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EXPERIMENTAL STUDY ON MECHANISM OF FAULT-INDUCED DAMAGE OF BRIDGES

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SUMMARY

In this study, it becomes clear that the fault-induced damage of bridges is strongly affected by the fault crossing angle by the experiment. The simple analytical method is proposed to evaluate the damaged margin length of the bridge girder to prevent the girder from falling off the pier. The practical nomogram is also developed, which shows the relationship between the crossing angle and the margin length.

INTRODUCTION

In the 1999 Koccaeli Earthquake in Turkey and the 1999 Chi-Chi Earthquake in Taiwan, a number of structures were damaged by significant surface deformations induced by fault ruptures[1) 2)]. In particular, damages of bridges crossing a fault were quite severe. Some bridge girders fell off the piers. The falling of girders was presumed to have been caused by the significant dislocation which appeared on the surface ground. It appeared that, in addition to the near-fault ground motion (shaking), the fault-induced surface ground dislocation was a major threat for transportation facilities.

In Japan, the seismic design code for railway facilities[3)] was revised after the 1995 Hyogoken Nanbu Earthquake. Since the possibility that a bridge directly suffers damage resulting from a tectonic fault rupture is generally very limited, countermeasures for fault ruptures have been disregarded in the seismic design. However, the above two earthquakes reveal the fact that appropriate countermeasures are required for a structure which is constructed to cross an active fault.

The best way to mitigate the fault-induced damage is to construct bridges without crossing an active fault. In California, the United States, a state law was established in 1972. It regulates the construction of structures in near-fault regions, in order to prevent structures from suffering damage. It is virtually impossible, however, to construct railway facilities without crossing an active fault in Japan where many active faults exist.

In this study, therefore, a series of deformation tests for a miniature bridge model which suffer a lateral dislocation are conducted in order to clarify the behavior of fault crossing bridges. Based on the test

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results, a simple numerical method is proposed to evaluate the behavior of the bridges which suffer surface fault dislocations. A practical nomogram is finally proposed, to which provide a margin length of bridge girders to prevent their falling off the pier.

TEST FOR SIMULATING FAULT-INDUCED DAMAGE OF BRIDGES

Test device

Fig. 1 shows a miniature test device to simulate the behavior of a bridge which is crossing a fault. The test device consists of two plates, one is a movable plate and the other is a fixed plate. The size of each plate is 1300 mm×650 mm. The plates are made of aluminum. The movable plate can be moved at arbitrary speed in the horizontal direction. The surface fault dislocation is simulated by this movement. The miniature bridge model is arranged onto the aluminum plates. The miniature piers and girders are made of acrylic resin. The bottom of the pier is completely fixed on the plates. Three types of girder length, 400, 800 and 1200 mm, are prepared. The model girder is supported by four model stoppers which are arranged on the pier. The stopper is made of a rubber column with a diameter of 5 mm. The geometric scale of the test specimen is 1/50.

An image processing system is used in the test. This system consists of a CCD camera, an image capturing board and image analysis software. Many targets (black article dots shown in **Fig. 1**) are arranged on the girders and the movement of these targets are filmed by the CCD camera. After the experiment, the displacement of each target is measured automatically by using the image analysis software.

