MANUAL FOR MENSHIN DESIGN OF HIGHWAY BRIDGES

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ABSTRACT

A three-year research program on "Development of Menshin Design of Highway Bridges" was made from April 1989 to March 1992. Concentrated efforts were paid to develop energy dissipating devices and falling-off prevention devices for bridges. An appropriate design method of highway bridges with energy dissipating devices and favorable application of the menshin design to highway bridges were studied. Final accomplishment of the three-year research was compiled in the form of "Manual for Menshin Design of Highway Bridges" in March 1992. This paper outlines the Manuals.

KEY WORDS
Menshin Design, Highway Bridge, Joint Research Program, Manual for Menshin Design

1. INTRODUCTION

A three-year Joint Research Program between the Public Works Research Institute and 26 groups consisting of 28 private firms on "Development of Menshin Design of Highway Bridges" was made from April 1989 to March 1992. This program intended to develop a rational seismic design method of highway bridges with energy dissipating devices. The highway bridges with span length from 20 m to 100 m were considered as the major target for this Joint Research Program.

As will be discussed later, "menshin" means "reduction of response" in Japanese. Although the menshin design is close with the base-isolation, natural period of bridge is not forcibly elongated in the menshin design, because there are various restrictions for increasing the natural period. Instead of elongating the natural period, emphasis is placed in the menshin design for increasing energy dissipating capability and distribution of lateral force to as many substructures as possible for decreasing lateral force for design of substructures.

As shown in Table 1, concentrated efforts were paid to 1) development of menshin (energy dissipating) devices for highway bridges, 2) development of falling-off prevention devices and expansion joints appropriate for the menshin bridges, 3) development of rational and simple menshin design method and 4) favorable application of menshin design to highway bridges.

In the research project, four high damping rubber bearings, 2 sliding friction dampers, a steel damper, a roller menshin bearing a link bearing and a viscous damper were newly developed for bridges (refer to Fig. 1). The menshin devices for highway bridges have to be more compact and more weather-proof than the base-isolation devices for buildings since the menshin devices are installed at narrow and exposed crest of bridge columns.

The knock-off mechanism at an abutment to ease the impact force induced by the collision between the deck and the abutment (refer to Photo 1), and a finger type expansion joint (refer to Photo 2) which is distinguished from regular finger joints by the transverse movement as well as the longitudinal movement were also developed.

In the research project, a simple but rational menshin design method was developed. A series of shaking table tests were made to study the response of menshin bridges, and to provide realistic data of the seismic response of menshin bridges (refer to Photo 3). Analysis of strong motion records measured at a menshin bridge was also made.

From the study to investigate the favorable application of menshin design, it was found that the menshin design is effective for constructing super-multi-span continuous bridge with total deck length over 1 km. Application of the menshin design for seismic retrofit of exiting bridges and deck connection for making existing simply supported girder bridges continuous was also studied (refer to Photo 4).

The reports of the project were compiled and published by the Public Works Research Institute in the form of the Joint Research Report. As well as these reports, as the final accomplishment of the three-year research program, the Manual for Menshin Design of Highway Bridges was compiled.

This paper presents the outline of the Manual.

2. SCOPES AND CONTENTS OF THE MANUAL

The Manual presents the seismic design method of highway bridges including design details when "the Structures Expecting Reduction of Inertia Force", which is specified in the "Part V Seismic Design" of the "Specifications of Design of Highway Bridges", is adopted Application of the

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menshin design to seismic strengthening of substructures and connection of adjacent decks for making existing simply supported girder bridges continuous is also presented.

It should be noted that although the description of the Manual is given in the format of the specifications, it merely represents the accomplishments of the three-year research program, and it is not the mandate specifications.

The table of contents of the Manual is as follows:

3. BASIC PRINCIPLE OF MENSHIN DESIGN

Whether the menshin design should be adopted or not has to be decided based on the advantages of increasing energy dissipating capability from not only seismic safety but function at normal time.

In general, menshin design can be adopted with advantage for the following conditions:

1) bridges on stiff and stable soils
2) bridges with stiff substructures with short natural period

It is recommended that the natural period of the bridge designed by the menshin design is at least 1.5 times longer than that of the bridge without menshin devices. Such elongation of the natural period of the menshin bridge makes the coupling vibration so small that the deformation of the bridge be concentrated at the menshin devices.

The most important decision of the menshin design is how much increase of the natural period be made. In Japan soils are generally very weak at the bridge construction sites. Significant earthquakes with magnitude over 8, which produce long period ground motions, occur at shorter recurrence period than other countries. Taking account such evidences into account, the design seismic force level is take very high for design of highway bridges in Japan in comparison with the seismic force level adopted in U.S.A.. New Zealand and Italy. The natural period at which the design acceleration decrease with increasing the natural period is taken longer, i.e., 1.1 second for type I soils (stiff site), 1.3 second for type II soils (medium site) and 1.5 second for type III soils (soft soils). Therefore, the advantage for reducing deck response can be realized only by elongating the natural period longer than 1.1 ~1.5 second.

However elongation of the natural period brings the increase of the deck response displacement, and this requires the adoption of joints with long legs. This is, however, a crucial requirements difficult to adopt, in particular, for overcrossing in city area because it causes noise and vibration pollution, which is the most serious concern in city area. Furthermore it will have the disadvantage for maintenance because replacement of the damaged expansion joint due to traffic load as well as the pavement adjacent to the joint has to be frequently made.

