Seismic conceptual design and analysis method of Bridges crossing active fault

Fang Huang 1*, Jie Li2, Wuyi Chen2 and Shuang Wang 3
1 Naval University of Engineering, Wuhan, Hubei, 430033, China
2 Central & Southern China Municipal Engineering Design and Research Institute Co.Ltd. Wuhan, Hubei, 430010, China
3 Wuhan Longfang Engineering Technology Co., Ltd. Wuhan, Hubei, 430034, China
*Corresponding author’s e-mail: 150149184@qq.com

Abstract. For bridges crossing active fault, combined with relevant standards and recent research results, the seismic conceptual design such as bridge axis trend planning, bridge type selection, fault trace avoidance distance of substructure, fault span and lap length are systematically summarized; some suggestions on seismic analysis methods such as the value of horizontal and vertical acceleration response spectrum, the generation of ground motion acceleration and displacement time history, and the input mode of time history are put forward.

1. Introduction
Existing research shows that there are at least 495 seismic fault zones in Southwest, Southeast and Northwest in China, and with the deepening of research, more seismic fault zones will be delineated in the future. These areas have high mountains, deep valleys and intensive bridge construction, which will inevitably cross faults. Therefore, it is urgent to study the seismic behavior of bridges across faults (especially active faults).

2. Seismic conceptual design of bridge across active fault
2.1. bridge axis direction planning
When the bridge axis is oblique or parallel to the active fault, the fault dislocation will increase the relative displacement along the bridge between the main beam and the substructure, resulting in the disaster of lowering of girder along the bridge. Design Standards for Railway Structures and Commentary (Seismic Design) (2012) [1] suggests that the bridge axis should be orthogonal to the active fault as far as possible.

For the simply supported beam bridge, Japan Railway Comprehensive Technology Research Institute adopted the test as shown in Figure 1 to study the lowering of girder conditions when the intersection angle between the bridge axis and the active fault is 30 °, 60 °, 90 °, 120 ° and 150 °, and the test objects are shown in Table 1.

| programme | Span across fault | Other spans | Span number | Beam end seam |
|-----------|-------------------|-------------|-------------|---------------|
| CASE-1    | 40cm              | 40cm        | 5           | 0.2cm         |
| CASE-2    | 120cm             | 40cm        | 3           |               |

Table 1. Test bridge objects
The test results as shown in Figure 2 show that as the crossing angle approaches 90°, the relative displacement between the movable disc and the fixed disc increases when reaching the bridge, showing a tendency that it is not easy to fall off the bridge. When the crossing angle is 90°, the beam will not fall in all cases. Therefore, this angle is the most favorable condition for the lowering of girder disaster. In addition, the longer the span, the easier it is to fall the beam.

2.2. bridge type selection

There are many factors to be considered in the selection of bridge structure types across active faults. Only a few key reference principles are listed below:

① The selection of bridge type across active fault shall be based on local conditions, according to the research and evaluation results of bridge site topography, and considering the design bridge location and bridge length, the appropriate bridge type shall be selected;

② The selection of bridge type across active fault shall consider the fault type and seismic characteristics, and select the appropriate bridge type according to the possible dislocation displacement on the surface;

③ Bridges across active faults should focus on post earthquake repairability;

④ Skew and curved bridges shall be avoided for bridges across active faults;

⑤ The bridge across active fault shall consider the needs of disaster prevention and relief, cooperate with the regional earthquake disaster prevention and rescue plan, and whether it is a disaster relief road bridge.

2.2.1. Simply supported beam bridge

The integrity of the superstructure and substructure of the simply supported beam bridge is poor. Once the substructure is damaged locally or has large displacement, it will easily lead to lowering of girder. However, in terms of economy and post earthquake repair, the construction of simply supported beam is simple, and the post earthquake repair of upper and lower structures is easy and rapid. The selection of simply supported beam is more cost-effective. Therefore, if the simply supported system is adopted for the bridge across the active fault, the overlapping length shall be increased, and the design of stop and anti falling beam device shall be paid attention to avoid falling beam. At the same time, strengthen the seismic capacity of pier columns and try to avoid the inclination or damage of pier after earthquake, resulting in "joint effect" and multi span lowering of girder.

