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EARTHQUAKE RESPONSE CHARACTERISTICS OF SUPER-MULTI-SPAN CONTINUOUS MENSHIN (SEISMIC ISOLATION) BRIDGES AND THE SEISMIC DESIGN

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ABSTRACT

Super-multi-span Continuous Menshin (Menshin means Seismic Isolation in Japanese [Sugita et al. (1994)]) Bridges with bridge lengths of over 1,000 m increase driving comfort, mitigate maintenance by saving the number of expansion joints, and reduce the inertia force of the superstructure which is transmitted to the substructure during earthquakes.

In designing the super-multi-span continuous bridges, there are several subjects to be investigated such as the limitation of continuous girder length, effect of the change of the ground condition in a bridge on the earthquake response characteristics, effect of the spatial difference of the earthquake ground motion and so on.

In this paper, the limitation of the continuous girder length was studied through the trial designs of three kinds of girder bridges. Then the effects of the change of ground condition and the variation of the earthquake ground motion were studied through the dynamic response analyses. Based on these studies, key issues for the seismic design of super-multi-span continuous Menshin bridges were summarized.

KEYWORDS: Menshin Bridge, Seismic Design, Super-multi-span Continuous Bridge, Seismic Isolation, Earthquake Response Characteristics

INTRODUCTION

Super-multi-span Continuous Menshin Bridges with bridges lengths of over 1,000 m increase driving comfort, mitigate maintenance by saving the number of expansion joints, and reduce the inertia force of the superstructure which is transmitted to the substructure during earthquakes.

The longest continuous girder bridge currently in Japan is the Ohito viaduct with 29-spans continuous hollow slab girder and the bridge length of 725 m in Shizuoka prefecture [Masumoto et al. (1993)]. The seismic isolation design was applied for the Ohito viaduct to decrease the effect of elongation and shrinkage of the girder by absorbing the displacement by rubber type bearings.

When the super-multi-span bridges is designed, there are several subjects to be investigated such as the limitation of continuous girder length, the effect of the change of ground characteristics in a bridge and the effect of spatial difference of input ground motion on the seismic response characteristics [Ministry of Construction (1993)].

In this paper, the limitation of the continuous girder length was studied through the trial designs of three kinds of girder bridges. Then the effects of the change of ground condition and the variation of the earthquake ground motion were studied through the dynamic response analyses [Ohsumi et al. (1997)]. Based on these studies, key issues for the seismic design of super-multi-span continuous Menshin bridges were summarized.

LIMITATION OF THE CONTINUOUS BRIDGE LENGTH

1. Model Bridge

Table 1 shows the conditions of bridge models analyzed. Straight horizontal linearity was assumed for the model bridges, because the design for displacement and shear strain of isolation bearings at the end of girder due to the temperature change becomes generally more critical for the straight bridges than the curved bridges. Three types of superstructures – steel plate girder, steel box girder and prestressed concrete box girder – were assumed. Figure 1 shows the typical section of the model bridges. Span lengths were assumed as 35 m, 60 m, 40 m for each types of girders, respectively. A cantilever type reinforced concrete columns with rectangular section for piers, spread footing for the type I ground condition (Ground type is defined in the Design Specifications of Highway Bridges in Japan [Japan Road Association (1996)], type I means stiff ground condition) and pile foundations for the type II ground condition (medium ground condition) were assumed. For isolation devices, high damping rubber bearings were assumed. It is also assumed that the distribution of inertia force of the superstructure to substructures is almost equal, except for the piers at the end of the girder and the same size bearings are used for all piers.

Table 1: Conditions of Model Bridges

Horizontal linearity	Straight
Type of superstructure (Span length)	Steel plate girder (35 m) Steel box girder (60 m) Prestressed concrete box girder (40 m)
Continuous spans	Steel plate girder: 700 m – 1,400 m Steel box girder: 1,200 m – 2,400 m Prestressed concrete box girder: 960 m – 1,600 m
Type of pier	Cantilever type rectangular pier
Type of foundation	Type I Ground: Spread footing Type II Ground: Pile foundation
Device for menshin	High damping rubber bearing

