of the relationship between optimal base isolation characteristic values and input earthquake motions can be drawn, which depends upon the stiffness or elasticity of the ground. By making some reference to this graph, designers can conclusively determine whether the base-isolated bridge is economically beneficial or not.

Natural Period T_h and yield strength ratio Q_d /W are used as indicators for specifying the characteristics of a seismic isolation device in a form which allows universal application to a certain extent . T_h is the fundamental natural period of the bridge model given in Fig. 2, while Q_d is the intercept of the hysteresis loop of that seismic isolation device on the vertical axis. And W is the weight of the superstructure. Natural Period T_h is assigned to the horizontal axis, while yield strength ratio Q_d /W to the vertical axis.

In this coordinate system, Fig. 3 shows a contour of the objective function z to be used for the assessment of inertial force reduction which has been obtained by Formula (4).

On the other hand, Fig. 4 indicates the displacement of a seismic isolation device. These graphs is made for the cases in response to 9 combinations of 3 representative characteristic values of substructure T_N and 3 input earthquake motions. T_h as each of the horizontal axes in Fig. 3 and Fig. 4 shows a natural period resulting from Design Earthquake L2. T_h is used to make a distinction between natural period resulting from Design Earthquake L1 and L2, by adding a subscript h.

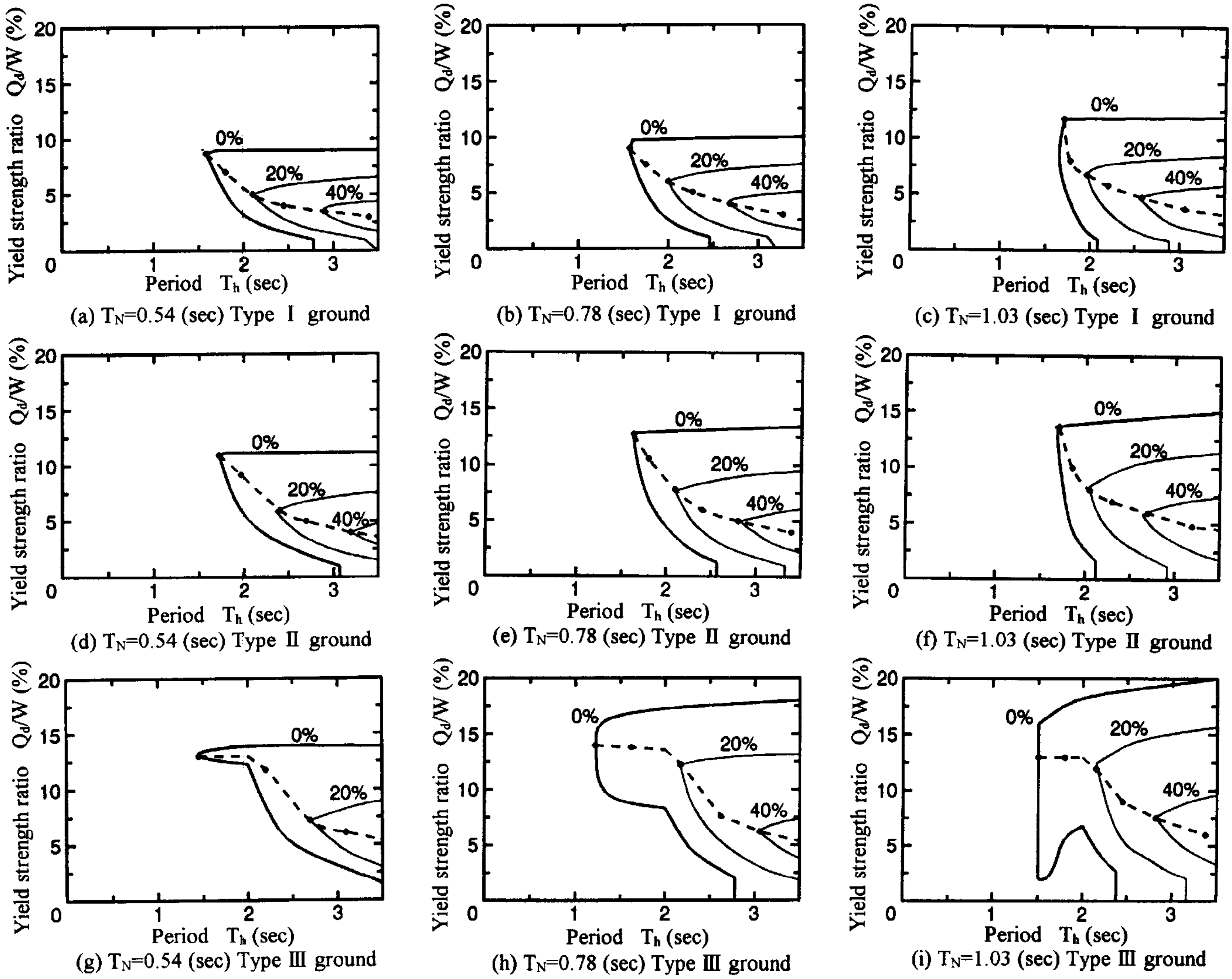


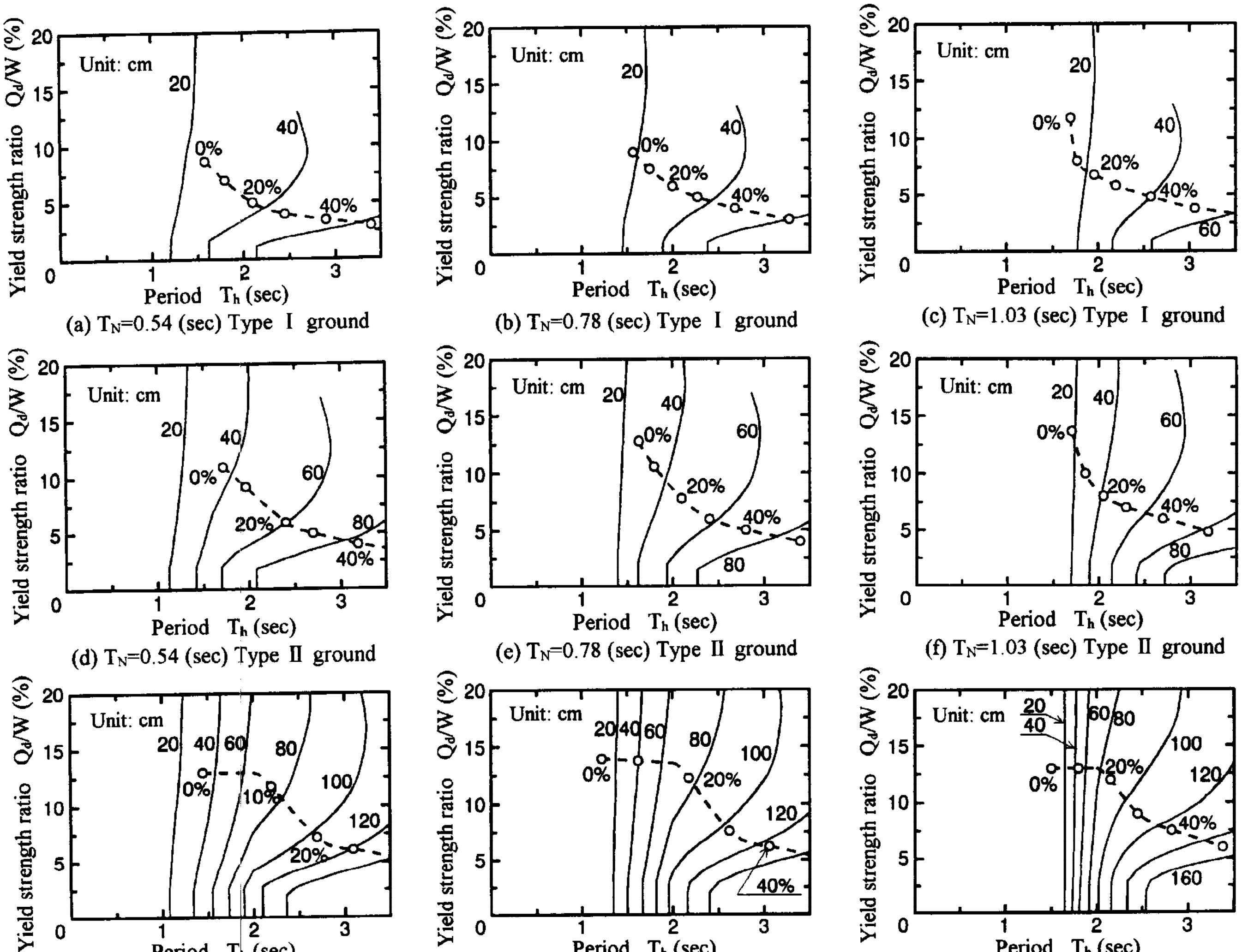
Fig. 3. Contours of objective function z