Based on these reasons, it is not adopted to forcibly elongate the natural period in order to decrease the deck response acceleration. It is therefore more appropriate to adopt the concept of base isolation not for elongating the natural period but for increasing energy dissipating capability. Distribution of the inertia force to as many substructures as possible, which is the practice adopted in Japan for long time, is also significantly advantageous.

Therefore basic principle recommended for introducing the base isolation to highway bridges in Japan is as follows :

1) Distribute the inertia force to many substructures so intentionally that the inertia force be distributed equally by selecting the spring stiffness of the isolators. Simultaneously, reduce deck response by increasing energy dissipating capability by means of damper.
2) Do not forcible elongate the natural period, but select the natural period so that the resonance of the bridge with soils be avoided.

Such design criteria is no more the "isolation" of the "base". Therefore it is proposed to call the design concept as "menshin". The "menshin" means "reduction of seismic response" in Japanese.

In menshin design, bridges can be designed by following the standard static design method (static frame analysis). More precise approve of the seismic safety can be made by the dynamic response analysis, if required. In such analyses, the menshin devices (isolators and dampers) are idealized by as a set of equivalent linear springs. Equivalent stiffness and the equivalent damping ratio of the isolator and damper are the major parameters used in the analyses. In the static frame analysis, natural period of the bridge can be computed for each seismic design structural unit as :

$$T = 2.01\sqrt{\delta} \qquad (1)$$

$$\delta = \frac{\int w_i \cdot u_i^2}{\int w_i \cdot u_i} \qquad (2)$$

where

- T : natural period (sec)
- w_i : dead weight (tf/m) of the seismic design structural unit (super structure and substructure above the ground surface assumed in seismic design) at point "i"
- u_i : lateral displacement (m) developed in the seismic design structural unit at point "i" when subjected to w_i in the direction considered in design

Damping ratio of the bridges is computed as

$$h = \frac{\Sigma K_{Bi} \cdot u_{Bi}^2 \cdot c_{hi}}{\Sigma K_{Bi} \cdot u_{Bi}^2 \cdot c_i} \qquad (3)$$

$$c_{hi} = h_{Bi} + \frac{h_{Pi}}{K_{Pi}} + \frac{h_{Fui}}{K_{Fui}} + \frac{h_{F\theta i} \cdot H^2}{K_{F\theta i}}$$

$$c_i = 1 + \frac{K_{Bi}}{K_{Pi}} + \frac{K_{Bi}}{K_{Fui}} + \frac{K_{Bi} \cdot H^2}{K_{F\theta i}}$$

where

- h : Modal damping ratio of bridge
- h_{Bi} : Damping ratio of i-th damper
- h_{Pi} : Damping ratio of i-th pier/abutment
- h_{Fui} : Damping ratio of i-th foundation associated with translational movement
- $h_{F\theta i}$: Damping ratio of i-th foundation associated with rotation
- K_{Pi} : Equivalent stiffness of i-th pier/abutment
- K_{Fui} : Translational stiffness of i-th foundation
- $K_{F\theta i}$: Rotational stiffness of i-th foundation
- u_{Bi} : Design displacement of i-th menshin device
- H : Height from the bottom of pier to the gravity center of deck

Eq.(3) give the approximate estimation of the damping ratio of bridge assuming that translation and rotation of the foundation are developed only by the inertia force of the deck. When the effect of the inertia force of piers and abutments for evaluating the translation and rotation of the foundation can not be disregarded, it is appropriate to compute the modal damping ratio as

$$h = \frac{\sum_{j=1}^{n} \phi_{ij}^T \cdot h_j \cdot K_j \cdot \phi_{ij}}{\phi_i^T \cdot K \cdot \phi_i} \qquad (4)$$

where

- ϕ_{ij} : Mode vector of j-th structural component for i-th mode
- h_j : Damping ratio of j-th structural component
- K_j : Stiffness matrix of j-th structural component
- ϕ_i^T : Mode vector of bridge for i-th mode
- K : Stiffness matrix of bridge

Table 2 shows the damping ratio recommended for structural components for Eqs.(3) and (4).

4. DESIGN FORCE FOR MENSHIN DESIGN

In menshin design, the menshin devices are designed by the Seismic Coefficient Method and the Bearing Capacity Method. In both method, the lateral force is statically applied to the bridge, and the seismic safety is examined based on the allowable stress design approach in the Seismic Coefficient Method and bearing capacity basis considering ductility in the Bearing Capacity Method. Bridges are designed by the Seismic

Coefficient Method, and then the ductility is checked for reinforced concrete piers by the Bearing Capacity Method.

In the Seismic Coefficient Method, the design lateral force coefficient k_h is given as

$$k_h = c_Z \; c_G \cdot c_I \cdot c_T \cdot c_E \cdot k_{h0} \geqq 0.1$$

where

$$c_T \cdot c_E \geqq 0.8 \qquad (5)$$

where
- k_h : Lateral force coefficient
- c_Z : Modification factor for zone (refer to Fig. 2)
- c_G : Modification factor for ground condition (refer to Table 3)
- c_I : Modification factor for importance (refer to Table 4)
- c_T : Modification factor for structural response (refer to Table 5)
- c_E : Modification factor for energy dissipation capability (refer to Table 6)
- k_{h0} : Standard design horizontal seismic coefficient (= 0.2)

Those factors excluding c_E are the ones specified in the Specifications of Design of Highway Bridges. The modification coefficient c_E takes a value as shown in Table 6 depending on the first modal damping ratio of the bridge Reduction of the design lateral force as large as 20 % is proposed in the Manual.