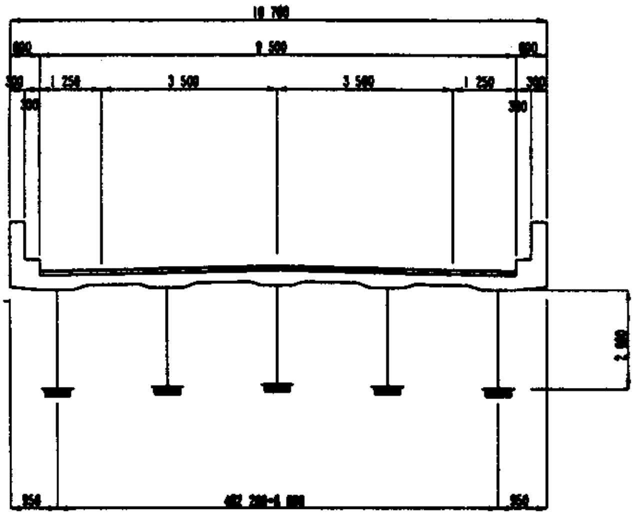

Fig. 1(a) Typical section of steel plate girder model bridges

The design was made according to the Design Specifications of Highway Bridges in Japan. The design method is based on the ductility design concept. Isolation bearings and bridge columns were designed under the design condition considering the effects of temperature change and the earthquake. In the design, based on the design specifications, the temperature change was assumed as –5°C to +40°C for concrete and –10°C to +40°C for steel. The earthquake design spectrum used is shown in Figure 2. Both the type I design spectrum which represents the plate-boundary earthquake ground motions and type II design spectrum which represents the inland earthquake ground motions are considered. The effects of the temperature change and the earthquake are not combined and are independently considered in the design. The number of spans was assumed to be 20, 30 or 40 for steel plate girders and steel box girders as an analytical parameter, and the length of spans was assumed to be constant. For the prestressed concrete girder, the number of spans was assumed to be 24, 32 or 40.

