OPTIMIZATION STUDY ON THE DESIGN PARAMETERS OF SEISMIC ISOLATED BEARING FOR RAILWAY BRIDGES

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ABSTRACT :

A parameter optimization model of seismic isolated bridge system considering soil-structure interaction and running safety is established. Mechanical parameters of the isolation bearing are taken as design variables, and the maximum moments at the bottom of bridge piers are employed as objective functions when the displacement between pier top and beam meets with the limited values. Through calculation analysis, the influence rules of dynamic parameters of the lead-rubber bearing on the seismic responses are given, which the ratio of the stiffness after yielding to the stiffness before yielding has important effect on the structural seismic responses in the seismic isolation design for simple supported beam bridge. Therefore, the design requirements for seismic responses of bridges can be satisfied by the simplified method of changing the stiffness ratio of isolated bearings. In order to enhance the optimal efficiency, the running safety can be considered out of the optimal process. The values of spectral intensity for the seismic input to the running vehicles can be checked after the determination of the optimal bearing parameters. Through the optimal analysis of isolated bridge system, the optimal design parameters of isolation bearing can be determined properly, and the seismic forces can be reduced maximally as meeting with the limits of relative displacement between pier top and beam, which provides efficient paths and beneficial references for dynamic optimization design of seismic isolated bridges.

KEYWORDS: optimal design, railway bridge, seismic isolation, running safety, lead core bearing

1. INTRODUCTION

Seismic absorption and isolation technology has been used in railway bridge engineering in China, but there still are many problems not solved in calculation analysis and design theory. In recent years, many researchers have investigated the seismic absorption and isolation design of bridges. Zhu Dongsheng et al. studied on the design parameters of the seismic isolation bridges, and the effects of initial period, ductility ratio as well as the ratio of the stiffness after yielding to the stiffness before yielding on the seismic isolation of bridges were investigated [1]. However, the seismic isolation design method considering all the parameters comprehensively weren't given. Li Jianzhong et al. researched on the optimum design of seismically isolated continuous bridges and presented the optimum design method for continuous bridges [2]. As for the application of isolation bearings, the beam displacements increase as soon as the forces at the bottom of the pier reduce on the seismic excitations. Kyu-Sik Park et al. solved the contradiction between the reduction of the maximum forces and the increment of the beam displacement by introducing the weight coefficients [3]. The soil-foundation interaction and the effects of the dynamic parameters of the lead core rubber bearing (LRB) on the Rayleigh damping coefficients weren't considered in the three studies above. The lead core rubber bearing between the beam and pier can reduce the seismic responses of bridges efficiently [4], and the optimum study on the LRB design parameters is studied in this paper through the single pier model considering the soil-foundation interaction. After the optimum design, the maximum forces of the bottom of the pier can be decreased at the most with the relative displacement between the beam and the top of the pier constrained in the allowable range.

The hysteretic energy-dissipated characteristics of LRB can be determined by its dynamic controlling parameters which include the yield stress, the stiffness before yielding and the ratio of the stiffness after yielding to the stiffness before yielding. The optimum study on the dynamic controlling parameters of LRB provides efficient way and reasonable reference for the seismic isolation design of the railway simple supported beam bridge.

2. ANALYSIS MODEL

2.1 Bilinear Model of the Lead Core Rubber Bearing

As shown in Figure 2.1, u_B represents the efficient design displacement of the bearing and (u_y, Q_y) represents the yield point of the bearing [4]. The value of yield stress Q_y mainly depends on the weight of the beam structure and the producing techniques, and u_y is the yield displacement of the bearing. The stiffness after yielding K_2 can be calculated according to Figure 2.1 by formula (2.1).

