Seismic performance analysis of a bridge-integrated structure based on IDA method

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Abstract: According to the incremental dynamic analysis method (IDA), the intensity amplitude of one or more seismic records is adjusted step by step, and then one or more sets of seismic records with increasing intensity are generated. The seismic records are used to perform nonlinear dynamic time history analysis of the bridge-integrated structure one by one until structural damage. Therefore, a comprehensive and realistic evaluation of the seismic capacity of the bridge-building station structure is made, and the response of the structure under the action of rare earthquakes and multiple earthquakes is deeply understood. This paper provides a reference for practical engineering design.

1. Introduction
The incremental dynamic analysis method [1, 2] (referred to as the IDA method) is an analytical method for evaluating the structural performance under earthquake action. It can formulate corresponding performance targets for different structures and fortification standards. After a series of designs, the structure is the response under different seismic levels, which can meet the pre-estimated seismic performance objectives, so as to achieve the purpose of seismic analysis according to performance [3].

2. Analysis steps of the IDA method
IDA is a method based on dynamic time history analysis [4]. The principle of this method is to amplify the ground motion intensity corresponding to the same seismic record step by step according to a certain ratio, and then perform multiple nonlinearities on the structure. Dynamic time history analysis, so that the seismic response results in each analysis can be obtained, and then the IDA curve can be drawn, through which the entire process of the dynamic characteristics of the structure can be fully understood until the collapse is destroyed [5]. Since the ground motion cannot be determined, IDA analysis is performed using multiple seismic records to obtain the IDA curve family. The specific steps for IDA analysis of the structure are as follows [6]:

(1) Create a reasonable analytical model that can reflect the main characteristics of the elastoplastic response of the structure under earthquake action;
(2) Select some representative ground motion records;
(3) Select a seismic wave to carry out the banner, then select a series of ground motion records after the banner, and perform multiple elastoplastic time-history analysis on the structure, and obtain the corresponding structural reaction data (IM-DM value), so that it can be drawn. The IDA curve under a single ground motion. In order to ensure that the structure of the first analysis is in the elastic phase, the banner should be analyzed with a relatively small intensity index to obtain the first IM-DM point, and connected to the origin to obtain the elastic slope Ke.
(4) According to the above method, the remaining seismic records of the structure are analyzed, and
multiple IM-DM curves are obtained. The results are analyzed and judged to evaluate the seismic performance.

3. Project Summary
Guzhenkou South Station is the second phase project of Qingdao Hongdao-Jinan Intercity Railway. It is a two-story island station on the road side. The structural form adopts a four-column frame structure with a combined structure of bridges, and the section bridges are connected to the station through the ox legs. The total length of the station is 126m, of which 85m is the main body of the station and 41m is the auxiliary equipment. The main body of the station is two floors above ground, from the bottom to the top, the exhibition hall floor and the platform floor.

The height of the structure 1 layer is 7.65 m, the height of the 2 layers is 1.6 m, and the total height is 9.25 m. It consists of three parts: a beam, a column and a plate unit, where the plate unit is modeled with a rigid plate. The model has 358 nodes, 572 beam units and 279 board units. The beam and column sections are modeled with solid rectangular sections.

4. Analysis of structural plasticity development law

4.1 Vertical plasticity structure development law
When the PGA=0.4g, the order of the pier vertical bridge is shown in Figure 2.

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(a) Station floor layer frame beam layout

(b) Platform floor beam layout plan

Figure 1. Station structure finite element model

4.2 Analysis of structural plasticity development law

(a) A-axis pier column hinge order

(b) B-axis pier column hinge order
Figure 2. Station hall layer pier column along the bridge

It can be seen from Fig. 2 that when PGA=0.4g, the first place where the plastic hinge appears is the bottom end of the pier and the bottom end of the KL3 pier. As time goes by, the other piers also have plastic hinges. However, the number of plastic hinges at the bottom end of the pier is higher than that of the top. In addition, between 4.01s and 4.55s, the side of the longitudinal beam will be plastically hinged.

4.2 The law of plasticity development of transverse bridges

When PGA = 0.6g, the order of the cross-bridge of the pier is shown in Figure 3.

Figure 3. The sequence of the hinges of the pillars in the station hall

It can be seen from Fig. 3 that when PGA=0.6g, the first place where the plastic hinge appears is the bottom end and the top end of the pier, and as time goes on, other piers also have plastic hinges.

Through the above discussion of the development law of structural members, the yield mechanism of the integrated structure of the bridge can be obtained as follows:

1. Compared with the building structure, the plastic hinge of the structure is mainly concentrated in the pier column, which is different from the “strong column beam” in the building structure.