In the Bearing Capacity Method, the lateral force coefficient k_{hc} and the equivalent lateral force coefficient k_{he} are given as

$$k_{he} = \frac{k_{hc}}{\sqrt{2\mu - 1}} \geqq 0.3 \qquad (6)$$

$$k_{hc} = c_Z \cdot c_I \cdot c_R \cdot c_E \cdot k_{hc0} \qquad (7)$$

where
- k_{he} : Equivalent lateral force coefficient for Bearing Capacity Method
- k_{hc} : Lateral force coefficient for Bearing Capacity Method
- c_Z : Modification factor for zone (refer to Fig. 2)
- c_I : Modification factor for importance (refer to Table 4)
- c_R : Modification factor for structural response (refer to Table 7)
- c_E : Modification factor for energy dissipation capability
- k_{hc0} : Standard lateral force coefficient for Bearing Capacity Method (=1.0)
- μ : Allowable ductility factor of reinforced concrete piers

The modification factors excluding c_E are the ones specified in the Specifications of Design of Highway Bridges. The modification factor c_E depends on the modal damping ratio of the bridge, and takes a value of Table 8. Reduction of the design force as large as 30 % is proposed.

5. DESIGN OF MENSHIN DEVICES

5.1 Characteristics Value of Menshin Devices

In the menshin design, the displacement assumed in design for the devices u_B (design displacement of menshin device), the equivalent stiffness K_B and the equivalent damping ratio h_B of the menshin device are the key factors. They are evaluated as:

(1) Design Displacement of Menshin Device

The design displacement of menshin device is evaluated as

$$u_B = \frac{k_h \cdot W_u}{K_B} \quad \text{(S. C. Method)} \qquad (8)$$

$$u_B = \frac{k_{hc} \cdot W_u}{K_B} \quad \text{(B. C. Method)} \qquad (9)$$

where
- u_B : Design displacement (m) of menshin device
- k_h : Lateral force coefficient by Eq.(5) for Seismic Coefficient Method
- k_{hc}: Lateral force coefficient by Eq.(6) for Bearing Capacity Method
- K_B : Equivalent stiffness (tf/m) of menshin device
- W_u : Weight of superstructure (tf) supported by the menshin device

(2) Equivalent Stiffness and Equivalent Damping Ratio

The equivalent stiffness and the equivalent damping ratio of menshin device are evaluated from the hysteresis loops as

$$K_B = \frac{F(u_{BE}) - F(-u_{BE})}{2u_{BE}} \qquad (10)$$

$$h_B = \frac{\Delta W}{2\pi W} \qquad (11)$$

where
- K_B : Equivalent stiffness (tf/m) of menshin device
- h_B : Equivalent damping ratio of menshin device
- u_{BE} : Effective design displacement (m) of menshin device, and is given as
  $u_{BE} = c_B \cdot u_B \qquad (12)$
- u_B : Design displacement (m) of menshin device
- c_B : Modification coefficient for evaluating the effective design displacement (=0.7)
- $F(u)$: Lateral force required to produce u for the menshin device
- W : Strain energy induced in menshin device associated with c_{BE} displacement (refer to Fig. 3)
- ΔW : Energy dissipated in menshin device per

cycle (refer to Fig. 3)

5.2 Requirements for Dynamic Load

(1) Menshin devices have to be designed and fabricated so that their equivalent stiffness K_B and equivalent damping ratio h_B be within ±20 % of the design values. The equivalent stiffness K_B and equivalent damping ratio h_B for this requirement have to be evaluated by Eqs. (10) and (11), and they shall be the ones averaged over K_B and h_B from 4th to 10th loading hysteresis among 10 cyclic loading reversals with harmonic displacement of c_{BE}. This is because deck acceleration and displacement are within tolerable range when the scatter of equivalent stiffness and the equivalent damping ratio are within ±20 % of the design values. However, the devices which produce unstable hysteretic behavior should not be adopted.

(2) Menshin devices have to be stable against 50 cycles of harmonic loading with displacement of u_B. The number of 50 was determined from the fact that number of load reversals developed during a major earthquake may be about 30. About 50 % tolerance was included in 50.

(3) Deck should return to the rest position even after it was subjected to a large earthquake. Therefore the residual displacement developed in menshin devices after smoothly releasing from the deformed displacement of u_B by Eq. (9) has to satisfy

$$u_{BR} \leqq 0.1\ u_B \qquad (13)$$

where

u_{BR} : Residual displacement (cm)

u_B : Design displacement(cm) of menshin device by Eq. (9)

(4) The equivalent stiffness and the equivalent damping ratio of menshin devices have to be stable against the change of load condition at normal time, change of natural environment such as the temperature change and cyclic loading developed by an earthquake. Stability has to be examined against the following requirements:

1) cyclic loading due to elongation and shrinkage of deck due to the temperature change and the active load
2) effect of loading hysteresis
3) variation of vertical loading
4) effect of loading rate
5) effect of pre-deformation due to creep and shrinkage
6) direction of excitation
7) change of the equivalent stiffness and the equivalent damping ratio depending on the temperature change

5.3 Requirements for Static Load

(1) Materials and mechanism of menshin devices have to give credit to long term use. They have to be stable against cyclic elongation and shrinkage of deck due to temperature change.