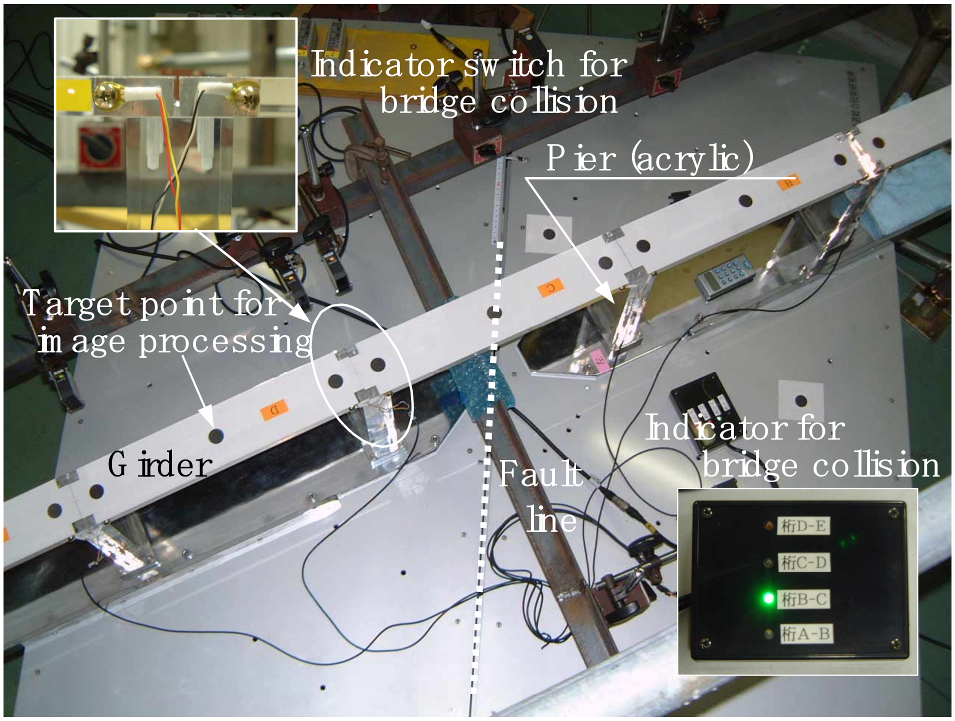


Figure 1 Experimental device

Test cases

The deformation tests are conducted for four cases as shown in **Fig. 2**. The crossing angle of bridge is changed from 30° to 150°, because the behavior of a bridge is supposed to be quite different when the crossing angle is different.

