Seismic Response of Highway Viaducts Equipping Base Isolation System Subjected to Long Duration Earthquake under Low Temperature

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1. INTRODUCTION

Base isolation system is one of the most effective technologies for protecting structures from damages in earthquakes. It has been extensively used worldwide in recent years, considering the increasing threat of great earthquakes. The basic strategy of base isolation system is that a structure can be uncoupled from the damaging effects of the ground movement in a strong earthquake, by taking advantage of the flexibility of base isolation devices. Base isolation devices, which are mainly made of material rubber, have temperature dependence behavior due to its material characteristics. The stiffness of polymer trends to increase with the decreasing temperature. With the increment of stiffness of rubber material, the flexibility of base isolation devices is deteriorated and therefore its seismic protection capability will be weakened.

In our previous study[1)], an overall three-dimensional non-linear numerical analysis was conducted, to evaluate the seismic performance of curved grillage girder viaducts equipped with base isolation system under severe cold environment. However, the duration of earthquake ground motion applied in the previous study[1)], which was obtained from 1995 Kobe earthquake, is only about 20 seconds. Its lasting time is too short to ensure enough heat production in bearing support location, for the case of low temperature effect study. According to the calculation of previous study[1)], the temperature of base isolation systems was only raised up to -10 ℃, resulting in only a slight variation of bearing properties. Thus, although low temperature effect has been well investigated and discussed, the application range of conclusions of previous study is still limited.

In order to extend the application range of low temperature effect investigation, a long duration earthquake lasting about 60 seconds is applied in the present study. Subjected to a longer duration earthquake, temperature rising of base isolation devices is increased, and variation of bearing properties is also enlarged consequently. Combining the results of the previous study[1)], more comprehensive conclusions of low temperature effect of base isolation system by seismic response analysis are drawn in this paper.

2. LOW TEMPERATURE EFFECT OF LRB

2.1 Time-varying temperature of LRB

Many innovative devices and systems are being developed for the purpose of seismic isolation of bridges. One of the most widely adopted isolation system is the lead-rubber bearing (LRB). In an earthquake event, base isolation bearings absorb earthquake energy and release it as heat. The heat production will raise the temperature of LRB. Thus, as the main objective of this study is to seek deep understanding of the thermo-mechanical behavior of LRB, and a dynamic stiffness definition composed of temperature variation of time and stiffness variation of temperature is proposed.

In this study, two functions are introduced to simulate the temperature/bearing property variation process: the time variation of temperature which is concluded by vibration tests of LRB, and performance variation due to temperature that is obtained by bearing performance test under different temperature conditions. The 2003 Tokachi-Oki earthquake ground motion is adopted, not only because it is a periodic great earthquake in Hokkaido Island, but also its duration (60 seconds) is a suitable time for this study.

The experimental studies conducted until now mainly focused on the sensitivity of time variations of temperature of base isolation devices. Vibration tests were conducted and temperature measurement during the tests clearly recorded the temperature increment. The case of 0.5Hz vibration frequency (2 seconds vibration period) and 20 seconds vibration duration has been extensively examined by Nakamura.T et al[2)], whose experiment conditions match well with this study. By carrying out numerical analysis on this experimental data and adopting the temperature increment condition, the relationship between time and temperature of LRB can be obtained, as shown in **Table.1**. It can be summarized that, for a earthquake with a duration of 60 seconds, the temperature increment is approximately 30℃, i.e. LRB devices are still influenced by low temperature effect to a certain extent. Therefore detailed quantitative analysis on temperature dependent performance of LRB is necessary.

2.2 Behavior variation with temperature

Experimental schemes composed of multiple test methods were proposed in past studies, among which a cooperative research on thermo-mechanical behavior of rubber made bearings by Rubber Bearing Association and Civil Engineering Research Institute for Cold Region is carried out, and obtained an integrated and practical conclusion[3].

Based on the experiment results, for the case of a long-term low temperature environment, the equivalent stiffness of LRB increases about 30%. And with the heat production during earthquake event, the temperature of LRB gradually increases while the stiffness of LRB accordingly decreases. The detailed bearing property can be calculated by the following equations.

$$y_1 = -0.206 \times \mathrm{Ln}(x+40) + 1.855 \quad (1)$$

$$y_2 = -0.335 \times \mathrm{Ln}(x+40) + 2.388 \quad (2)$$

Where, y_1 is stiffness ratio; y_2 is yield force ratio;

x is temperature.

By adding a matrix substitution statement at the beginning of calculation loop in FEM analysis program, these equation can be used to build a dynamic bearing property definition, as shown in **Table 1**.