Seismic Design Specification of Highway Engineering (1989) [2], Manual for seismic design of
foundation structures (Q&A) (2004) [3], and Ken-ichi TOKID (2004) all suggest that simply supported beam bridges can be used for bridges across faults.

2.2.2. steel bridge
Because the steel itself has the characteristics of excellent compression and tensile capacity, high material strength, good toughness and light weight, it is especially suitable for places with large span and large curvature. Considering that the steel bridge can be repaired easily and quickly after the earthquake, the steel structure can be considered for the upper part of the bridge crossing the active fault. The steel box girder simply supported bridge is adopted for the Puqianwan bridge in Hainan, China.

2.2.3. Long span bridge
Long span bridge (suspension bridge and cable-stayed bridge) is a flexible bridge with good seismic performance. If the planned span of bridge across active fault is large and the surface fracture zone of fault can be determined, long-span bridge can be considered to reduce the impact of lateral, longitudinal and vertical displacement caused by fault dislocation, such as Akashi Strait Bridge in Japan under construction in 1995 (Figure 3), Although it crossed the nodao fault, it still successfully resisted the attack of the Hanshin earthquake.

![Figure 3. Japan's Akashi Strait Bridge across the nodao fault](image)

2.2.4. Cantilever bridges are set on both sides of the fault
Cantilever construction bridges can be used on both sides of the fault respectively, and the bridges on both sides are connected above the fault with cantilever ends. At this time, if the bridge on both sides is separated due to the dislocation of the active fault, each side of the bridge can still maintain a relatively independent stable state and effectively avoid lowering of girder. Cantilever bridges are used to cross the active fault at the mileage of 22K + 265 of Taichung link, Taiwan in China.

For the fault that may have large vertical dislocation, the cantilever beam bridge with hanging hole can be used for crossing. By releasing the bending moment of the main beam, it can better adapt to the possible vertical relative displacement at both ends of the beam (Figure 4).

![Figure 4. cantilever beam bridge with hanging hole crossing active fault](image)
Considering the long-term smoothness of the bridge deck, the cantilever bridges at both ends can also be provided with piers near the possible rupture of the ground surface. In normal times, the piers play a supporting role; In case of large displacement on the ground, if the pier is damaged, it will not cause the cantilever end beam to fall. Doushan No. 2 viaduct in Taiwan, China uses a cantilever bridge to cross the active fault, and piers are added at the junction above the crossing fault at the cantilever ends of the bridges on both sides (Figure 5).

In addition, the c295 section of Taiwan High Speed Railway in China and the Kawabata bridge in Japan adopt the rigid frame type, and the 55-0837s bridge in California adopts the continuous beam type to cross the active fault.

See Table 2 for bridge types across active faults recommended in relevant seismic standards, and see Table 3 for some built bridges across faults.

### Table 2. recommended bridge types across active faults

| standard                                                                 | Recommended bridge type                                                                 |
|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Design Standards for Railway Structures and Commentary (Seismic Design)2017 | Even if there is relative displacement between the upper and lower structures, it is difficult for the upper structure to drop the beam immediately or the bridge with high follow-up to the relative displacement of the upper and lower structures. |
| Manual for seismic design of foundation structures (Q&A) (2004)          | Simply supported bridge                                                                |
| Seismic Design Specification of Highway Engineering (1989)              | Simply supported bridge                                                                |
| Seismic Design Specification of Railway Engineering (2009)              | Simply supported bridge                                                                |

2.3. avoidance distance of substructure fault trace

For the avoidance distance, California formulated the "earthquake fault zoning act" in 1994, which stipulates as follows: if the active fault trace can be accurately determined, the avoidance distance can be set as 50 feet (about 16m).