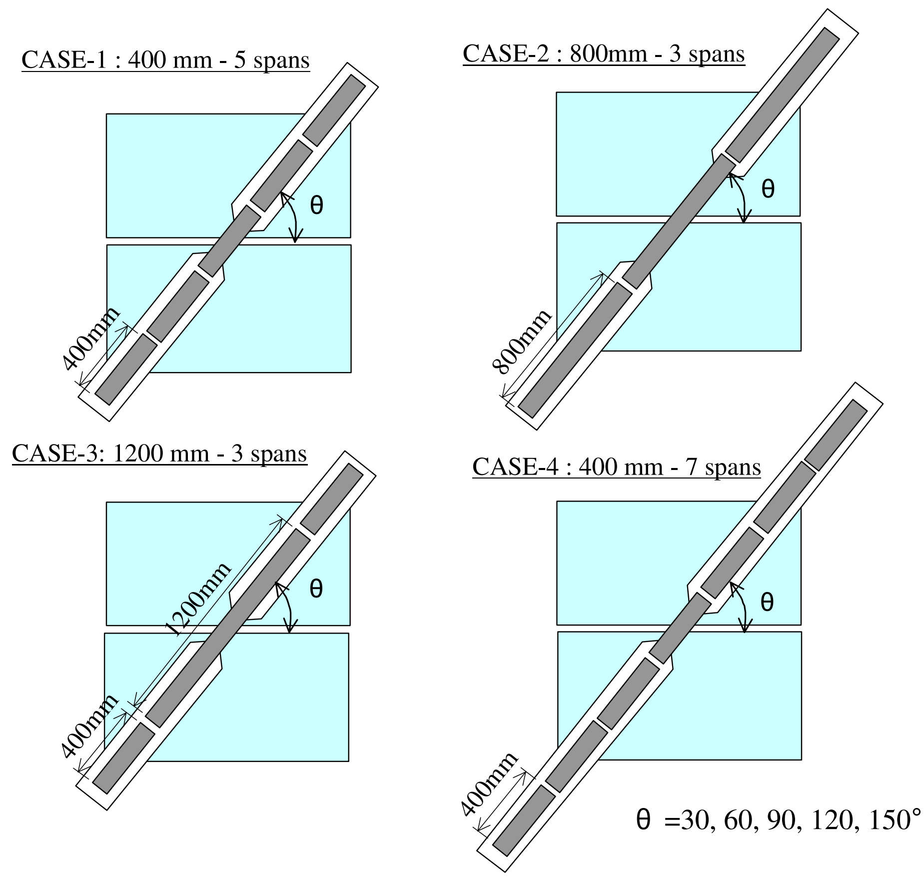


Figure 2 Test cases

TEST RESULTS

Effects of fault crossing angle on mechanism of girder falling

Fig. 3 shows the allowable limit displacement for girders not to fall off the pier. As the crossing angle becomes close 90 °, the allowable limit displacement increases. When the crossing angle is just 90 °, the girder does not fall off the pier. This fact shows that it is recommended for bridges to across the fault of 90 °.

The allowable limit displacement is also affected by the length of the girder. As the girder length becomes larger, the allowable limit displacement becomes smaller. This is because when the girder is longer, both the rotation angle of the girder and the added margin length δ become smaller, as shown in **Fig. 4**. This fact suggests that it is not an effective countermeasure to make the girder longer.

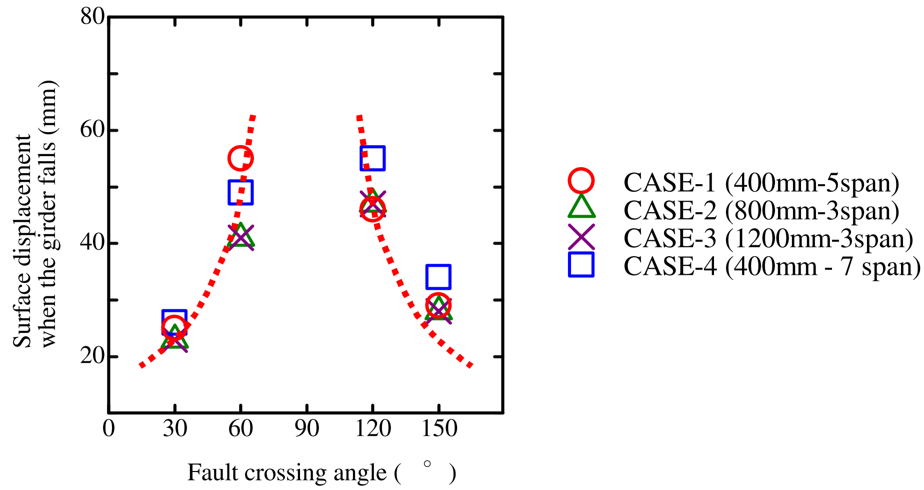


Figure 3 Experimental results

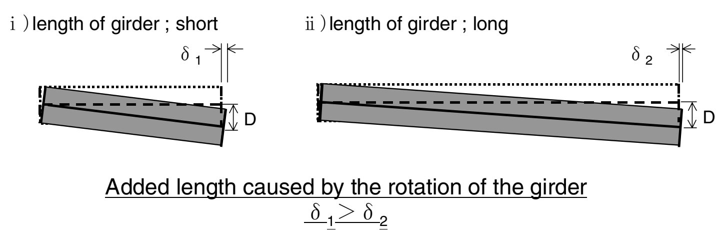


Figure 4 Added margin length caused by rotation of girder

Falling mechanism of girders[4)]

Fig. 5 shows the traces of girder movement which is measured by using the image analysis software. It should be noted that the scales of the horizontal and vertical axes differs are different in this chart. The deformation mode of girders is quite different in each case. The colored girder indicates the one which falled off the pier during the test. The limit displacement is also shown in each Figure.

When the crossing angle is smaller than 90 °, the interval in the x-direction between the piers which exist on both sides of the fault (piers of the girder B and girder D) becomes larger with the dislocation of the fault. Therefore, only the girder just above the fault (the girder C) falls off. The damage does not appear in other spans.

When the crossing angle is 90 °, girder do not fall off the pier, because the interval in the x-direction is unchanged.

When the crossing angle is larger than 90 °, all girders collide with each other because the interval becomes larger. As a result, the girders away from the fault (girders A and B) fall off, though the girder just above the fault does not.