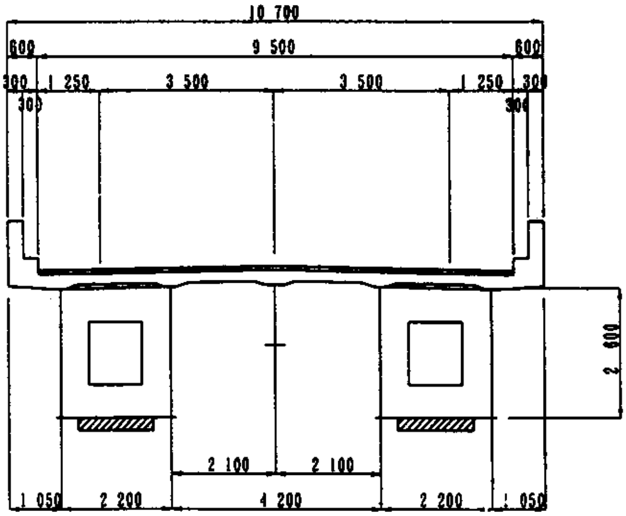

Fig. 1(b) Typical section of steel box girder model bridges

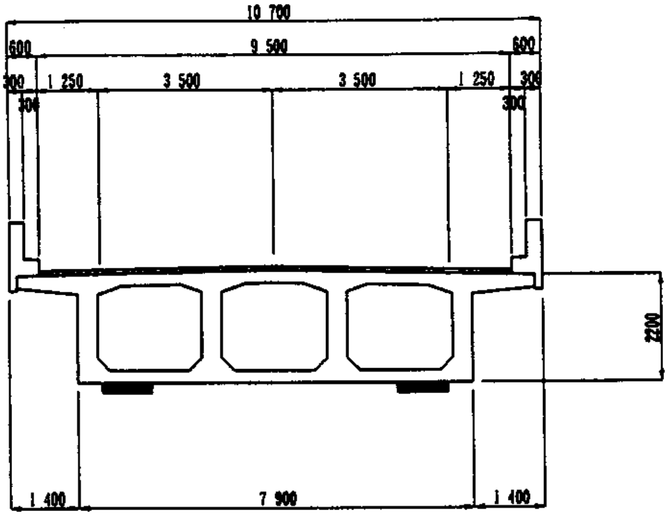

Fig. 1(c) Typical section of prestressed concrete box girder model bridges

2. Effect of Continuous Girder Length

2.1 Volume of Bearing

Figure 3 shows the relationship between the length of continuous girder and the volume of rubber bearings a pier. In the Design Specifications of Highway Bridges in Japan, when the isolation bearings, which have the function to elongate the natural period of a bridge, are designed, the natural period ratio of the bridge should be about 2 or more. It should be noted here that the natural period ratio of bridges is defined as the ratio of the natural period of Menshin designed bridge divided by the natural period of bridge with hinged bearings. In this study, natural period ratio is assumed as more than 2 according to the design specifications, and the isolation bearings are designed under the condition that the volume of rubber bearings be minimum. Figure 3 shows that the volume of bearings increases with increase of the continuous length of girder in spite of types of girders. This is because the number of laminated rubber layers becomes large and the area of a bearing also becomes large at the end of girder with increase of continuous length. The number of rubber layer is strongly dependent on the local shear strain of the rubber and the area of bearing is dependent on the vertical loads. In the middle of girder, only the number of rubber layer becomes larger.

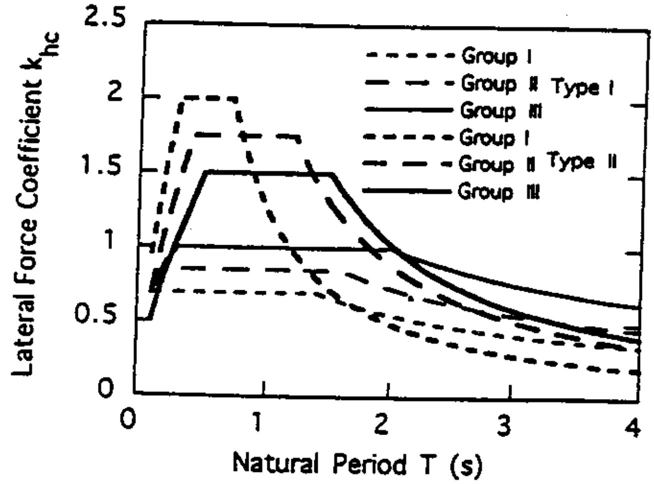

Fig. 2 Design earthquake spectrum used in this study

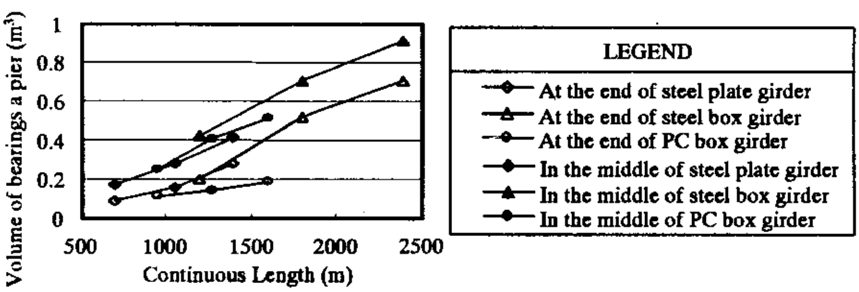

Fig. 3 Relationship between continuous length and volume of bearings

In case of the steel box girder with bridge length of 1,200 m, for example, the size of bearing is 65 cm × 65 cm in plan and 24 cm in total rubber thickness at the end of girder, 96 cm × 96 cm in plan and 19.5 cm in total rubber thickness in the middle of girder. In case of bridge length of 2,400 m, the size of bearing is 90 cm × 90 cm in plan and 43.5 cm in total rubber thickness at the end of girder, 103 cm × 103 cm in plan and 39 cm in total rubber thickness in the middle of girder. The plan area of bearings at the end of girder was smaller than that of bearings in the middle of girder because of the difference of the vertical dead load. It should be noted here that the volume of bearings in the middle of girder increases with continuous girder length as shown in Figure 3, this is because the distribution of the lateral inertia force of the superstructure was assumed to be equal for all piers then the stiffness of the bearings was determined in the design of the effect of earthquake rather than the temperature change for each continuous girder length. Although the size of bearings increases with increase of the continuous length, a super-multi-span continuous bridge with the bridge length up to 2,400 m is found to be practically designed based on the above trial designs. It should be noted here that although the thickness of the isolation bearings is relatively large at the end of girder, the stability check was not made in this analysis. It is required to assure the stability of the bearings in the condition of the large displacement.