(2) Menshin devices have to be stable against local shear strain. Check of the local shear strain has to be made in accordance of "3.6 Design of Rubber Bearings" of the "Design Guidelines of Bearings".

(3) For rubber-type menshin devices, the creep of rubber in vertical direction due to dead weight of superstructure shall not exceed 5 % of total thickness of the rubber.

(4) The equivalent stiffness of menshin device at -10℃ normalized by the equivalent stiffness at 40 ℃ shall not exceed 1.5. Because the temperatures of -10℃ and 40℃ is for moderate climate area, at cold area they have to be decided based on the appropriate site condition.

(5) Menshin devices have to have appropriate initial stiffness so that harmful displacement of deck due to non-seismic lateral force such as wind effects be avoided.

6. APPROVING TESTS OF MENSHIN DEVICES

6.1 General

Because the menshin device is one of the the important structural components of menshin bridges, their requirements have to be well approved by the tests. There are various types of menshin devices for use of bridges. Based on the mechanism for producing the energy dissipation, the devices may be classified into three groups as

(a) displacement dependent type,
(b) friction force type, and
(c) velocity dependent (viscous) type.

The approving tests for the menshin devices are presented in the Manual for each of the three types.

6.2 Approving Tests for Dynamic Loads

For approving the requirements for dynamic loads presented in 5.2, the following approving tests are provided in the Manual.

(1) Approving test for confirming the equivalent stiffness and the equivalent damping ratio

(2) Approving test for confirming stableness against 50 cycles harmonic load reversals with u_B displacement

(3) Approving test for confirming residual displacement requirement

(4) Approving tests for confirming stableness against variation of load condition at normal time, change of natural environment such as the temperature change and cyclic loading developed by an earthquake. These tests include :

(a) Stableness against Cyclic Load Reversals

Some menshin devices have the dependence of the equivalent stiffness and the equivalent damping ratio on number of cyclic loading. Because considerable change of these parameters during an earthquake produces bridge response significantly different from the one assumed in design, it is not desirable.

(b) Stableness against Load Hysteresis

In some menshin devices, the equivalent stiffness and the equivalent damping ratio depend on the past experience, in particular, the largest deformation ever experienced. Such dependence of K_B and h_B on the hysteresis ever experienced is significant, it produces different bridge response during an earthquake. Therefore, effect of load hysteresis has to be examined.

(c) Stableness against Change of Compression Force

Compression force applied to the menshin device due to dead weight of superstructure may change associated with the error involved in construction stage and settlement of substructure. If the menshin device shows significantly different stiffness and damping properties due to such change of compression force, it brings different structural response . Therefore, stableness of the equivalent stiffness and the equivalent damping ratio of menshin devices have to be checked.

(d) Stableness against Change of Loading Rate

Because loading rate to the menshin devices is not the same during excitation, dependence of the equivalent stiffness and the equivalent damping ratio on the loading rate has to be examined.

(e) Stableness against Pre-deformation

Menshin devices often start to deform from the displacement drifted to the rest point. This is actually developed if an earthquake occurs when the menshin devices deform due to the deck elongation associated with temperature change and shrinkage of concrete. Because the equivalent stiffness and the equivalent damping ratio depend on the amount of such pre-deformation, their properties have to be checked.

(f) Stableness against Temperature Change

Menshin device have to be stable against daily and yearly change of temperature.

6.3 Approving Tests for Static Loads

For approving the requirements for static loads presented in 5-3, the following tests are required.

(1) Approving test for confirming durability and stableness against cyclic loading associated with the daily and yearly elongation and shrinkage of deck.

(2) Test for evaluating the stiffness of menshin devices subjected to extremely low-rate deformation such as the one encountered due to yearly temperature change and concrete creep. The stiffness of the menshin device during such low-rate deformation is quite important in static design for computing the lateral force developed in substructures due to the temperature change and shrinkage of concrete.

(3) Approving test for confirming the dependence of the equivalent stiffness of menshin device on temperature.

6.4 Two examples of the Approving Test

Approving test methods presented in 6.2 and 6.3 are precisely described in the Manual for each of the displacement dependent type devices, friction force type devices and the velocity dependent type devices. As the example of such approving tests, the test method for confirming stableness against cyclic loading and the test method for confirming the effect of loading rate are briefly described for the displacement dependent type devices in the following.

(1) Approving Test for Confirming Stableness against Cyclic Loads

At the room temperature of 20℃ apply 10 cycles of harmonic lateral load to the menshin device with loading displacement of u_B computed by Eq. (9) or smaller and with the frequency of 0.5 Hz. The vertical load equivalent to the design dead load shall be simultaneously applied. The equivalent stiffness and the equivalent damping ratio from the test have to satisfy Eqs. (14) and (15).

$$R_{KC} = \frac{|K_{Bj} - K_{Bm}|}{K_{Bm}} \begin{array}{l} \leq 0.3 \ (j=1,2,3) \\ \leq 0.1 \ (j=4,5 \cdots 10) \end{array} \tag{14}$$

$$R_{hC} = \frac{|h_{Bj} - h_{Bm}|}{h_{Bm}} \begin{array}{l} \leq 0.3 \ (j=1,2,3) \\ \leq 0.1 \ (j=4,5 \cdots 10) \end{array} \tag{15}$$

where,

R_{KC} : Variation ratio of equivalent stiffness

R_{hC} : Variation ratio of equivalent damping ratio

K_{Bj} : Equivalent stiffness at j-th load reversal(tf/m)