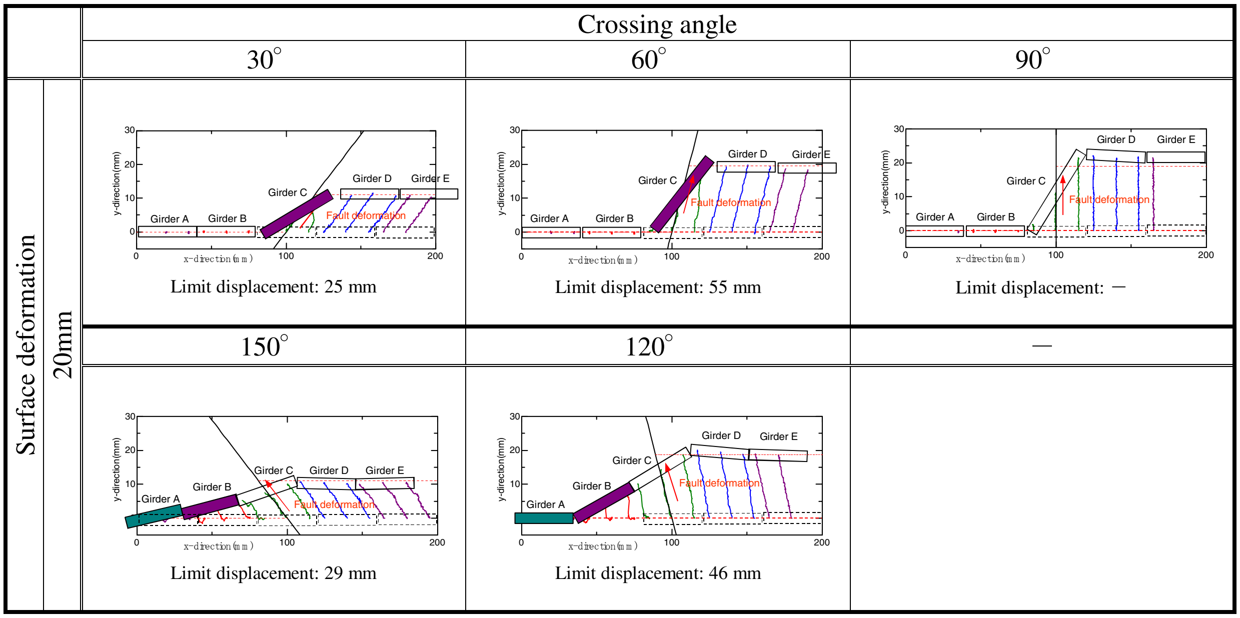


Figure 5 Deformation mode of bridges caused by surface