2.2 Displacement of Isolation Bearings

Figure 4 compares the maximum displacement of bearings caused by the effect of the temperature change and by the effect of the earthquake under the design condition of minimizing the volume of isolation bearings. The maximum displacement of bearings increases with increase of the continuous length in all bridge types and the displacement caused by the effect of the earthquake is larger than that by the temperature.

Figure 5 shows that the relation between the natural period ratio and the maximum displacement of isolation bearings caused by the effect of earthquake for the steel box girder which had the largest displacement in Figure 4, which was obtained under the design condition of controlling the natural period ratio. When the natural period ratio decreases, the displacement of bearings also decreases. But, for example, when the natural period ratio is 2, the intersections of bearings become large to increase the horizontal stiffness of the bearing, therefore the volume of bearings increases from 1.8 to 2 times.

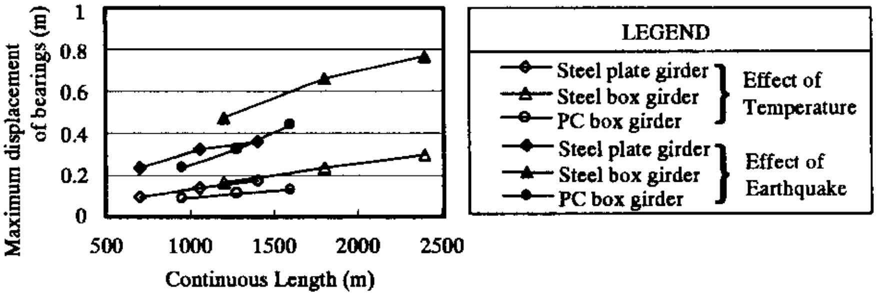

Fig. 4 Relationship between continuous length and maximum displacement of bearings

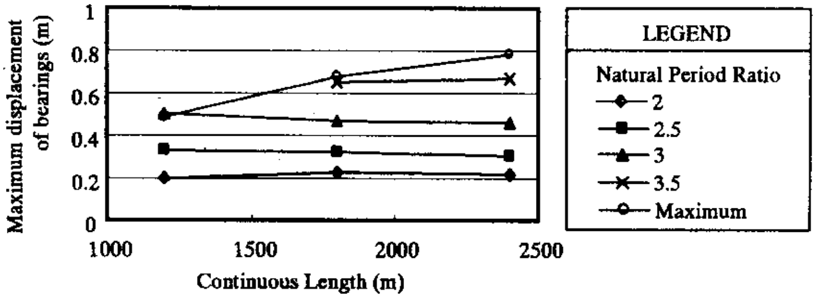

Fig. 5 Relationship between natural period ratio and maximum displacement of bearings caused by the effect of earthquake (steel box girder)

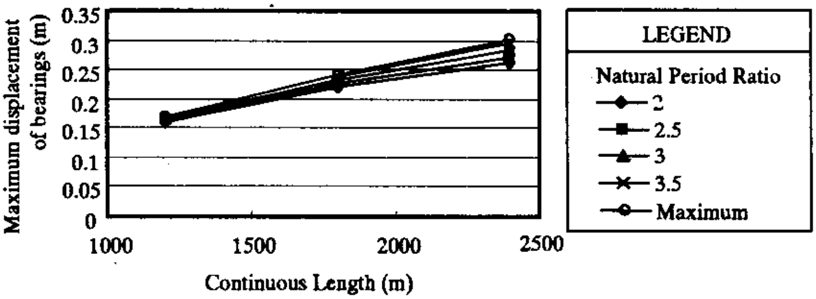

Fig. 6 Relationship between natural period ratio and maximum displacement of bearings caused by the effect of temperature (steel box girder)

Figure 6 shows the relationship between the natural period ratio and the maximum displacement of bearings caused by the effect of the temperature. The displacement of bearings caused by temperature become larger with increase of the continuous girder length, and it hardly depends on the natural period ratio. Comparing Figure 6 with Figure 5, in only case that the natural period ratio is 2 and the continuous length is 2,400 m, the displacement of bearings caused by the effect of temperature is larger than that caused by the earthquake. Therefore, longer continuous girder makes the effect of the temperature change larger than that of earthquake in the design of the bridges.