In Fig. 3 the full lines show contours of the objective function z , and the broken line shows a ridge line of contours. The selection of a characteristic value for reduction of inertial force that is equally achieved for both Design Earthquakes L1 and L2 at the same time is obtained on a ridge line of contours. Hereafter, this ridge line will be called optimal curve of objective function z.

In Fig. 4 the full lines show contours of the displacement of a seismic isolation device, and the broken line shows a optimal curve of the objective function z which is already given in Fig. 3. Intersection of the full line and the broken line indicate the optimal characteristic value for each value of displacement of a seismic isolation device.

Designers should follow these steps as follows in view of the above mentioned figure.

- First of all, displacement of a seismic isolation device should be set to a level that can be tolerated in consideration of the complexity inherent in the bridge system;
- Then, choose one full line in Fig. 4, and find intersection of the full line and the broken line.



(a) T_N=0.54 (sec) Type I ground (b) T_N=0.78 (sec) Type I ground (c) T_N=1.03 (sec) Type I ground

(d) T_N=0.54 (sec) Type II ground (e) T_N=0.78 (sec) Type II ground (f) T_N=1.03 (sec) Type II ground

(g) T_N=0.54 (sec) Type III ground (h) T_N=0.78 (sec) Type III ground (i) T_N=1.03 (sec) Type III ground

Fig. 4. Contours of displacement of seismic isolation devices and optimal curves of objective function z

- Substitution of a selected T_h into Formula (13) gives the equivalent stiffness of the seismic isolation device and the cross-sectional area of a lead plug can be obtained using the value of Q_d computed through Q_d /W and the weight W:

$$K_b = \frac{1}{\frac{1}{M}(\frac{T}{2\pi})^2 - \frac{1}{K_p} - \frac{1}{K_F}} \qquad (13)$$

If the seismic isolation device is, for example, designed to have an allowable displacement of 50 cm or so, there will be 10 % or more of the inertial force reduction found in all figures except Fig. 4 (g).
If it is designed to have an allowable displacement of 40 cm or so, the rate of reduction that can be obtained using the input earthquake motion of type I ground will be 20 % or more for each of the 3 cases given in Fig. 4 (a); (b); and (c).

In the case of using the input earthquake motion of type II ground, it comes to have a rate of reduction of

10 % or more for each of the 2 cases given in Fig. 4 (e); and Fig. 4(f).

It is difficult to determine to what extent the displacement of a seismic isolation device can be tolerated without thinking of the complexity inherent in the bridge system, but it is possible to design a seismic isolation device if a displacement of a seismic isolation device is kept in about 40 cm to 50 cm .

CONCLUSION

This paper proposes a practical method of searching for the optimal characteristic value of a seismic isolation device that can be used in the design of the base isolated bridge. Then, these results are represented graphically on a specific basis, so that any of those designers can easily reference to the graphs. The results of this search can be summarized as follows:

- It is possible to select a characteristic value of a seismic isolation device, which is equally effective for Design Earthquakes L1 which can be used for the service ability limit state design method and for Design Earthquake L2 which can be used for the ultimate limit state design method;
- The optimal curve diagram, which is drawn for 3 levels of generalized indicator of a substructure T_N , and the displacement diagram prove that there is an influence which results from the fact that stiffness vary with substructure. In particular, any value of the middle level of T_N can be interpolated from the graphical relation established by the calculated results;
- 20 % or more of the inertial force reduction is achieved for Ground Type I by allowing a displacement of up to 40 cm. On the other hand, 10 % or more is made for Ground Type II by allowing a displacement of up to 50 cm . it is possible to design a seismic isolation device if a displacement of a seismic isolation device is kept in about 40 cm to 50 cm .

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