Pushover analysis in different lateral force distribution patterns of bridge piers

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Abstract. Basic principles of pushover analysis method and several different lateral force distribution patterns are briefly described in this paper. A long span concrete continuous rigid frame bridge is taken as an example to carry out the pushover analysis under rarely occurred earthquake. The demand curve and the capability curve are combined to form the capability spectrum to evaluate the seismic performance of the bridge. Analysis results show that different lateral force distribution patterns have great influence on Pushover analysis results.

1. Basic principles of Pushover

If the vertical load remains constant, a horizontal lateral force is applied to the structure, which increases step by step, so that the structure gradually yields from the elastic stage until the failure collapses, and the method of obtaining the seismic performance of the structure is called the Pushover analysis. It is essentially a kind of nonlinear static analysis of the structure, which can obtain dynamic characteristics approximately. Through this method, the weak parts of the structure can be determined.

This method has been written into the FE-MA273, ATC-40 and FEMA 356 research report of the United States. In Japan, this method is used to check the seismic performance of buildings, and it is gradually popularized and applied in the seismic design of bridges in China [1-2].

1.1. Basic assumption

Two main assumptions of Pushover analysis methods are as follows. The response of the structure is mainly controlled by the first-order mode, so that the influence on other modes can be neglected. Under the action of earthquake, the deformation of the structure along the height is controlled by the shape vector and remains unchanged in the direction of the height and during the whole earthquake process.

1.2. Analysis procedure

There are four steps in pushover analysis process of an engineering structure, which is listed as follow [3].

Building a structural computational model and then inputting the required parameters.
Applying horizontal static load, especially the distribution pattern of lateral force along the height of the structure, which is used to simulate the repeated action of the design earthquake. The analysis
usually has several patterns, such as acceleration constant distribution, concentrated force loading, first order mode loading, and generalized multiplier distribution based on bottom shear method etc.

Increasing the horizontal load gradually so that one or a number of members crack or yield. For cracking or yielding members, modify their stiffness and then increase the load, so that a new group of members crack or yield. Repeating this step until the structure reaches a certain target displacement or the whole structure is destroyed.

Drawing a Pushover curve, namely, the relationship curve between the base shear force and the displacement of the top of the structure.

1.3. Capability spectrum method

Pushover analysis alone cannot obtain the response of the structure under earthquake, and it also needs to be determined by the capacity spectrum method. Capacity spectrum is a single degree of freedom system acceleration and displacement curve converted from the load-displacement curve obtained by Pushover analysis. The ability spectrum method is to draw the capacity spectrum and the demand spectrum modified on the response spectrum in the same graph, and the intersection point of the two curves is defined as the target displacement point or the performance point. Then the displacement corresponding to the performance point is compared with the displacement tolerance value to determine whether it meets the seismic requirements [4-5].

2. Engineering example

2.1. Earthquake action

The seismic fortification intensity of the continuous rigid frame bridge is 6 degrees and the seismic peak acceleration value is 0.05 g, seismic fortification group is the first group. The engineering site category is class II.

According to Code for Seismic Design of Highway Bridges (JTG-T2231–01-2020), the control parameters of the velocity response spectrum of rarely occurred earthquake are listed in Table 1.

| Earthquake parameters                                | Value                  |
|------------------------------------------------------|------------------------|
| Bridge classification                                | A                      |
| Seismic fortification intensity                      | VI                     |
| Seismic importance factor $C_i$                      | 1.7                    |
| Peak acceleration $A$ of basic ground motion in horizontal design | 0.05 g                 |
| Seismic fortification grouping                       | I                      |
| Partition characteristic period $T_g$                | 0.35s                  |
| Characteristic period $T_g$                          | 0.35s                  |
| Type of site                                         | II                     |
| Site coefficient $C_s$                               | 1.0                    |
| Damping ratio                                        | 0.05                   |
| Maximum response spectrum of horizontal design acceleration $S_{max} = 2.25C_sC_d A$ | 0.1913 g              |

The horizontal design acceleration response spectrum of rarely occurred earthquake is shown as Figure 1.
2.2. Engineering profile
The span arrangement of the concrete continuous rigid frame bridge of a highway is 85+150+85m, and the bridge width is 28m. The superstructure adopts three-way prestressed concrete continuous rigid frame, the main pier adopts double thin-walled pier, and the foundation adopts bored cast-in-place pile foundation.

The cross section of box girder adopts single box and single chamber straight web section, the width of top plate is 13.5m, the height of box girder near block 0 is 10m, the height of box girder is 3.5m in middle and side span closure section. The lower edge curve of box girder bottom plate is 1.5 parabola.

The main pier is double thin wall pier. The transverse length of cross section of bridge pier is 7.75m, the outer distance of double thin wall pier is 8m. The main pier adopts single layer main reinforcement with 32mm diameter and 10cm spacing. The main pier foundation is integral cap with 4.5m thickness, and the pile foundation is 9 bored piles with diameter 2.5m. The transition pier is a rectangular solid pier with section size 7.75m×2.5m, cap thickness is 3.0m. The pile foundation is 4 bored cast-in-place piles with 2.0m diameter.

2.3. Establishment of Finite Element Calculation Model
Building the bridge finite element calculation model with Midas Civil 2019. The X axis, Y axis and Z axis of computational model are respectively along the bridge longitudinal direction, transverse direction and vertical direction. Main girder, pier and cap are modeled by space beam element. The second stage dead load is converted to equivalent mass.