$$K_2 = \frac{F(u_B) - Q_y}{u_B - u_y} \tag{2.1}$$

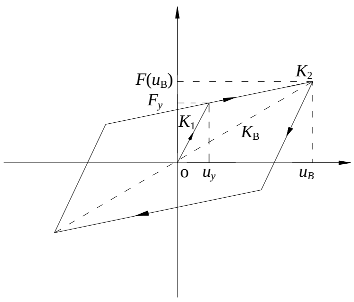


Figure2.1 Controlling parameters of LRB

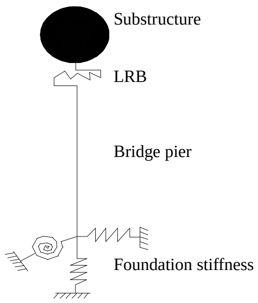


Figure2.2 FEA model

2.2 FEA Model for the Railway Simple Supported Beam Bridge

A typical pier of a super giant railway simple supported bridge is researched in this study, and the basic design parameters of the bridge can be seen in Table 2.1. According to the Code for Design on Subsoil and Foundation of Railway Bridge and Culvert [13], the foundation elastic stiffness can be calculated by M-method. The FEA model of the beam-bearing-pier-soil system is shown in Figure 2.1. The general program ANSYS is used for the calculation analysis. In this model, the dynamic characteristics of LRB can be simulated by nonlinear element Combin39, and Mass21 element is applied for the substructure. The soil-foundation interaction is well simulated by an arbitrary element (Matrix27) whose geometry is undefined but whose elastic kinematics response can be specified by stiffness, damping, or mass coefficients. The foundation elastic stiffness values are listed in Table 2.2. The site which the bridge locates is I-site, and San Fernando earthquake wave record in S-W direction is selected as the excitation for the optimization of the LRB design parameters.

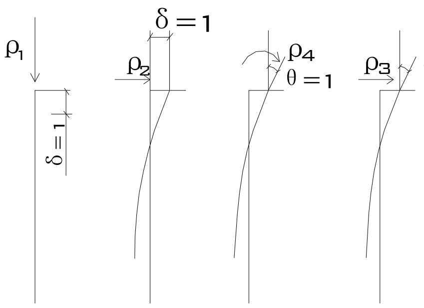
Table2.1 General design parameters of the typical pier

Design parameters of the pier-section	Lumped mass on the top of pier (ton)	Height of the pier(m)
Solid circle-head shape, diameter of the pier top:2.10m,width of the retangular:1.70m， slope:1/40	420	21

Procedures of determining the foundation elastic stiffness by M- method:

(1)Determining the stiffness of the single- pile-head(Figure 2.3);

(2)According to the pile-head stiffness and the array modes of the piles, the stiffness of the cushion cap can be calculated through formulation (2.2)~(2.5), and the calculation stretch is shown in Figure 2.4.



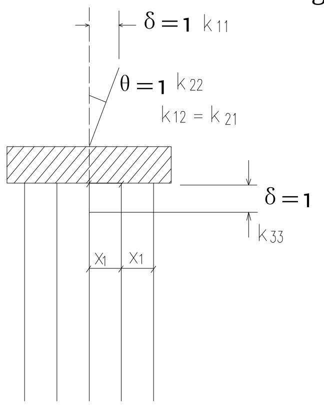


Figure2.3 Deformation stiffness of the single pile   Figure2.4 Deformation of the cushion cap

$$k_{11} = \sum \rho_2 \tag{2.2}$$

$$k_{12} = -k_{21} = \sum \rho_3 \tag{2.3}$$

$$k_{33} = \sum \rho_1 \tag{2.4}$$

$$k_{22} = \sum \rho_4 + \sum x_1^2 \rho_1 \tag{2.5}$$

As seen in Table 2.2, the foundation stiffness values for the typical railway simple supported beam bridge are calculated by M-method when the m-value equals to 50000 KPa/m^2.