Seismic Design Specification of Highway Bridges (2020) [4] suggests that class a bridges should avoid the main fault. In areas with seismic fortification intensity of VIII and IX, the distance from the pier edge to the outer edge of the main fault zone should not be less than 300m and 500m respectively.

The geotechnical evaluation and seismic application of European Standard EC8 (2006) [5] suggests that the hanging wall avoidance distance is 30m for normal fault, reverse fault and strike slip fault; The avoidance distance of footwall is (30 + 1.5H) m, (30 + 2H) m and 30m respectively, and H is the thickness of overburden.
2.4. across fault span
Take the simply supported mid span fault beam in Figure 6a) as an example, although the pier can avoid the theoretical surface fracture position according to the minimum avoidance distance in the planning and design. However, due to the variability of surface fracture (deviation of surface fracture position in actual earthquake), if the span of simply supported beam is small, the deviated surface fracture position may be under the pier, which will lead to pier instability and lowering of girder disaster, as shown in Figure 6b).

At the same time, considering that the long-span structure is conducive to absorb fault dislocation displacement. Ken-ichi TOKID (2004) and Takashi Nakata (2006) all recommend long-span fault crossing.

2.5. lap length
Fault dislocation will lead to large relative displacement of two piers on both sides of the fault, which will increase the risk of superstructure unseating or even lowering of girder. The lap length formula in the Seismic Design Specification of Highway Bridges (2020) [4] is mainly for far-field bridges, without considering the relative displacement of upper and lower structures caused by fault dislocation. For simply supported beams across faults, Ken-ichi TOKID suggest that the following formula can be used to simply calculate the longitudinal and transverse overlapping length.
Figure 7. Schematic diagram of fault dislocation and simply supported beam displacement

\[ d_x = (D \cos \theta + L) \left[ 1 - \frac{L}{\sqrt{(L + D \cos \theta)^2 + (D \sin \theta)^2}} \right] \]  
(1)

\[ d_y = (D \sin \theta) \left[ 1 - \frac{L}{\sqrt{(L + D \cos \theta)^2 + (D \sin \theta)^2}} \right] \]  
(2)

Among,  
- \( d_x \): relative displacement of main beam and pier along the bridge direction (m);  
- \( d_y \): transverse relative displacement of main beam and pier (m);  
- D: seismic fault dislocation (m);  
- L: span of main beam (m);  
- \( \theta \): intersection angle (°).

3. Seismic analysis method of bridge across active fault

3.1. active fault acceleration design response spectrum

At present, the design acceleration response spectrum of active fault is obtained by modifying the far-field design acceleration response spectrum with near source factors and fault strike component ratios. The near fault factor mainly considers the influence of the distance between the bridge site and the fault, and the fault strike component ratio is to determine the amplification effect in the fault strike and orthogonal direction.

3.1.1. American UBC97 specification

Based on the study of the 1994 Los Angeles Beiling earthquake, the standard first introduced near fault factors \( N_a \) and \( N_v \) to modify the far-field design acceleration response spectrum to obtain the near fault design acceleration response spectrum.

3.1.2. Standard for seismic design of highway bridges (2008) in Taiwan, China

The standard introduces the near-field adjustment factor of the fault in the equal acceleration section of the response spectrum and the near-field adjustment factor of the fault in the equal velocity section of the response spectrum to modify the far-field design acceleration response spectrum.
3.1.3. Standard for seismic design of buildings (2010) [6]
It is suggested in article 3.10.3 that for structures located within 5km away from both sides of the seismic fault and within 10km, the increase coefficient of ground motion parameters shall not be less than 1.25; For structures within 5km, the increase coefficient of ground motion parameters is 1.5.

The design response spectrum of near fault acceleration is not separately described in China's bridge seismic standard, and the specific project implementation can refer to the relevant provisions of standard for seismic design of buildings (2010).