2.3 LRB modeling

The force-displacement relationship of LRB is trilinear hysteretic, as shown in **Fig.1**. K_1 the is initial stiffness and K_2 is the yield stiffness, respectively. K_3 is introduced to represent the strain hardening at a high shear strain. F_1 is the yield force and F_2 is the design force.

Room temperature (20℃) condition and low temperature (-30℃) condition are discussed and compared. As to the low temperature condition, both fixed and dynamic stiffness cases are considered in this study. Although fixed conditions have no reality, they still represent the cases that maximum stiffness value are applied and therefore can contribute to understanding of the low temperature effect on seismic performance. The input ground motions, temperature schemes and corresponding performance of bearings are summarized in **Table.2** and **Table.3**. It should be noticed, for the low temperature condition cases, only initial values are listed in this Table.

3. NUMERICAL MODEL OF VIADUCT

3.1 Superstructure and substructure

The curved highway viaduct considered in the analysis is a three-span-continuous bridge having an overall length of 120.0 m with equal spans of 40.0 m and supported on four steel piers of 20.0 m height, as shown in **Fig.2**. The bridge alignment is horizontally curved in a circular arc and the radius of curvature is 100m. And the total weight of superstructure is 8.82MN. The bridge is equipped with base isolation bearings on the top of each pier to improve seismic performance.

Table 1 Time sample points list

Time (s)	Temperature (℃)	Stiffness ratio (y_1)	Yield force ratio (y_2)
0	-30.00	1.38	1.62
10	-24.67	1.29	1.47
20	-19.35	1.23	1.37
30	-14.02	1.18	1.30
40	-8.69	1.14	1.23
50	-3.37	1.11	1.18
60	1.96	1.08	1.14

Table 2 Analytical cases

Case	Earthquake ground motion	Temperature
1	Tokachi	+20℃, fixed
2	Tokachi	-30℃, increasing
3	Tokachi	-30℃, fixed
4	Tokachi - triple	+20℃, fixed
5	Tokachi - triple	-30℃, increasing
6	Tokachi - triple	-30℃, fixed
7	Kobe	+20℃, fixed
8	Kobe	-30℃, increasing
9	Kobe	-30℃, fixed

Table 3 Bearings properties (K(MN/m) F(MN))

Case	K_1	K_2	K_3	F_1	F_2
1/4/7	2.662	0.380	0.984	0.096	0.191
2/5/8	3.674	0.524	1.358	0.155	0.309
3/6/9	3.674	0.524	1.358	0.155	0.309

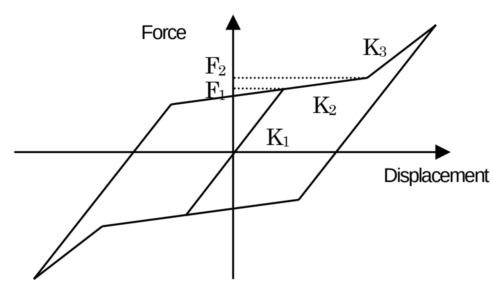

Fig.1 Analytical model of LRB

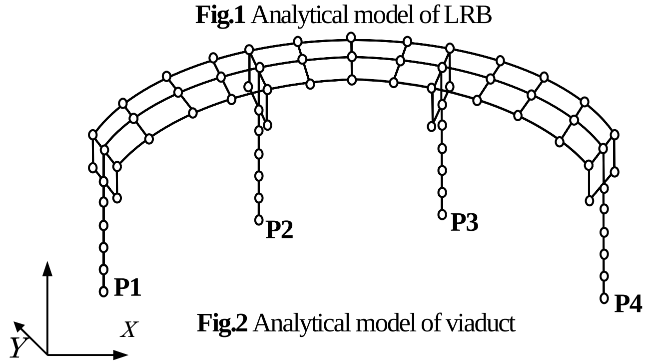

Fig.2 Analytical model of viaduct

The highway viaduct is supported by four thin-walled steel hollow box section piers, having the same height of 20.0 m. Characterization of the non-linear pier structural is based on the fiber flexural element modeling. The yield stress is 235.4MPa, the modulus of elasticity is 200GPa and the strain hardening in plastic area is equal to 0.01.

3.2 Earthquake ground motions

To assess the seismic performance of the viaduct in this study, the nonlinear bridge model is subjected to the longitudinal, transverse and vertical components of a strong ground motion records from 2003 Tokachi-Oki Earthquake, in which a 60 seconds cut is adopted, being considered as a proper record for this study. Since the seismic intensity of this earthquake is only Level 6, which may not cause enough damage to evaluate the seismic performance of base-isolated bridge, earthquake ground motions of triple amplification cases are also calculated.