This article A general rule of structural Pushover analysis of piers and columns, Therefore, the pile-soil interaction is not considered, and the bottom of the cap is fixed Type processing. The finite element calculation model is shown in Figure 2.
3. Pushover analysis of different lateral force loading patterns

Pushover analysis uses the increasing horizontal lateral force of a certain distribution pattern to represent the distribution of the inertial force of the structure. The difference of the distribution pattern will directly affect the results of the Pushover analysis, so the selection of the lateral force distribution pattern is a key problem in the Pushover analysis.

FEMA-273 of the United States recommend three Pushover lateral force distribution patterns:

- Constant acceleration distribution pattern: load distribution is uniform and the acceleration of each layer of the structure under earthquake action is the same;
- First order mode distribution pattern: the corresponding inertial force distribution pattern of the first order mode of the structure are adopted to load;
- SRSS distribution: the lateral force loading of the structure is carried out according to the inertial force by SRSS combination of the response spectrum mode.

In addition to the above three Pushover lateral force distribution patterns, single point load on pier top and CQC distribution pattern are also adopted to conduct Pushover analysis and research. The first three lateral force distribution patterns are shown in in Figure 3.

3.1. Comparison of SRSS and CQC analysis of lateral force distribution patterns

SRSS and CQC mode combination methods, as the two most commonly used combination methods of reaction spectrum, are widely used. As the simplest and most common method, SRSS method has good accuracy for plane structure with good frequency distribution. However, for frequency-intensive spatial structures, the coupling terms between modes are neglected, so the reactions of structures are often overestimated or overestimated. E.L.Wilson and others regarded the ground motion as a wide-band and Gaussian stationary process in 1981. According to the stochastic process theory, they derived the CQC(Complete Quadratic Combination) method multi-degree-of-freedom systems. CQC method takes into account the mode correlation when the frequency is close, and overcomes the deficiency of the SRSS method[6].

This paper firstly carries on the reaction spectrum analysis to the continuous rigid frame bridge and the mode combination way adopts the SRSS and the CQC method. Both of them adopt the first 200 order vibration modes and the vibration modes participation coefficient in the bridge structure calculation direction reaches 95%. Through the analysis of reaction spectrum, the SRSS and CQC lateral force distribution patterns of the 1# pier column structure are obtained. Based on two lateral force distribution modes, the longitudinal and transverse Pushover of the 1# pier column are analyzed, and the bottom shear force and the displacement of the pier top relationship curve are obtained, as shown in Figure 4.
3.2. Evaluation and analysis of seismic performance of bridges

According to United States ATC-40, the seismic performance evaluation of bridge structures should adopt the capability spectrum method. Based on the capability spectrum method, CQC, the first order mode, acceleration constant and pier top single point load are applied to the bridge pier in longitudinal direction and transverse direction. Through Pushover analysis, the pier bottom shear force and pier top displacement relationship curves are shown in Figure 5.
The performance points obtained from four lateral force distribution patterns of 1# pier column structure are listed in Table 2.

| Direction of loading | Lateral force distribution pattern | Displacement (unit: cm) | Acceleration (unit: g) |
|----------------------|-----------------------------------|-------------------------|------------------------|
| Longitudinal direction | CQC                                | 2.5                     | 4.27E-02               |
|                      | First order mode                   | 3.1                     | 3.46E-02               |
|                      | Acceleration Constant              | 2.7                     | 3.95E-02               |
|                      | Pier top single point load         | 3.1                     | 3.46E-02               |
| Transverse direction  | CQC                                | 1.5                     | 6.98E-02               |
|                      | First order mode                   | 2.0                     | 5.32E-02               |
|                      | Acceleration Constant              | 1.7                     | 6.20E-02               |
|                      | Pier top single point load         | 2.4                     | 4.47E-02               |

Through the analysis of Figure 4 ~ Figure 6 and Table 2, we can see that the Pushover analysis of pier column structure can be carried out by using four lateral force distribution load modes, such as CQC, first order mode, acceleration constant and single point load at the top of pier. The pier bottom shear force corresponding to the same pier top displacement obtained by the CQC distribution lateral force loading mode is the largest, and the corresponding capacity spectrum curve is also the largest. The pier bottom shear force and pier top displacement curve obtained by the first order mode lateral force distribution pattern and the pier top single point load lateral force distribution pattern, and the corresponding capacity spectrum curve are similar, the maximum error is within ±5%. Because the demand spectrum curve and the ability spectrum curve obtained by four lateral force distribution patterns have performance points, the displacement deformation ability of pier column structure of long span continuous rigid frame bridge meets the requirements under rarely occurred earthquake. The bridge structure has good seismic performance.

4. Conclusions
This paper uses four lateral force distribution patterns to analyze the Pushover response of a long-span continuous rigid frame bridge structure under rare earthquake. The general rules of Pushover analysis of long-span continuous rigid frame bridge are as follows:
Nonlinear Pushover analysis method is a simple and effective seismic performance evaluation method. Fiber element can simulate the nonlinear mechanical properties of structure well, which is the premise and foundation of Pushover analysis. Different lateral force distribution patterns have a great influence on the Pushover analysis results. Therefore, the rational choice of lateral force distribution pattern is very important for correctly evaluating the seismic performance of bridge structures.

SRSS mode combination method and CQC mode combination method are the two most commonly used mode combination methods in reaction spectrum method. The results of the two methods are very similar for bridge structures with less dense frequency, and the structure capacity spectrum curves are similar.

The lateral force distribution pattern of elastic response spectrum multi-mode combination (SRSS combination and CQC combination) can represent the inertial force distribution of pier column structure under earthquake. As for the lateral force distribution patterns such as the first order mode, the acceleration constant and the single point load at the top of the pier, it is quite different from the actual situation. Therefore, when the Pushover analysis method is used to evaluate the seismic performance of the bridge structure, the lateral force distribution pattern should be selected reasonably according to the characteristics of the bridge structure.

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