EFFECT OF CHANGE OF GROUND CHARACTERISTICS

1. Model Bridge Analyzed

The effect of change of ground characteristics on the earthquake response of the super-multi-span continuous bridge was investigated through the dynamic response analyses. The prestressed concrete box girder was employed for the analysis and the condition of bridge is the same as shown in Table 1. Figure 7 shows the beam-mass model for the dynamic analysis. For the simplicity of the analytical conditions, it is assumed that the spring coefficient of foundations is independent on the type of foundation. In the analysis, the stiffness of a column bottom is assumed to be yielding stiffness, stiffness of upper parts of a pier is assumed to be elastic stiffness, in which the yielding stiffness and elastic stiffness represent the stiffness when the longitudinal re-bars starts yielding and the stiffness in which it is calculated from the section area and the elastic modulas of concrete, respectively. The stiffness of isolation bearings is assumed to be equivalent linear stiffness which is calculated from the reaction force and the design displacement of bearings.

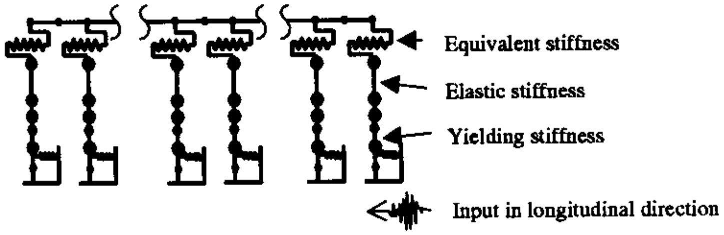

Fig. 7 Analytical model

As analytical parameters, type of ground, number of continuous spans, and difference of input phase of ground motion were varied. Standard earthquake ground motions which are provided in the Design Specifications of Highway Bridges in Japan applying to the type I and II ground conditions for the ductility design method, are used as input ground motions. The dynamic response analyses were made for the longitudinal direction of the bridge.

2. Effect of Change of Ground Characteristics

Figure 8 shows the maximum displacement of bearings for the 24 span continuous bridge caused by the change of ground characteristics. The piers numbering 1 to 12 are on type I ground condition, and those numbering 13 to 25 are on type II ground condition. For comparison, the maximum displacement of bearings when the whole bridge is on type I ground or on type II ground are also shown in the figure. Eventhough there is change of ground characteristics in the bridge, the maximum displacement of all bearings are almost the same. It means that the whole superstructure behaves as a rigid body even against the different input ground motions. The maximum displacement of bearings of the bridge with the change of ground characteristics is just between the bridges without the change of ground characteristics. Since the displacement of bearings are simply related to the horizontal force transmitted to the columns, the bending moments developed in the columns have the same tendency with the displacement of bearings.

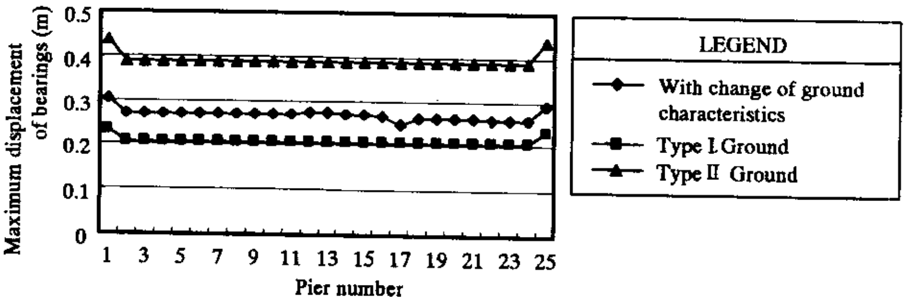

Fig. 8 Maximum displacement of bearings of 24 span continuous bridge caused by the change of ground characteristics

Figure 9 shows the axial stresses developed in a girder. When the bridge is on the same ground condition, the axial force is small because the girder behaves as a rigid body. But when there is a change of ground characteristics, the large axial force are developed at the point of change of ground characteristics. Since this large axial force is developed by the effect of out-of-phase ground motion, the magnitude of the axial force is dependent on the stiffness of substructures and bearings as shown later. The axial force is about 30 MN in this case.