dislocation at 20 mm

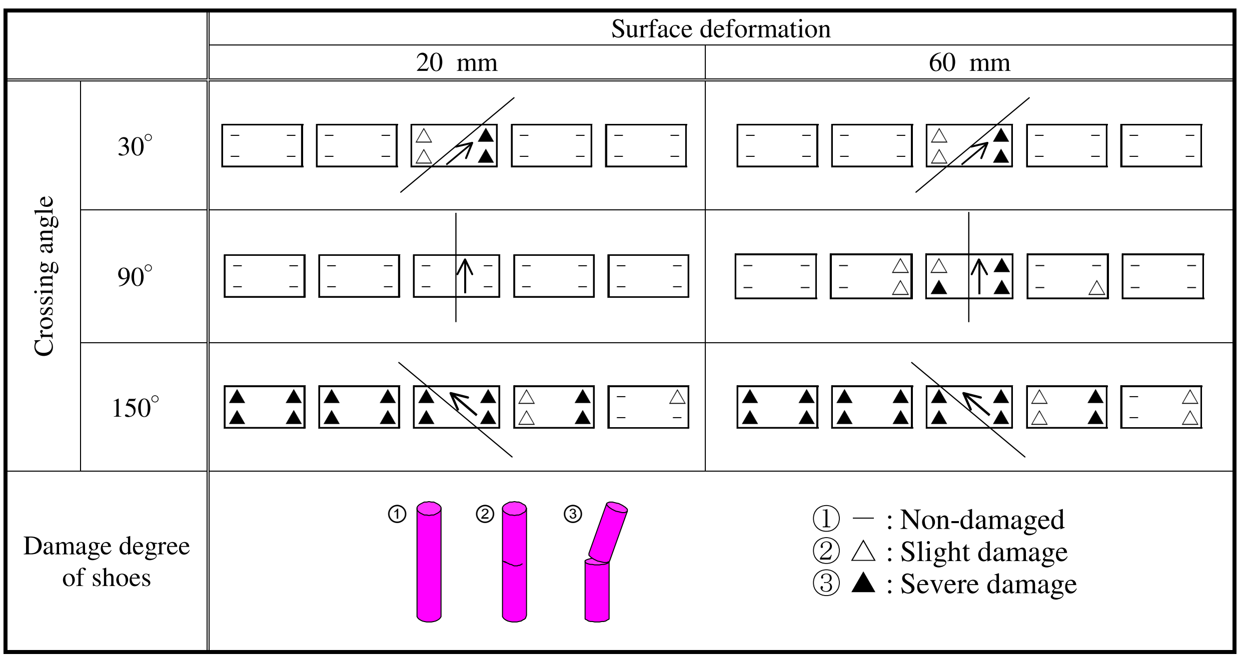
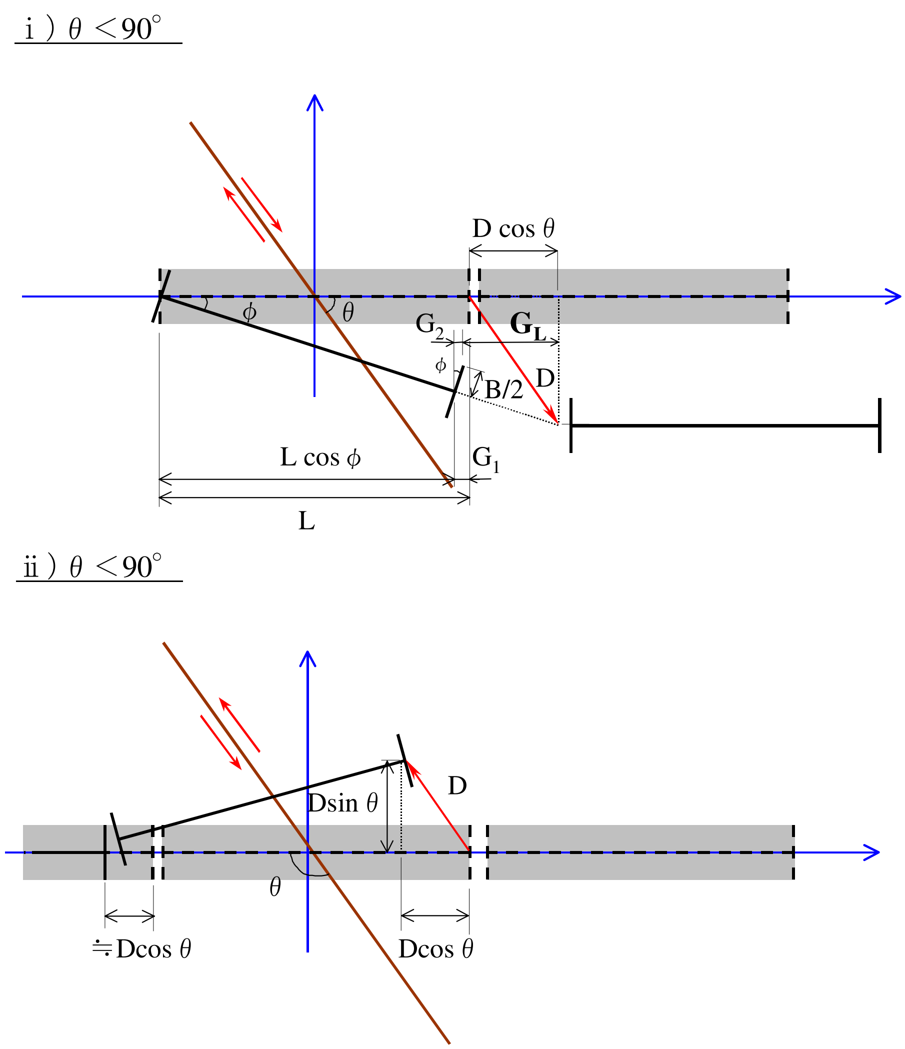