From the seismic observation records, the peak value of vertical surface acceleration recorded in near fault seismic records is significantly larger than that in far field. For example, the peak value of vertical acceleration recorded at 6.97 Sitel station of Nahanni earthquake in 1985 reached 2.086g. Therefore, for bridges across faults, the ratio coefficient of vertical design acceleration response spectrum and horizontal design acceleration response spectrum can be taken as 1.

3.2. Seismic time history and input mode of active fault
Due to the directional effect of fault rupture and the generation of permanent surface displacement, the biggest feature of surface movement caused by fault dislocation is that there are long-period high-energy pulses in the velocity time history. This pulse will amplify the long-period acceleration response spectrum, and may increase the nonlinear seismic demand of the structure. According to different pulse forms, the types of near fault surface movement can be roughly divided into four types: type A (Figure 8a)), type B (Figure 8b)), type C-I and type C-II [7].
The mixed simulation method proposed by Park et al. (2004) [8], Tian Yuji et al. (2007) [9], Rodriguez et al. (2012) and Hui Yingxin et al. (2014) can be used to simulate the low-frequency pulse component (less than 1Hz, corresponding to near-field ground motion, type B can be used considering the directivity effect, type A can be used considering the slip impact effect) and high-frequency component (greater than 1Hz), Corresponding to far-field ground motion), and then the two are superimposed to generate acceleration time history.

Because the observed surface acceleration time history implies random background white noise and low-frequency noise, the velocity time history and displacement time history obtained by direct integration will often produce distortion and offset. Therefore, the acceleration time history must be baseline corrected. The baseline correction process usually uses low-order polynomial regression or high pass filter to remove the low-frequency noise. However, since the ground motion of active fault is often accompanied by permanent surface displacement, special baseline correction methods need to be adopted, such as the regression analysis method of three line segment model proposed by iwan in 1985. Only the EPS method of Y.Ohta can retain the permanent surface displacement in the displacement time history.

In terms of seismic input mode, it is recommended to input the seismic time history in three directions at the same time. The non-uniform excitation displacement time history can be used in the direction of fault dislocation, and the acceleration time history can still be used in other directions without fault dislocation. Taking a three span bridge with a middle span across a strike slip fault as an example, when the earthquake is input along the bridge, the uniform excitation acceleration time history can be adopted at all abutments and piers, as shown in Figure 9a); For seismic input across the bridge, non-uniform excitation displacement time history can be adopted, that is, one group of displacement time history is adopted for No. 1 abutment and No. 2 pier on the left side of the fault, and another group of displacement time history is adopted for No. 3 pier and No. 4 abutment on the right side of the fault. The two groups of displacement time histories have the same size and opposite direction, as shown in Figure 9b).
4. Conclusion

(1) Compared with far-field bridges, the seismic design of bridges across faults is particularly important. On the basis of considering the influence of dislocation in all directions of faults, comprehensive consideration should be given to disaster lethality, post earthquake repair difficulty and economy;

(2) Based on the research results at home and abroad, the seismic conceptual design and analysis methods of cross fault bridges can be referred to the Table 3 below.