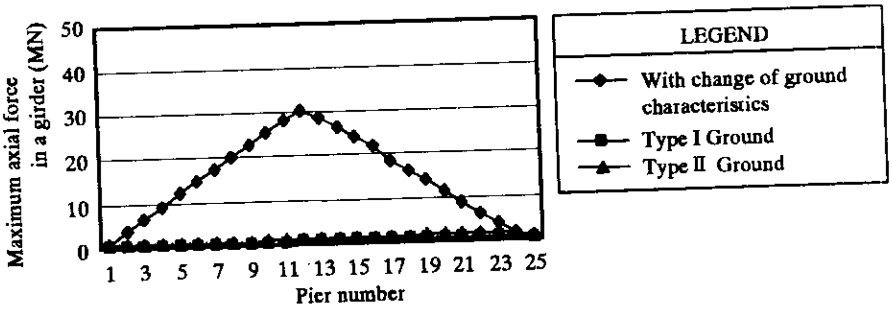

Fig. 9 Maximum axial force in a girder of 24 span continuous bridge caused by the change of ground characteristics

Table 2 shows the result of the safety check that the developed axial force is allowable or not for the safety of the girder. In consideration of effects of dead load of girder, dead load of slab, live load, prestressing force and horizontal force from bearings, the axial stress in the girder exceeded the allowable level at the upper end of the girder in tension. But the exceeded stress can be easily compensated by increasing the number of reinforcement in the girder without changing the girder section.

Table 2: Check of Axial Stresses (N/mm^2) in Girder

	Axial stress (Tension)				Axial stress (Compression)			
	Supporting point		Middle of span		Supporting point		Middle of span	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Dead load of girder	−4.93	5.94	2.46	−2.97	−4.93	5.94	2.46	−2.97
Dead load of slab	−1.09	1.32	0.56	−0.68	−1.09	1.32	0.56	−0.68
Flexural moment by earthquake	0.20	−0.24	0.20	−0.24	−0.20	0.24	−0.20	0.24
Axial force by earthquake	−3.90	−3.90	−3.90	−3.90	3.90	3.90	3.90	3.20
Prestressing force	7.69	−0.91	−1.25	9.88	7.69	−0.91	−1.25	9.88
Total	−2.02	2.21	−1.93	2.10	5.37	10.49	5.46	9.68
Check	< −1.5 out	< 210 ok	< −15 out	< 210 ok	< 210 ok	< 210 ok	< 210 ok	< 210 ok

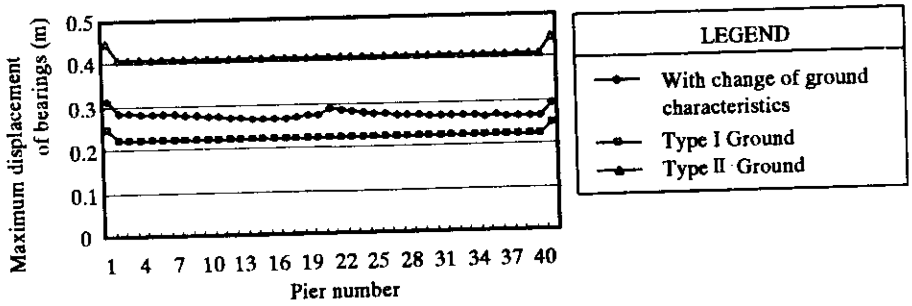

Fig. 10 Maximum displacement of bearings of 40 span continuous bridge caused by the change of ground characteristics

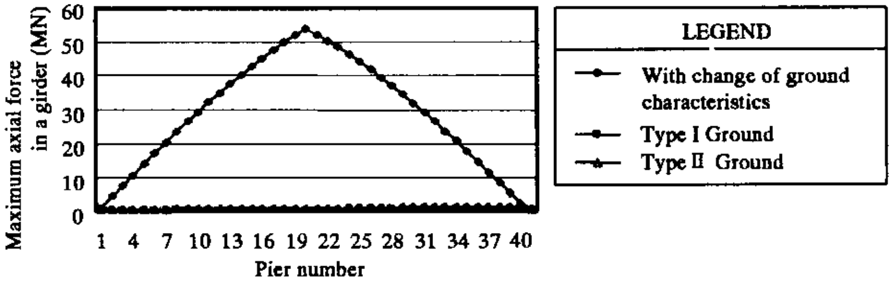

Fig. 11 Maximum axial force in a girder of 40 span continuous bridge caused by the change of ground characteristics