3.3 Non-linear dynamic analysis

The analysis on the highway viaduct model is conducted using an numerical method based on the elasto-plastic finite displacement dynamic analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities, is adopted in this study, with the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The stress-strain relationship of the beam-column element is modeled as a bilinear type. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed as a Rayleigh's type, assuming a damping coefficient of the first two natural modes as 2%.

4. NUMERICAL RESULTS

4.1 Shear force-displacement response at bearing

The calculation results of shear force-displacement relationship at bearing are shown in **Fig.3**. As expected, both the deformation of the bearings and the area of the hysteresis loops decrease under low temperature. One of the most effective ways to provide a substantial level of additional damping is through hysteretic energy dissipation. Therefore, the reduction of area of the hysteresis loops results in the deterioration of base isolation function. On the other hand, with the flexibility decreases and natural period shortens, the response force increases as shown in the same figure.

Triple amplification cases (case 4, 5, 6) that undergo 60 seconds vibration show similar results as Kobe earthquake cases (case 7, 8, 9) whose duration is only 20 seconds. While short duration and less heat production show low temperature effect more in Kobe earthquake cases, this effect is also shown clearly in long duration earthquake cases.

4.2 Bending moment-curvature response at pier base

Fig.4 shows the bending moment-curvature response at the base of piers, which is considered to be a good indicator to decide the earthquake damage level. It is clearly shown that a proper LRB bearing system can effectively reduce inertial forces acting on bridge piers.

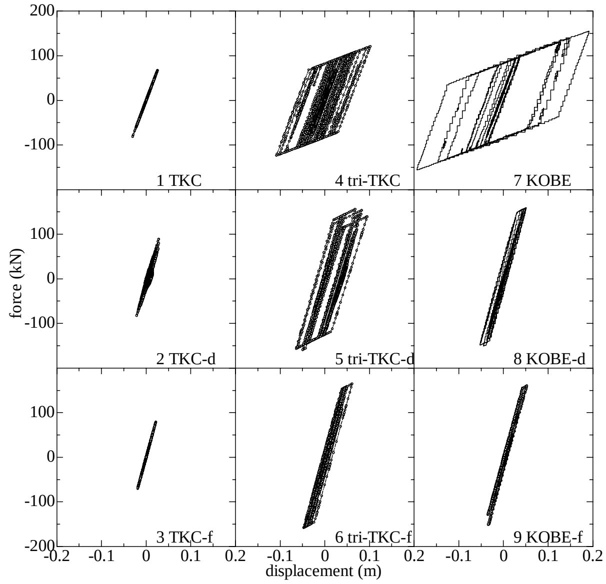

Fig.3 Shear force-displacement response at bearing (P3 X-Direction)

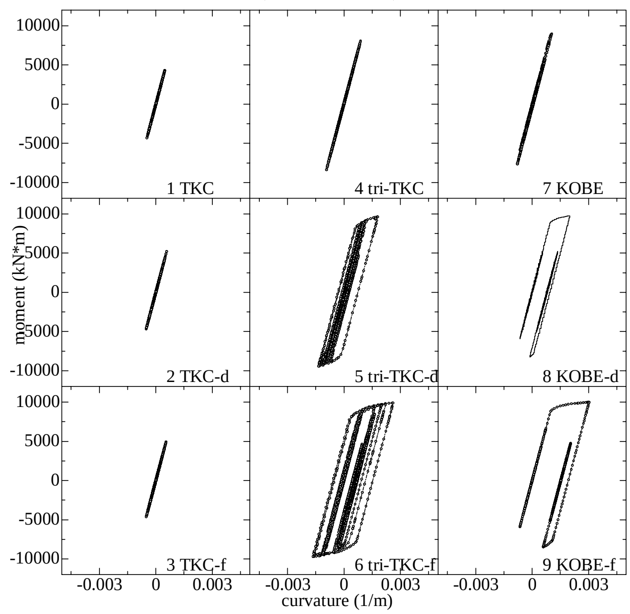

Fig.4 Bending moment-curvature response (P3 X-Direction)

The base isolation function should not only ensure the period shift that can protect superstructure but also reduce the inertia force to keep the substructure remain in the elastic range as much as possible. However, in this study, the yield moment of the pier is 84.8MN,and therefor inelastic deformation occurred in all cases. It can be acceptable that, in certain cases, the substructure has a post elastic behavior. The comparison of ending moment and curvature response can still make clear the damage conditions for different cases. It definitely shows us that the bridge system withstands more earthquake damage under low temperature. Base isolation function is conspicuously weakened with stiffness increasing, therefore results in a higher damage level. And more shear force response (being carried out in Section 4.1), leads to more bending moment at the base of piers, which is also shown in this figure.