K_{Bm} : Averaged equivalent stiffness by Eq. (16)

h_{Bj} : Equivalent damping ratio at j-th load reversal

h_{Bm} : Averaged damping ratio by Eq. (17)

$$K_{Bm} = \frac{1}{7} \sum_{j=1}^{10} K_{Bj} \tag{16}$$

$$h_{Bm} = \frac{1}{7} \sum_{j=1}^{10} h_{Bj} \tag{17}$$

Being different with Eqs. (10) and (11), the equivalent stiffness and the equivalent damping ratio for the approving tests are defined as

$$K_B = \frac{F(u_B) - F(-u_B)}{2u_B} \tag{18}$$

$$h_B = \frac{\Delta W}{2\pi W} \tag{19}$$

where

K_B · Equivalent stiffness (tf/m) of menshin device

h_B : Equivalent damping ratio of menshin device

u_B : Design displacement (m) of menshin device

F(u) : Lateral force (tf) required to produce u displacement for the menshin device

W : Strain energy (tfm) induced in menshin device associated with u_B displacement (refer to **Fig. 4**)

ΔW : energy dissipated in menshin device per cycle (refer to **Fig. 4**)

(2) Approving Test for Confirming the Stableness against Loading Rate

At the temperature of 20℃ apply 10 cycles of harmonic load with the displacement equivalent to either 100 % of the total thickness of rubber or ± 15 cm. Frequency of the load reversal shall be 0.1 Hz, 0.5 Hz and 1 0 Hz. The equivalent stiffness and the equivalent damping ratio have to satisfy Eqs. (20) and (21).

$$R_{KT} = \frac{|K_{Bm1} - K_{Bmj}|}{K_{Bm1}} \leq 0.2 \quad (j=1,2) \qquad (20)$$

$$R_{hT} = \frac{|h_{Bm1} - h_{Bmj}|}{h_{Bm1}} \leq 0.2 \quad (j=1,2) \qquad (21)$$

where,

R_{KT} : Variation ratio of equivalent stiffness

R_{hT} : Variation ratio of equivalent damping ratio

K_{Bm1}, K_{Bm2}, K_{Bm3} : Equivalent stiffness by Eq. (16) at frequency of 0.5 Hz, 0.1 Hz and 1.0 Hz, respectively

h_{Bm1}, h_{Bm2}, h_{Bm3} : Equivalent damping ratio by Eq. (17) at frequency of 0.5 Hz, 0.1 Hz and 1.0 Hz, respectively

7. CONCLUDING REMARKS

Excluding specially long-span bridges, it is not easily adopted for highway bridges to reduce the lateral force by forcibly elongating the natural period, because seismic force level is very high even at long natural period, and because the increase of deck response displacement brings various problems such as environmental pollution. Therefore the menshin design, which places emphasis not on the forcible elongation of the natural period but on the increase of energy dissipating capability and distribution of inertia force of superstructure to as many substructures as possible, is proposed. By the menshin design, it is proposed to decrease the lateral force as large as 20 % for the Seismic Coefficient Method and 30 % for the Bearing Capacity Method

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Table 1 Research Theme and Organizations of Joint Research Program between the Public Works Research Institute and 28 Private Firms for Developing Menshin Design Method of Highway Bridges

Research Theme	P	Ka	Si	Ob	Ku	Tn	H	Ni	Su	M	G	Ok	Ti	I	Nk	Ko	Ns	Ol	Y	To	Bs	Bb	Se	Sh	Pc	J	N	Chief	Sub-Chief
1. Development of Device for Isolation																												Ol	Bs
1.1 High Energy Absorbing Rubber Bearing								○											○	○	○			○					
1.2 Friction Damper													○									○	○						
1.3 Steel Damper								○							○														
1.4 Link Bearing Develop of																	○												
1.5 Viscous Damper																		○											
1.6 Test Method	○							○							○		○	◎	○	○	○	○	○	○					
2. Development of Expansion Joint and Falling-off Prevention Device for Isolated Bridge																												Tc	—
2.1 Expansion Joint				○									○																
2.2 Falling-off Prevention Device	○												○					○											
3. Development of Design Method for Isolated Bridge																												Ka	Pc
3.1 Design Philosophy	○	○	○	○		○						○	◎					○							○	○	○		
3.2 Dynamic Responce Analysis Method	○		○		○	◎		○			○			○															
3.3 Design Method of Device for Isolation	○						○	○				◎	○		○		○	○	○	○	○	○	○	○					
3.4 Simplified Design Method	○	○	◎		○	○					○	○																	
3.5 Design Method of Expansion Joint and Falling-off Prevention Device	○			○			○								○			○							◎				
4. Application of Base Isolation to Bridge																												Ob	J
4.1 Application to Prestressed Concrete Bridge	○	◎							○	○			○														○		
4.2 Application to Steel Bridge	○													○	○	○											◎		
4.3 Application to Multiple Super-long Bridge	○			◎					○							○									○	○	○		
4.4 Application to Seismic Retrofit	○									○				○				○								◎			

P: Public Works Research Institute, Ka: Kajima, Si: Shimizu, Ob: Ohbayashi, Ku: Kumagai, Tn: Takenaka Doboku + Takenaka, H. Hazama, Ni: Nishimatsu, Su: Sumitomo, M: Mitsui, G: Goyoh, Ok: Okumura, Ti: Taisei + Tokyo Fablic + Nippon Chuzo, I: Ishikawajima Harima, Nk: NKK + Nippon Chuzo, Ko: Kobe Steel, Ns: Nippon Seiko, Oe: Oiles, Y: Yokohama Rubber, To: Toyo Rubber, Bs: Bridgestone, Bb: BBM, Se: Seibu Polymer, Sh: Showa Densen, Pc: Pacific Consultants, J: Japan Engineering Consultant, N: New Structural Engineering Consultants.