Table 2.2 Foundation elastic stiffness for m=50000 KPa/m^2

Foundation stiffness	k_{11} ($\times 10^9$)	$k_{12} = -k_{21}$ ($\times 10^9$)	k_{22} ($\times 10^9$)	k_{33} ($\times 10^9$)
Values	1.6206 (N/m)	-3.3422 (N/rad)	9.859 (N·m/rad)	76.011 (N/m)

3. OPTIMIZATION PROGRAM

3.1 Mathematic Description of the Design Parameters Optimization of LRB

The dynamic controlling parameters consist of the yielding strength Q_y, the stiffness before yielding K_1 and the ratio of the stiffness after yielding to the stiffness before yielding α. The seismic absorption and isolation can be realized by the application of LRB for its good hysteretic property. It is known that the application of LRB can lengthen the structural period and reduce the earthquake forces, but it may increase the displacement between beam and top of pier[5]. This indicates that there exist optimum values of the dynamic design parameters for which the earthquake forces in the bridge are minimum. Therefore, Q_y, K_1 and α are taken as the design variables for the optimization of the whole structural system. Three types of intensities including minor earthquake, design earthquake and severe earthquake are considered in the optimal design for the whole isolated bridge system, so that the bridge structure can remain elastic when subjected to a minor earthquake, while the LRB can undergo inelastic deformation to dissipate the seismic energy under a severe earthquake.

The maximum moment of the bottom of the pier on design earthquake excitation is taken as the objective function. Because the application of LRB enlarges the relative displacement between beam and top of pier, the beam would collapse on the design seismic excitation if the displacement weren't constrained. Accordingly, as the state variable in the optimum process, the relative displacement between beam and top of pier should be constrained so as to ensure the maximum relative displacement in the permissible range. The running safety of vehicles can be ensured by the index of spectral intensity *SI*[11-12]. The optimization problem of the design parameters of LRB for railway simple supported bridge can be mathematically described as follows [6].

The objective function is

$$\min_{x} \max_{t\in T}\{abs(\mathrm{M}(x,t))\} \tag{3.1}$$

where $\mathrm{M}(x,t)$ is the moment of bottom of pier; and the constrains are

$$x_i^L \le x_i \le x_i^U \qquad （i＝1，2，3） \tag{3.2}$$

$$\max_{t\in T} abs(rd_j(x,t)) \le [rd] \quad （j＝1，2，3，\cdots,n） \tag{3.3}$$

$$SI \le SI_{\mathrm{Lim}} \tag{3.4}$$

where the vector of design variables $\mathrm{X}^T = [x_1, x_2, x_3]^T = [Q_y, K_1, \alpha]$; T =the delay time of the seismic excitation and Δt =the record interval of the seismic excitation, $n = \frac{T}{\Delta t}$; x_i^U =the upper limit value of the design variable and x_i^L = the low limit value of the design variable; X_U^T, X_L^T =the upper limit vector and the low limit vector of the design variables. According to the test datum of the lead core rubber bearings from China Academy of Railway Science, $\mathrm{X}_L^T = [2\times10^4\,\mathrm{N}, 1\times10^7\,\mathrm{N/m}, 0.1]$ and $\mathrm{X}_U^T = [2\times10^5\,\mathrm{N}, 1\times10^8\,\mathrm{N/m}, 1]$ [7]; rd_j =the relative displacement between beam and top of the pier at different time of the seismic excitation history; $[rd]$ =the acceptable value of relative displacement between beam and top of the pier. *SI* is the spectral intensity corresponding to the fundamental period of the isolated bridge, and SI_{Lim} is the limit value of *SI*. The value of SI_{Lim} is selected as 4000mm according to reference [12].

3.2 Solution for the Parameters Optimization of LRB

The first order optimization method is adopted to solve the optimum problem. The fundamental theory of this method is transforming the common optimum problem to single unconstrained optimum problem by the mixed penalty function, and many analysis loops can be carried out in an optimum iteration [8], [9]. The unconstrained version of this optimum problem is formulated as follows.

$$Q(X,q) = \frac{M}{M_0} + \sum_{i=1}^{n} p_x(x_i) + q\sum_{j=1}^{n} p_{rd}(rd_j) \tag{3.5}$$

where p_x , p_{rd} =penalties applied to the constrained design and state variables; q = Response surface parameter; M_0 =initial objective function value which is selected from the current group of design moments.