2. Compared with the bridge structure, the longitudinal bridge to the plastic hinge appears on the upper and lower ends of the pier, and the multi-pillar steel bridge with the bottom of the pier is consolidated, and the longitudinal bridge appears only to the plastic hinge.

3. The weak links in the structure of building a bridge are: the bottom pier and the side of the station hall.

5. Statistical methods for IDA curves

Due to the difference in ground motion and the uncertainty of selection [7, 8], the IDA curves obtained are often different, resulting in a discrete type of analysis results. Therefore, statistical analysis of a large number of IDA analysis results is needed to reduce this. Difference [9]. In this paper, the IDA analysis results were quantified by quantile regression method to obtain three fractional curves of 16%, 50% and 84%, respectively, to characterize the discrete and average levels of the IDA curve family. The statistical methods are as follows:

1. Under the action of multiple ground motions, the same structural performance parameter DM is obtained. Under the conditions of different intensity indicators IM (PGA, etc.), seeking the median Natural logarithmic standard deviation $\beta_{IM/DM}$.

2. Calculated separately $\eta_{IM/DM}e^{+\beta_{IM/DM}}$ with $\eta_{IM/DM}e^{-\beta_{IM/DM}}$. Value, obtained under different ground motion strength conditions ($\eta_{IM/DM}e^{+\beta_{IM/DM}}$, IM) and ($\eta_{IM/DM}e^{-\beta_{IM/DM}}$, IM), respectively, the
curve is 84%, 16% quantile curve.

6. Establishment of a single IDA curve
The seismic intensity parameters of the structure were analyzed by IDA [10] using the PGA method. When drawing the curve, the amplitude modulation step is 0.2g, the step growth is 0.05g, and the first analysis is taken by PGA=0.05g to analyze the time history of the structure, and the analysis results are summarized, so that the structure can be obtained when the structure PGA=0.05g. Maximum interlayer displacement angle $\theta_{1\max}$. According to the first analysis method, the maximum interlayer displacement angle after each banner is obtained in turn until the interlayer displacement angle is diverged (the slope is less than 0.2Ke or $\theta_{\max}$ More than 0.1), stop amplitude modulation.

Table 1. Seismic record adjustment.

| Serial number | Computational PGA (g) | $\theta_{\max}$ |
|---------------|-----------------------|-----------------|
| 1             | 0.05                  | 0.0009          |
| 2             | 0.05+0.2              | 0.004           |
| 3             | 0.25+0.2+1x0.05       | 0.0071          |
| 4             | 0.25+0.2+2x0.05       | 0.012           |
| 5             | 0.25+0.2+3x0.05       | 0.0185          |
| 6             | 0.25+0.2+4x0.05       | 0.025           |
| 7             | 0.25+0.2+5x0.05       | 0.0323          |
| 8             | 0.25+0.2+6x0.05       | 0.04            |
| 9             | 0.25+0.2+7x0.05       | 0.05            |
| 10            | 0.25+0.2+8x0.05       | 0.0588          |
| 11            | 0.25+0.2+9x0.05       | 0.0714          |
| 12            | 0.25+0.2+10x0.05      | 0.0833          |
| 13            | 0.25+0.2+11x0.05      | 0.0909          |
| 14            | 0.25+0.2+12x0.05      | 0.1             |
| 15            | 5.75+(6.55-5.75)/3    | 0.095           |
| 16            | 6.017+(6.55-6.017)/3  | 0.1             |
| 17            | (6.017+5.75)/2        | 0.093           |
| 18            | (5.75+5)/2            | 0.087           |
| 19            | (5+4.3)/2             | 0.0769          |
| 20            | (4.3+3.65)/2          | 0.0667          |
| 21            | (3.65+3.05)/2         | 0.0556          |
| 22            | (3.05+2.5)/2          | 0.0455          |
| 23            | (2.5+2)/2             | 0.0357          |
| 24            | (2+1.55)/2            | 0.0286          |
| 25            | (1.55+1.15)/2         | 0.0217          |
| 26            | (1.15+0.8)/2          | 0.0154          |
| 27            | (0.8+0.5)/2           | 0.0093          |
| 28            | (0.5+0.25)/2          | 0.0053          |

The Coyo seismic record was analyzed by amplitude modulation for 28 time-course analysis, and 27 PGA points were obtained. $\theta_{\max}$ For the maximum interlayer displacement angle of the bridge, the discrete points are labeled in the coordinate system, and then these points are analyzed by cubic spline interpolation to obtain the entire IDA curve. As shown in Figure 4, the IDA curve can maintain a linear change at the beginning because the deformation of the structure is within the elastic range.