Figure 6 Schematic figures of damage mode of shoes caused by surface deformation of 20 and 60 mm

Damage mechanism of supporting shoes

Fig.6 shows the damage of shoes when the surface dislocations is 20 mm and 60 mm. The mark △ shows that the shoe is slightly damaged (with some cracks) while the mark ▲ shows that the shoe is completely broken.

When the crossing angle is 150°, shoes of all girders are damaged. On the other hand, when the crossing angle is 30 ° and 90 °, the damage is concentrated on the girder just above the fault.



D :Surface fault displacement

L :Length of girder

B :Breadth of girder

G_1: Displacement of girder in the x-direction

G_2 : Added margin length caused by the rotation of girder

G_L :Relative displacement between pier and girder in the x-direction

G_T :Relative displacement between pier and girder in the y-direction

Figure 7 Geometric relationship between fault dislocation and bridge deformation

SIMPLIFIED ANALYTICAL METHOD

The experimental results prove that the mechanism of fault-induced damage of bridges is strongly affected by the fault crossing angle θ.

Based on the results, the following assumptions are adopted here to derive a simplified method to judge whether the girder falls off the pier.

a) The deflection of the pier itself is neglected. In other words, the movement of the pier is equal to that of surface dislocation.

b) The girder moves with the pier geometrically. The deflection of the girder itself is neglected.

c) When the crossing angle is less than 90 °, only the girder just above the fault rotates and falls off the pier.

d) When the crossing angle is larger than 90 °, the girder just above the fault pushes out the neighboring girders. Thus, the girder away from the fault falls off.

Fig.7 shows the geometric relationship between the movement of the girder, pier and surface dislocation. The relative displacement between pier and girder can be expressed by the following Eqs. (1) and (2).

$$G_L = D\cos\theta + (L - L\cos\varphi) - \frac{B}{2}\sin\varphi \qquad (\text{for } \theta < 90^\circ) \tag{1}$$

$$G_L = D\cos\theta \qquad (\text{for } \theta > 90^\circ) \tag{2}$$

in which L is the girder length; B is the girder width; D is the surface dislocation; θ is the fault crossing angle; φ is the girder rotation angle; and G_L is the relative displacement between the pier and the bridge girder. When the relative displacement G_L is equal to the margin length, the girder is judged to fall.

The allowable limit deformations calculated by using the proposed formula are shown in **Fig. 8**, compared with the test results.

The similar method has already been proposed by Tokida[5)]. However, the method only refers to the case of the crossing angle θ<90° and the effect of the added margin length caused by the rotation of the girder is neglected in the formula.