Suppose the reference objective function value is $\mathrm{M}(\mathrm{X}^{(j)})$, thus the sensitivity of the objective function to the design variables can be described as follows.

$$\nabla(X^{(j)})=[\frac{\partial M(X^{(j)})}{\partial x_1},\frac{\partial M(X^{(j)})}{\partial x_2},\frac{\partial M(X^{(j)})}{\partial x_3}] \tag{3.6}$$

The gradient vector is computed using an approximation by forward difference method as follows:

$$\frac{\partial M(X^{(j)})}{\partial x_i}\approx\frac{M(X^{(j)}+\Delta x_i e)-M(X^{(j)})}{\Delta x_i} \tag{3.7}$$

where e=vector with 1 in its ith component and zero for all other components

$$\Delta x_i=\frac{\Delta D}{100}(x_i^U-x_i^L) \tag{3.8}$$

ΔD =forward difference (in percent) step size， and it equals to 50% commonly.

The steepest gradient method is used to search the optimum solution and the iteration formulation is shown as follows.

$$X^{(j+1)}=X^{(j)}+s_j d^{(j)} \tag{3.9}$$

where s_j =the line search parameter and the convergence condition of the iteration process is shown in formulation (3.10).

$$M^{(j+1)}-M^{(j)}\le\tau \tag{3.10}$$

where τ =objective function tolerance，and the τ value can be set with the need of the calculation accuracy. In common conditions, τ value is set to one percent of M_0 .

In the optimum process, the damping of the structural system is considered in the form of Rayleigh damping coefficients by formulation (3.11)[10].

$$C=\alpha M+\beta K \tag{3.11}$$

where

$$\alpha=\frac{2\omega_1\omega_2(\xi_1\omega_2-\xi_2\omega_1)}{\omega_2^2-\omega_1^2} \tag{3.12}$$

$$\beta=\frac{2(\xi_2\omega_2-\xi_1\omega_1)}{\omega_2^2-\omega_1^2} \tag{3.13}$$

The damping ratio of the structural system is determined as 5% in the optimum analysis, but the Raleigh damping coefficients vary in the optimum process according to the variations of the structural fundamental frequencies induced by the change of LRB design parameters. Consequently，before the time history analysis for the isolation system, the first two frequencies(ω_1,ω_2) of the system should be obtained through modal analysis, then the Rayleigh damping coefficients corresponding to the change of LRB design parameters can be calculated through formulation (3.12) and (3.13).

4. OPTIMIZED RESULTS

Three dynamic controlling parameters of LRB are taken as design variables in the optimization of LRB, and the limit values of the relative displacement between beam and top of the pier corresponding to three intensities of earthquakes are set at 2cm, 5.5cm and 10cm respectively. Three intensities of earthquakes are minor earthquake, design earthquake and severe earthquake. The initial values of the LRB dynamic controlling parameters and the feasible solutions which include the optimum solution in the optimum process are shown in Table 4.1. According to the design requirements, the minimum value of the maximum moments of bottom of pier can reach 2.561×10^7 N · m when the maximum relative displacement is in the acceptable range.

Table 4.1 Design parameters of LRB and the seismic responses corresponding to different earthquake intensities

Items	Initial values	minor earthquake	design earthquake	severe earthquake
Q_y (10^5N)	1.5	1.0	1.2	1.1
K_1 (10^7N/m)	5.0	2.1	3.8	5.8
α	0.10	0.35	0.30	0.34
rd (cm)	2.86(minor earthquake) 8.27(design earthquake) 18.31(severe earthquake)	3.97	5.47	9.99
SI (mm)	479(minor earthquake) 1583(design earthquake) 3128(severe earthquake)	550	2024	4499
M (10^7 N · m)	0.858(minor earthquake) 2.012(design earthquake) 3.780(severe earthquake)	0.617	2.561	6.247

The optimum results in Table 4.1 present that the ratio of the stiffness after yielding to the stiffness before yielding α are 3.5, 3.0 and 3.4 times of the initial values respectively for minor earthquake intensity, design earthquake intensity and severe earthquake intensity. However, the other two design parameters of LRB (Q_y, K_1) after optimization vary more little comparing with the initial values. The iteration histories of the relative displacement and the maximum moment at bottom of the pier for design earthquake intensity are shown in Figure 4.1 and Figure 4.2 respectively.