In this section, low temperature effect still makes sense in long duration earthquake cases as well as in short duration earthquake cases. Furthermore, the triple amplification cases show large responses similar to Kobe earthquake cases and the amount of energy dissipation significantly decreases under low temperature. Therefore, when a bridge confronts extreme strong earthquakes, the deterioration of energy dissipation function of base isolation system due to low temperature, may cause serious problem.

4.3 Energy-time history

The energy dissipation performance of the bearing systems is summarized by comparing the energy-time histories, as shown in **Fig.5**. While a bridge system is base isolated, the total earthquake energy is increased due to the large seismic energy dissipation at the isolators, i.e., most of the energy is dissipated by the isolators instead of by the structural members, thus resulting in considerable reduction of seismic damage. With the stiffness increasing and base isolation function weakening under low temperature, the energy response tends to be closer to fix support cases, and strain energy that represents the energy dissipation mechanism by hysteresis loops at bearing significantly decreases. Thus, the inelastic behavior at piers absorbs earthquake energy in these cases, and consequently resulting in the structural damage.

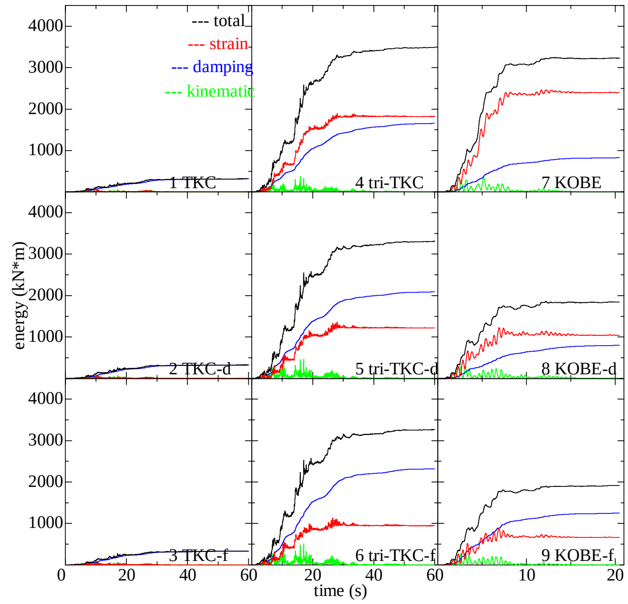

Fig.5 Energy-time history

5. CONCLUSIONS

In this study, a dynamic bearing property definition method is introduced in a nonlinear 3-dimensional seismic response analysis of a highway viaduct with proper base isolation system. Numerical results under changeable temperature are carried out. Seismic responses are examined and compared to investigate the influence of bearing conditions on the overall behavior of the bridge, in which low temperature effect is focused on particularly. In order to examine heat production during earthquake thoroughly, both short duration earthquake and long duration earthquake ground motions are adopted and evaluated. And the conclusions are drawn as follows.

(1) In previous studies, whether low temperature effect should be considered in seismic response analysis was doubted, because during an earthquake event, the base isolation devices absorb earthquake energy and release it as heat. By intuition, such a great thermal behavior will raise the initial low temperature condition to room temperature level immediately. In this study, by adopting dynamic bearing property definition method and examining the numerical results, the necessity of considering low temperature effect, not only in a short-duration earthquake, but also in a long-duration earthquake, has been clearly indicated. More accurate seismic design considering low temperature effect should be taken into account in cold regions.

(2) Under low temperature, base isolation devices that are mainly made from rubber are hardened because of the material characteristics. A harder state of base isolation device, which means the loss of flexibility, has less base isolation function than its original state. By comparison with fixed room temperature and fixed low temperature cases, it is found that the changeable low temperature cases with dynamic bearing property have intermediate base isolation performance. This is just simply because the stiffness values of changeable low temperature cases are also between those of other two conditions.

(3) Short duration strong earthquake is more dangerous when considering low temperature effect, because inadequate heat conduction keeps base isolation devices cool and hard. Although long time vibration raises the temperature over freezing value, low temperature effect still has a significant influence on seismic response behavior of a base-isolated bridge.

References

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