Table 2 Damping Ratio Recommended for Structural Components

Structural Components	Steel	Concrete
Superstructures	0.02~0.03	0.03~0.05
Menshin Device	Damping Ratio by Eq.(11)	
Pier/Columns	0.03~0.05	0.05~0.1
Footing	0.1~0.3	

Table 3 Modification Factor for Ground Condition c_G

Ground Group	I	II	III
c_G	0.8	1.0	1.2

Table 4 Modification Factor for Importance c_I

Group	c_I	Definition
1st class	1.0	Bridges on expressway (limited access highways), general national road and principal prefectural road. Important bridges on general prefectural road and municipal road.
2nd class	0.8	Other than the above

Table 5 Modification Factor for Structural Response c_T

Ground Group	Structural Response Coefficient c_T		
Group I	$T < 0.1$ $c_T = 2.69T^{1/3} \geqq 1.00$	$0.1 \leqq T \leqq 1.1$ $c_T = 1.25$	$1.1 < T$ $c_T = 1.33T^{-2/3}$
Group II	$T < 0.2$ $c_T = 2.15T^{1/3} \geqq 1.00$	$0.2 \leqq T \leqq 1.3$ $c_T = 1.25$	$1.3 < T$ $c_T = 1.49T^{-2/3}$
Group III	$T < 0.34$ $c_T = 1.80T^{1/3} \geqq 1.00$	$0.34 \leqq T \leqq 1.5$ $c_T = 1.25$	$1.5 < T$ $c_T = 1.64T^{-2/3}$

Table 6 Modification Factor for Energy Dissipation Capability c_E

Damping Ratio h	Modification Factor c_E
$h < 0.1$	1.0
$h \geqq 0.1$	0.9

Table 7 Modification factor for Structural Response c_R

Ground Group	Structural Response Coefficient c_R		
Group I	$T_{EQ} \leqq 1.4$ $c_R = 0.7$		$1.4 < T_{EQ}$ $c_R = 0.876 T_{EQ}^{-2/3}$
Group II	$T_{EQ} < 0.18$ $c_R = 1.51 T_{EQ}^{1/3} \geqq 0.7$	$0.18 \leqq T_{EQ} \leqq 1.6$ $c_R = 0.85$	$1.6 < T_{EQ}$ $c_R = 1.16 T_{EQ}^{-2/3}$
Group III	$T_{EQ} < 0.29$ $c_R = 1.51 T_{EQ}^{1/3} \geqq 0.7$	$0.29 \leqq T_{EQ} \leqq 2.0$ $c_R = 1.0$	$2.0 < T_{EQ}$ $c_R = 1.59 T_{EQ}^{-2/3}$

Table 8 Modification Factor for Energy Dissipating Capability

Damping Ratio h	Modification Factor c_E
$h < 0.1$	1.0
$0.1 \leqq h < 0.12$	0.9
$0.12 \leqq h < 0.15$	0.8
$0.15 \leqq h$	0.7