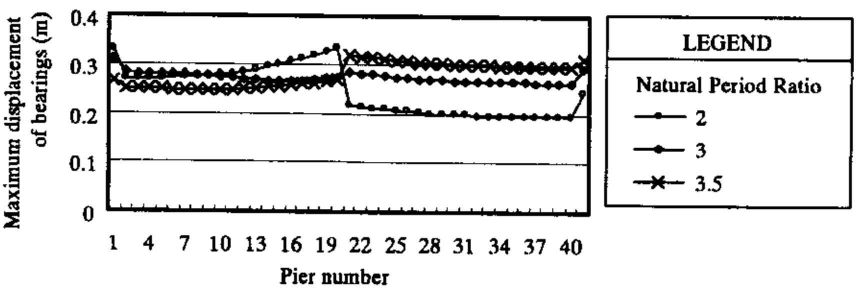

Fig. 12 Relationship between natural period ratio and maximum displacement of bearings

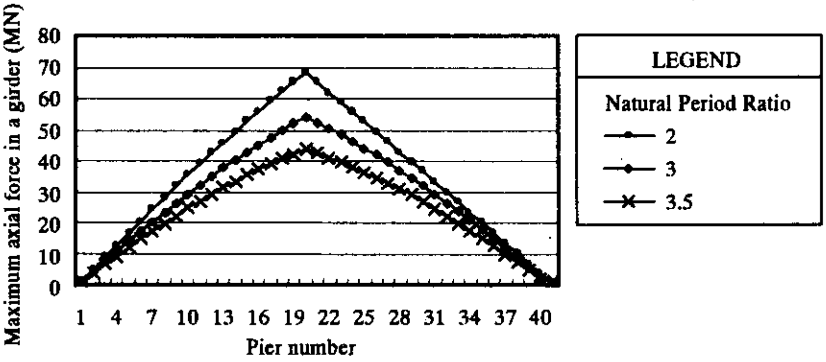

Fig. 13 Relationship between natural period ratio and maximum axial force in a girder

Similarly, the maximum displacement of bearings and the maximum axial force developed in girder for 40 span continuous girder is shown in Figure 10 and Figure 11, respectively. The displacement of bearings is almost the same as for the case of 24 spans. But, the maximum axial force in case of 40 spans is much larger than that of 24 spans. It is hard to be compensated by only increasing the reinforcement in the girder.

To reduce the axial force developed in the girder, the natural period of the bridge was increased by designing the smaller stiffness of bearings. Figure 12 and Figure 13 show the comparison of the maximum displacement of bearings and maximum axial force developed in the girder depending on the natural period ratio, respectively. Although the maximum displacement of bearings does not change significantly, the maximum axial force developed in the girder can be effectively reduced by increasing the natural period.

3. Effect of Spatial Difference of Input Ground Motion

Figure 14 shows the maximum displacement of bearings of 24 span continuous bridge caused by the effect of spatial difference of input ground motion. The spatial difference of input ground motion is assumed as phase lag in travelling wave with shear wave velocity. The shear wave velocity equal to infinity means that the input ground motions to all piers have the same phase. Figure 14 shows that the maximum displacement of bearings changes depending on the input phase. When the shear elastic wave velocity is 250 m/s or 500 m/s, the displacement becomes larger at both ends of girder. In the middle of girder, the displacement is the largest when the bridge is subjected to input motion with the same phase, and at the ends of girder the displacement becomes larger when the bridge is subjected to ground motion with different phases.