Table 3. Seismic design table of bridge across fault

| Intersection angle between bridge axis and fault | right angle |
|-----------------------------------------------|-------------|
| Bridge system                                 |             |
| The fault trace is obvious                    | Simply supported system |
| The fault trace is not obvious                | Continuous system |
| Plane layout                                  |             |
| Straight bridge, avoid skew bridge and curved bridge |             |
| span                                          |             |
| Long span is recommended from the perspective of energy absorption |             |
| Small span is recommended from the point of view of facilitating repair and reducing economic loss after lowering of girder |             |
| Pier position                                 |             |
| Away from fault trace                         |             |
| Superstructure                                |             |
| Lightweight of superstructure (such as steel girder) |             |
| Bearing                                       |             |
| Vibration reduction and isolation bearings shall be used as far as possible, and the pull-out resistance design shall be considered for rubber bearings |             |
| Buffer device                                 |             |
| Buffer devices such as rubber pads shall be installed inside expansion joints and stops |             |
| Cushion stone                                 |             |
| Adjustable bearing pad stone is adopted to adapt to the vertical dislocation of fault |             |
| Anti falling beam system                      |             |
| deck                                          |             |
| The deck of simply supported beam bridge shall be continuous, and the connection stiffness of adjacent beams shall be appropriately increased |             |
| Lap length                                    |             |
| Fully considering the influence of fault dislocation displacement, the longitudinal and transverse overlapping length of simply supported beams can be calculated respectively with reference to equations (1) and (2) |             |
| Anti falling beam device                      |             |
| Longitudinal installation of buffer steel chain, steel splint and other anti falling beam devices; Metal energy dissipation block or isolation block shall be used transversely, and sufficient clearance shall be reserved |             |
| Segmental difference structure                |             |
| When the support is damaged or the main beam is unseated, the segment difference structure can effectively reduce the vertical displacement of the main beam and ensure the smoothness of the bridge deck |             |
pier

Enhance the shear capacity, especially prevent brittle shear failure in the non dense area of stirrups

pile foundation

Permanent steel casing shall be reserved for the pile foundation near the fault trace to increase the bending and shear resistance of the pile body

abutment

"Touch and take off" abutment can be adopted to effectively protect the substructure of abutment, which can meet the traffic of emergency vehicles after earthquake, and the repair cost is small.

| Analytical method | Response spectrum analysis | Horizontal direction | The response spectrum formula of seismic standard for highway engineering is modified, and the increase coefficient can be taken as 1.5 |
|-------------------|---------------------------|----------------------|----------------------------------------------------------------------------------------------------------------|
|                   |                           | vertical             | The ratio coefficient of and horizontal response spectrum is taken as 1                                                                 |
|                   | Time history analysis     | characteristic       | The velocity time history includes pulse effect, and the displacement time history in staggered direction includes permanent displacement |
|                   |                           | Input mode           | Uniform excitation acceleration time history can be adopted for non staggered direction, and non-uniform excitation displacement time history can be adopted for staggered direction. |

reference:
[1] Railway Technical Research Institute. (2012) Design Standards for Railway Structures and Commentary (Seismic Design). Drawn up by Railway Technical Research Institute, Published by Maruzen; Tokyo, Japan.
[2] Seismic Design Specification of Highway Engineering.(1989) China Communications Press Co.,Ltd.
[3] Railway Technical Research Institute. (2004) Manual for seismic design of foundation structures (Q&A). Drawn up by Railway Technical Research Institute; Tokyo, Japan.
[4] Seismic Design Specification of Highway Bridges.(2020) China Communications Press Co.,Ltd.
[5] Bouckovalas G. (2006) ETC-12: Geotechnical Evaluation and Application of the Seismic Eurostandard EC8[M]. Greece: National Technical University,2006: 55–64.
[6] Seismic Design Specification of building.(2010) China Architecture & Building Press.
[7] Makris, N., and S.-P. Chang. (2000) Effect of viscous, viscoplastic and friction damping on the response of seismic isolated structures, Earthquake Engrg. Struct. Dyn. 29, 85-107.
[8] Park S W, Ghasemi H, Shen J, et al.(2004) Simulation of the Seismic Performance of the Bolu Viaduct Subjected to Near-fault Ground Motions[J]. Earthquake Engineering&Structural Dynamics, , 33(13): 1249-1270.
[9] Tian, Y.J., Yang,Q.S., Lu,M.Q.(2007) Simulation method of near fault pulse ground motion [J]. Journal of Seismology, 29 (1): 78-84.
[10] Goel R K, Chopra A K. (2008) Simplified Analysis of Bridges Crossing Fault-rupture Zones[C]/Sixth National Seismic Conference on Bridges and Highways.