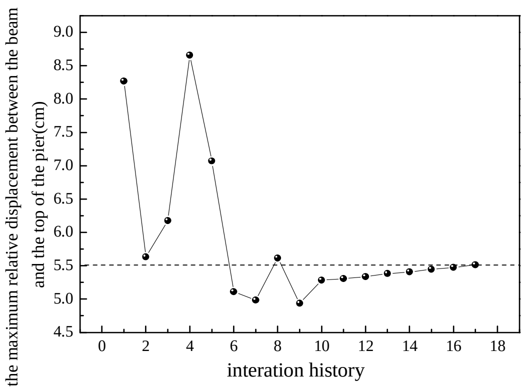


Figure 4.1 Iteration history of the maximum relative displacement between beam and the top of the pier

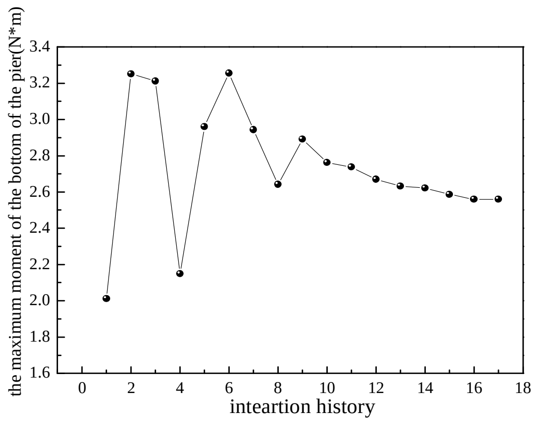


Figure 4.2 Iteration history of the maximum moment at the bottom of the pier

As shown in Figure 4.1 and Figure 4.2, the optimum analysis can converge quickly and obtain optimum solution by using first order method. The relative displacement histories corresponding to initial design parameters and optimum design parameters for the design intensity earthquake are presented in Figure 4.3, and the results indicate that the maximum relative displacement can be reduced efficiently through the optimum of the LRB design parameters.

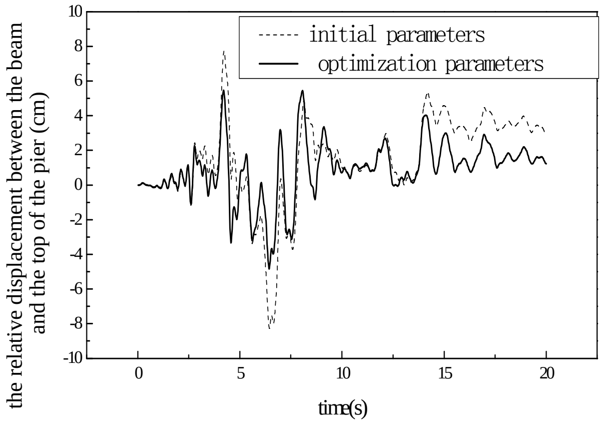


Figure 4.3 Time-history of the relative displacement between beam and top of the pier

5. CONCLUSIONS

Through establishing the seismic isolation bridge model considering soil-foundation interaction and running safety of vehicles, the design optimization on the LRB parameters constrained by relative displacement is studied. The convergence process of the optimum iteration as well as the analysis results indicate some conclusions as follows.

(1) The first order method is appropriate to solve large-scale dynamic optimum problem and it's easy to converge in the calculation analysis.

(2) In the seismic isolation design of railway simple supported beam bridge by using LRB, the ratio of the stiffness after yielding to the stiffness before yielding α is the most important factor which affects the responses of the structural system. The optimum value of α is 3.0 times of the initial value for the design earthquake intensity, while the yield stress Q_y and the stiffness before yielding K_1 vary in a small range. Therefore, the seismic responses requirement of bridge can be satisfied through the simplified method of changing the α value in the seismic isolation design for bridges.

(3) The variation of the LRB dynamic controlling parameters have significant effects on the seismic response of the railway simple supported bridge, so the dynamic optimization of the LRB dynamic controlling parameters is a key problem in the seismic isolation design for bridges. The research in this paper provides some useful reference for the bridge seismic isolation design.

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