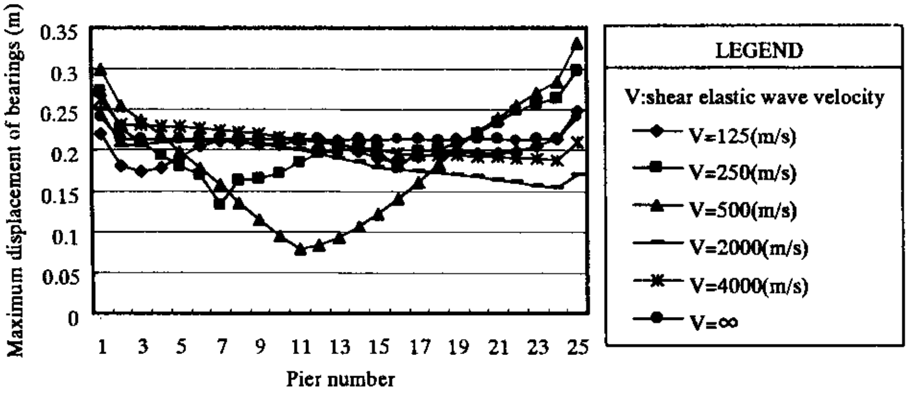

Fig. 14 Maximum displacement of bearings caused by difference of phase of inputs

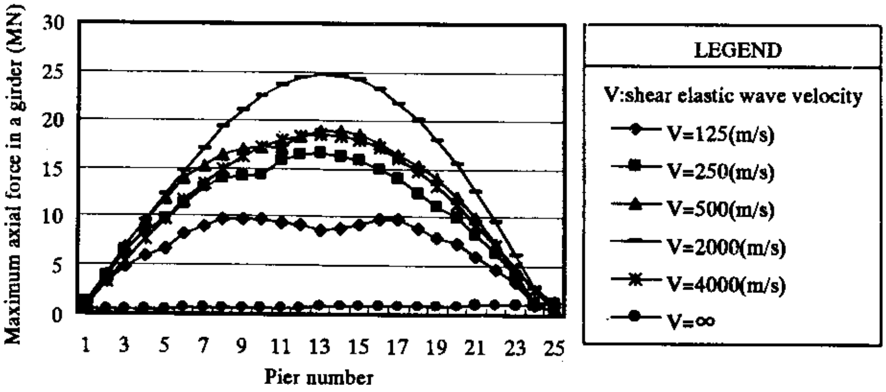

Fig. 15 Maximum axial force in a girder caused by difference of phase of inputs

Figure 15 shows the maximum axial force developed in a girder of 24 span continuous bridge when subjected to the different inputs phase. The maximum axial force developed in the girder changes depending on the input phase. The axial force when the bridge is subjected to the same input phase is almost zero, but the axial force reaches about 24.5 MN for a traveling velocity of 2,000 m/s. Since this axial force is less than 30 MN that was obtained in Figure 9, it does not exceed the allowable level.

CONCLUSIONS

In this paper, the earthquake response characteristics and the design method of the super-multi-span continuous girder bridges with the Menshin (seismic isolation) design concept was studied. The limitation of continuous length of girder, the effects of change of ground characteristics and the spatial difference of input ground motion on the earthquake response characteristics were analytically studied. The following conclusions may be deduced.

1. Increase of the length of continuous girder requires larger volume of the bearings. Under the condition to minimize the volume of bearings, the size of bearings is generally determined by the effect of the earthquake rather than the temperature change. Continuous bridge with total length up to 2,400 m may be designed with paying attention to the design of the natural period.

2. When the bridge is subjected to the earthquake ground motion in the longitudinal direction, the displacement of bearings was not significantly affected by the change of ground characteristics. But the axial force developed in the girder increases around the change point of ground characteristics.
3. Maximum displacement of bearings are affected by the spatial difference of the input ground motion in longitudinal direction. The axial force developed in a girder becomes larger by the difference of input phase.
4. Based on the result of the above studies, attentions to be paid in the seismic design of super-multi-span continuous Menshin bridge may be described as follows.

1. Design Method of Natural Period

The displacement of bearings caused by the effects of the temperature change and the earthquake becomes larger with increase of the continuous length. In the Design Specifications of Highway Bridges in Japan, when isolation bearings are designed so that the natural period ratio of bridges should be about 2 or more, but it is necessary that the natural period should be given adequately to control the displacement of bearings rationally.

2. Design of Superstructure against Axial Force

The axial force developed in a girder is significant for the bridge with the change of ground characteristics in a bridge and when the bridge is subjected to the different ground motions. The axial force in girder can be reduced by increasing the natural period ratio, and it needs to pay attention to the increase of displacement of bearings at the same time.

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