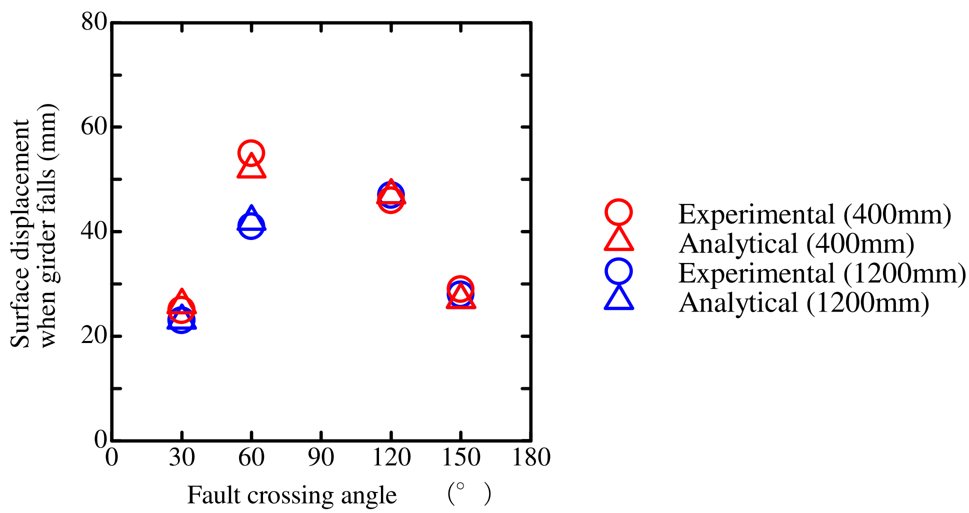


Figure 8 Surface displacement when the girder falls

NOMOGRAM FOR PRACTICAL DESIGNING

By using the proposed simplified method, it is possible to estimate the margin length required for a bridge girder to prevent it from falling off a pier. **Fig.9** shows the relationship between the fault crossing angle and the margin lengths which are estimated by using Eqs. (1) and (2). **Fig.9** is calculated for the girder with $B = 4$ (m) and $L = 10$ (m) .

Once the surface fault displacement D and fault crossing angle θ are known, the damaged margin length can immediately be estimated by using this nomogram. Bridges to cross an active fault can be designed based on this margin lengths. The most effective countermeasure is to enlarge the width of piers to satisfy the required margin length.

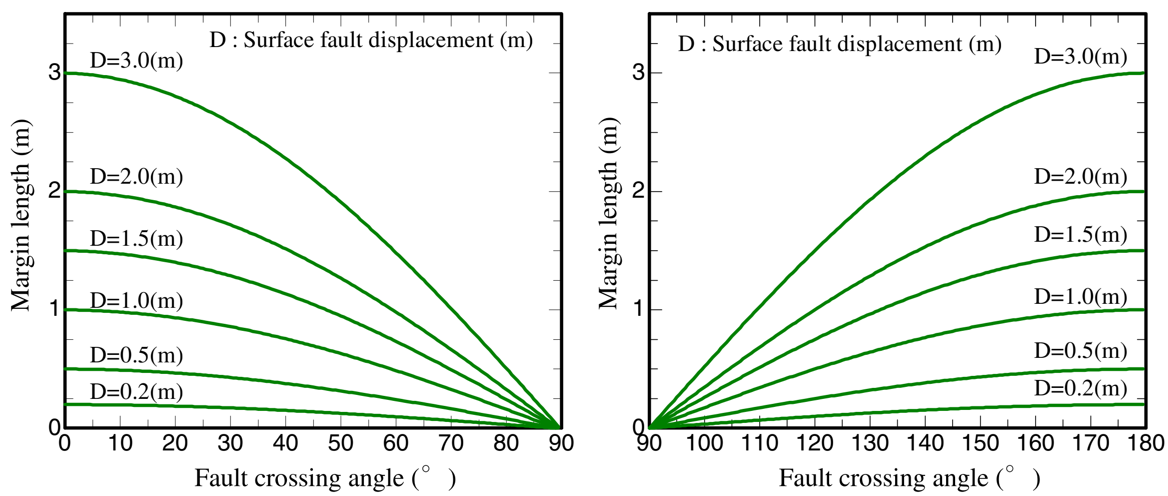


Figure 9 Practical nomogram for designing

CONCLUSIONS

In this paper, it becomes clear that the fault-induced damage of bridges is strongly affected by the fault crossing angle. A simple analytical method is proposed to evaluate the damaged margin length of a bridge girder to prevent it from falling off the pier. A practical nomogram is also developed, which shows the relationship between the crossing angle and the margin length. The characteristics of the behavior of girders are classified below.

1) $\theta < 90^\circ$: The girder just above the fault fall off the pier. The damage of shoes does not appear in other girders.

2) $\theta = 90^\circ$: Any girder does not fall off.

3) $\theta < 90^\circ$: Girders away from the fault fall off the pier. The damage of shoes appeares on all girders, because the girders will collide with each other.

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