In order to apply the IDA curve to the seismic analysis according to performance, define the limit state point on the curve. As can be seen from the figure, when $\theta_{\max}$=1/550, when PGA=0.0713g, the
structure reaches the immediate use limit state; \( \theta \max = 1/400 \), when PGA = 0.1165g, the structure reaches the usable limit state; \( \theta \max = 1/250 \), when PGA = 0.25g, the structure reaches the limit state after repair; when \( \theta \max = 1/50 \), when PGA = 1.24g, the structure reaches the life safety limit state; \( \theta \max = 0.1 \), when PGA = 6.55g, the structure reaches the limit state of preventing collapse and destruction;

7. Establishment of multiple IDA curves
In order to better predict the seismic performance of the evaluated structure [11], it is necessary to select some seismic records for time history analysis to obtain multiple IDA curves. According to the method described above, the remaining 9 seismic records were subjected to IDA analysis, and the obtained 10 IDA curves were plotted in the same coordinate system as shown in Figures 4 and 5. Since the shape of the IDA curve has a large relationship with the selected seismic record, different seismic records are input into the same structure, and the IDA curve has a large dispersion [12]. Therefore, these different curves were processed using a 16%, 50%, 84% quantile curve to reduce the difference, as shown in Figures 6 and 7.

![Figure 4. Shun bridge to IDA curve](image)

![Figure 5. Cross-bridge IDA curve](image)

![Figure 6. Shunt Bridge to Quantile Curve](image)

![Figure 7. Cross-bridge quantile curve](image)

By summarizing the IDA curve, each limit state point on the quantile curve can be obtained. The specific data is shown in Table 2 and Table 3.

| Percentile curve | Use point now | Available point | Repair point | Life safety point | Prevent collapse |
|------------------|---------------|-----------------|--------------|-------------------|------------------|
|                  | \( \theta \max \) | \( \text{PGA (g)} \) | \( \theta \max \) | \( \text{PGA (g)} \) | \( \theta \max \) | \( \text{PGA (g)} \) | \( \theta \max \) | \( \text{PGA (g)} \) | \( \theta \max \) | \( \text{PGA (g)} \) |
| 16%              | 1/550         | 0.0912          | 1/400        | 0.1447            | 1/250            | 0.2732            | 1/50         | 1.0777          | 0.058            | 2.3887 |
| 50%              | 1/550         | 0.1259          | 1/400        | 0.1749            | 1/250            | 0.2785            | 1/50         | 1.1962          | 0.1              | 4.65  |
| 84%              | 1/550         | 0.1315          | 1/400        | 0.1788            | 1/250            | 0.2822            | 1/50         | 1.5463          | 0.1              | 7.28  |
Table 3. Slope value of the transverse bridge to the limit state

| Percentile curve | Use point now | Available point | Repair point | Life safety point | Prevent collapse |
|------------------|---------------|-----------------|--------------|------------------|------------------|
| θ₀ | PGA (g) | θ₀ | PGA (g) | θ₀ | PGA (g) | θ₀ | PGA (g) | θ₀ | PGA (g) |
| 16% | 1/550 | 0.1242 | 1/400 | 0.1905 | 1/250 | 0.3186 | 1/50 | 1.3376 | 0.0785 | 3.3063 |
| 50% | 1/550 | 0.1328 | 1/400 | 0.1917 | 1/250 | 0.3618 | 1/50 | 1.5093 | 0.055 | 3.366 |
| 84% | 1/550 | 0.1855 | 1/400 | 0.252 | 1/250 | 0.3859 | 1/50 | 1.8462 | 0.1 | 8.102 |

8. Conclusion

In this paper, based on the actual subway bridge construction project, the incremental dynamic analysis method (IDA) is used to discuss the selection process of each parameter, and the seismic performance and plasticity development of the structure are analyzed. The following conclusions can be drawn:

1. The yielding mechanism of the bridge-integrated structure is different from the building structure and the bridge structure. The plastic hinge of the structure mainly appears at the upper and lower ends of the pillars of the station hall.

2. The weak link of the structure is the frame column of the station hall and the longitudinal beam of the end frame.

3. Through the incremental dynamic analysis of the structural system, the structural performance can be changed as the seismic vibration intensity changes. Structural response analysis under different seismic records can better reflect the response of the structure to ground vibrations in the future.

4. According to the defined limit states, combined with the IDA curve to obtain the point values of each quantile, these are used as reference values for structural performance evaluation.

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