Fig. 1 Menshin Devices Developed

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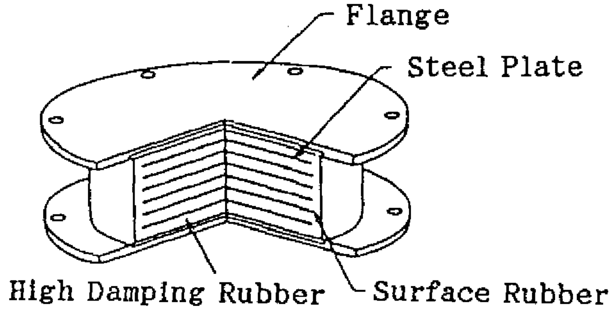
RUBBER BEARING</td><td>
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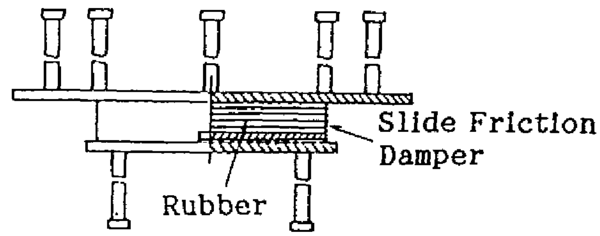
<tr><td>SLIDE FRICTION
-RUBBER BEARING</td><td>
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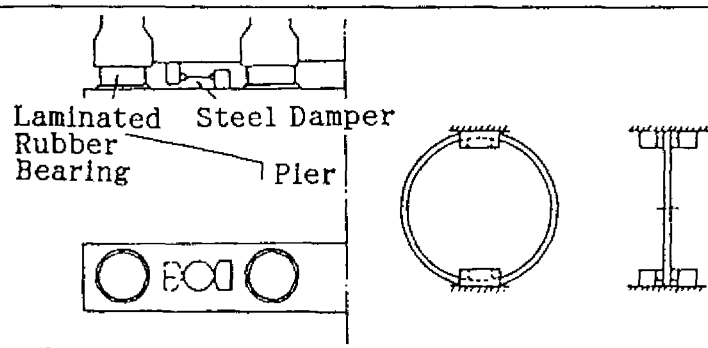
<tr><td>STEEL DAMPER</td><td>
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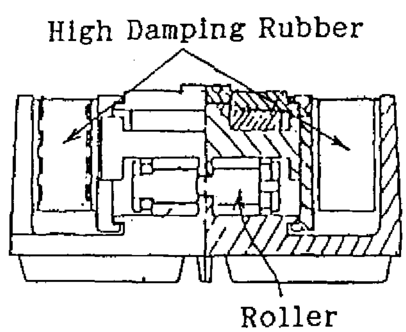
<tr><td>ROLLER MENSHIN
BEARING</td><td>
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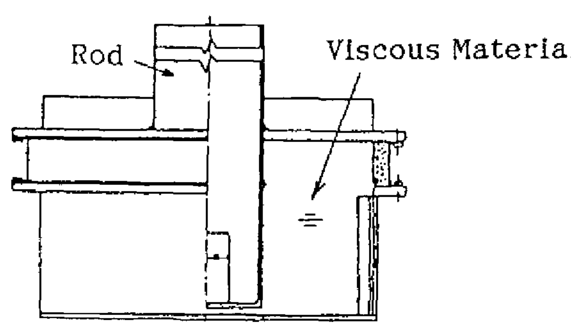
<tr><td>VISCOUS</td><td>
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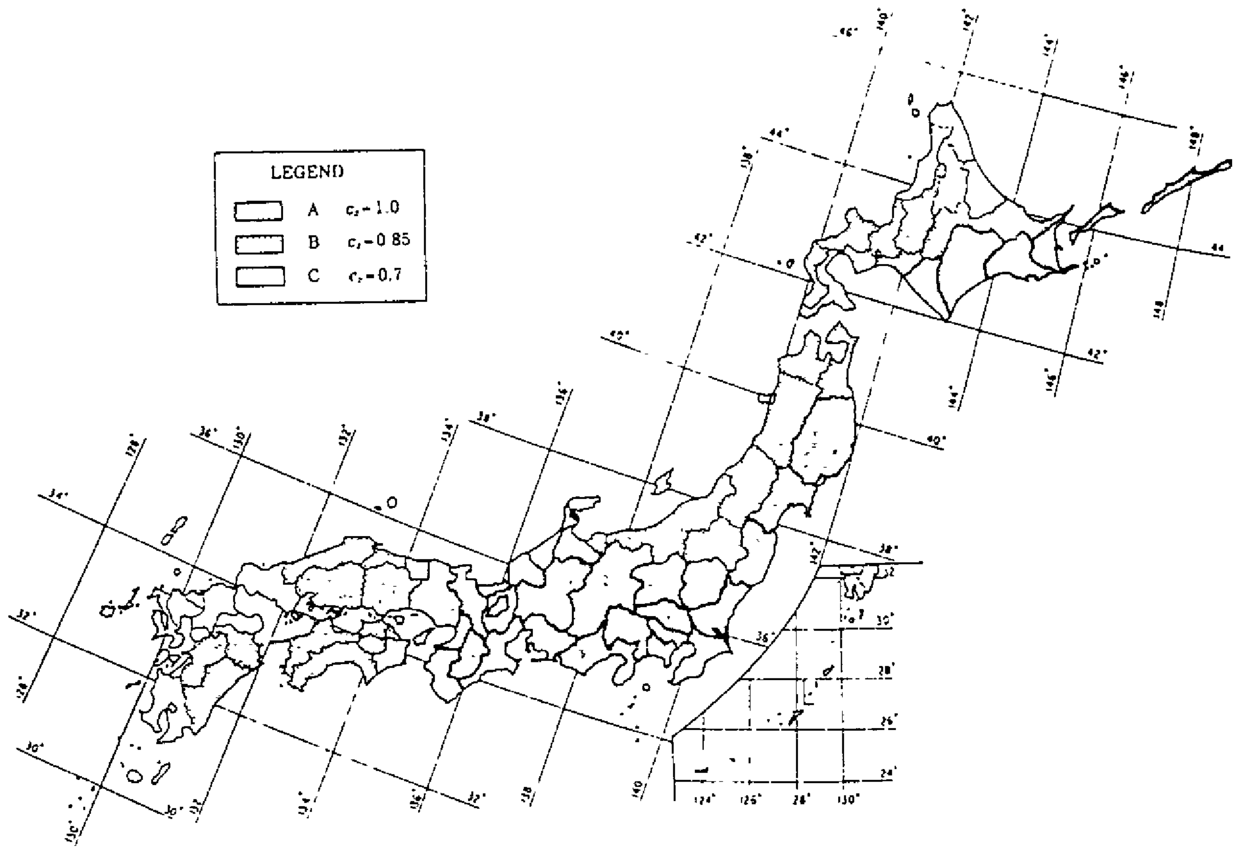

Fig. 2 Modification Factor for Zone c_z

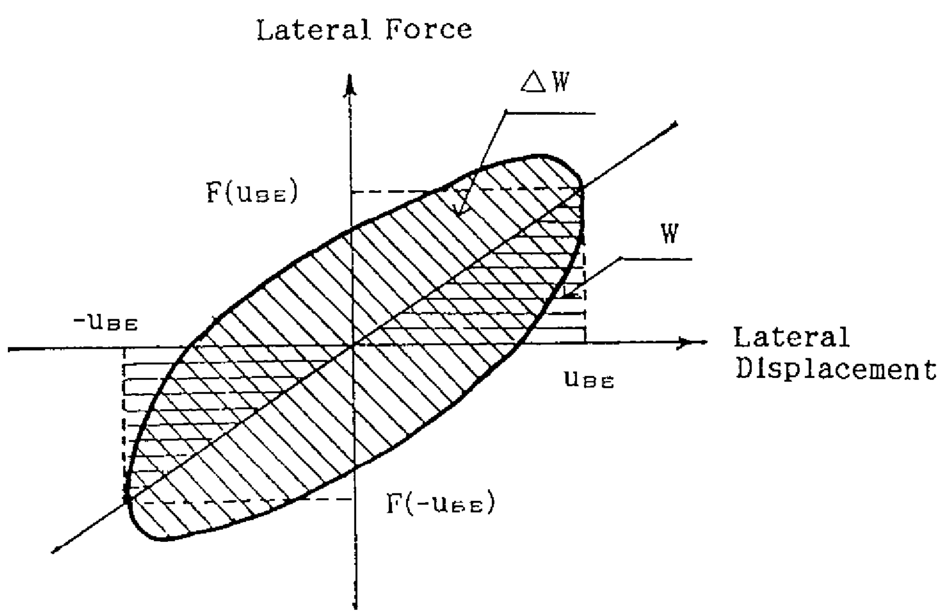

Fig. 3 Definition of Equivalent Stiffness and Equivalent Damping Ratio of Menshin Device for Design of Menshin Device

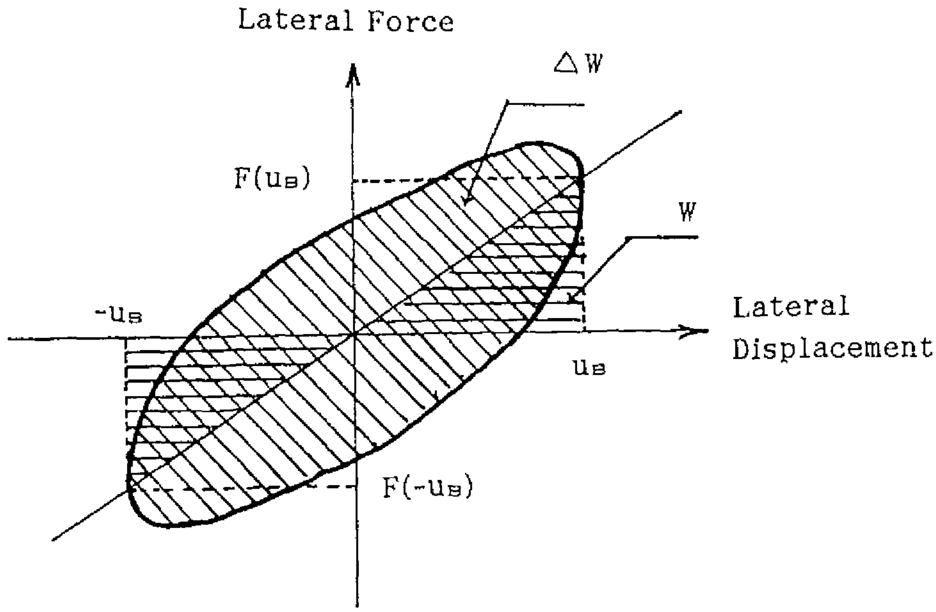

Fig. 4 Definition of Equivalent Stiffness and Equivalent Damping Ratio of Menshin Device for Approving Tests

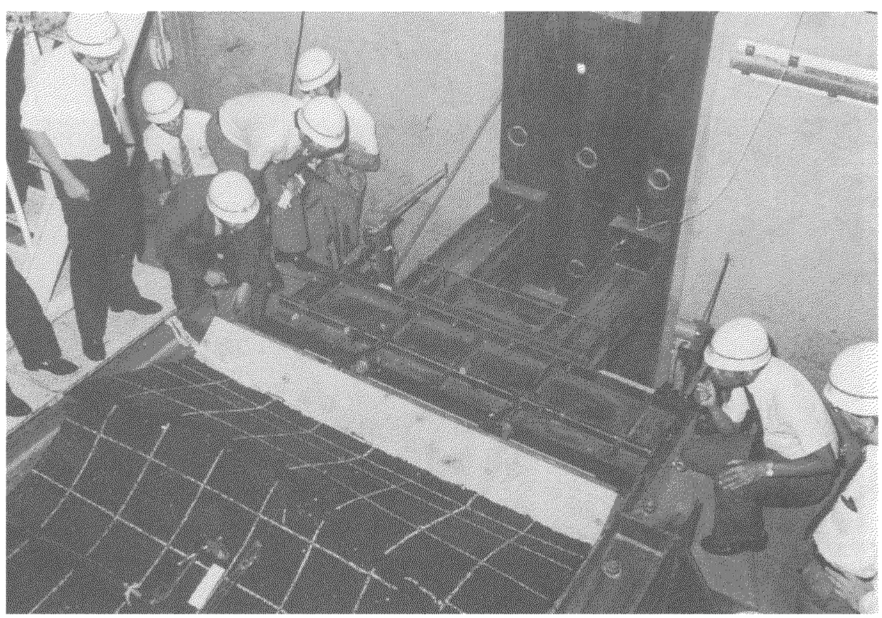

Photo 1 Knock-off Abutment