Some Tendencies in the Failures of Bridges and their Foundations during Earthquakes

J. Kodera *

In this paper, the tendencies of the damage of the railway bridges and their foundations during the past earthquakes in Japan are investigated. The data of damage is taken mainly from the report of the Kanto (1923), Fukui(1948) and Tokachioki(1952) earthquake, and the data of soil conditions is taken mainly from recent investigations for the construction of new railway bridges. Compared to ordinary buildings, the following characteristics have a strong influence to the earthquake damage of the bridges:

(a) In most of the bridges each pier foundation is independent.
(b) In most of bridges piers and girders are not monolithic, but connected by shoes.
(c) The substructure of the bridge is often influenced by the soil masses, such as embankments, cutting or the slope.

1. The Intensity of the Earthquake and the Damage to the Railway Bridges

Fig. 1 shows the area where the railway bridges suffered damage during past earthquakes in Japan. The most severe damage, such as falling down of the girders or turning over of the piers, has happened only in the area with an intensity of VII in the Kishodai scale(more than 30% of the total wooden houses are completely damaged). Such failures as cracks in the masonry piers, displacement of the girders, piers and abutments, settlement of the foundation, become prevalent with an intensity VI in the Kishodai scale(1 to 30% of the total wooden houses are completely damaged). When the ground at the bridge site is locally very soft, above-mentioned failures happens even in areas where the general intensity is V.(cracks in the wall, tombstones turn over)

2. Shearing-off of the Anchor-bolts

Shearing-off of the anchor-bolts of the girders is one of the most prevalent failures during earthquakes. In many cases the estimated force necessary for cutting off these anchor-bolts is greater than the weight of the girder. This means, that according to the statical calculation, the seismic coefficient is larger than 1. But such failures have happened even in those areas with an intensity of V.

One of the reasons of such failures seems to be the unequal movement of the substructures which support the girders(see article 6).

*Chief of Bridge Department, Yachiyo Engineering Company
Japan

In case of the Tokachioki earthquake, all the railway bridges at which the anchor-bolts were cut-off, were located on muddy ground.

3. Displacement and Falling down of the Girders

Photo. 1 shows transverse displacement of the shoe of a railway bridge which suffered the Tokachioki earthquake. All the anchor-bolts of this shoe were cut-off and the concrete surrounding one of the bolts was spalled out.

Photo. 2 shows a railway bridge which suffered such a large displacement that it fell down from the piers. All the other trusses suffered also transverse and longitudinal displacement toward the span of the fallen truss.

Fig. 2 and Photo. 3 show the damage of Itagaki Bridge by the Fukui earthquake. All concrete girders moved transversally and longitudinally, and some of them fell down. The right-hand abutment moved forward and pushed the girders to the left. The parapet of the left-side abutment was cut-off and the girder SP 1 moved to the left. In this example the concrete girder was simply put on the pads and no other connection between the girder and the pier existed.

Fig. 3 shows a bridge under construction, which suffered an earthquake with an intensity of V. All the three trusses moved to the open span and fell down. The concrete surrounding the anchor-bolts of the fixed shoes was destroyed.

Photo. 4 shows a span, at which both piers have moved outward and the movable end of the girder has fallen down.(Niigata Earthquake)

When the girders fall down not only the girders are destroyed, but also the pier to which the girder leans seems to suffer a damage, as seen in Fig. 2 and Photo. 5.

To avoid falling down of the girders, following methods are recommended.

(a) to make the clearance between the ends of the girders as small as possible.
(b) to make the abutment and its parapet strong enough to prevent the outward movement of the girders.
(c) to restrict large displacement of the girders even at the movable shoe.
(d) to avoid large transverse displacement.

4. Horizontal Displacement and Inclination of the Piers.

As seen in Photo. 6, a pier standing on a slope, which becomes unstable during the earthquake, is often inclined. The foundation of this pier was shifted downward(to the left in the photograph), and the top of the pier was resisted to move by the right-hand girder, and so the upper part of the pier inclined to the left.

Photo. 7 shows similar damage of a pier standing at a riverside (Niigata Earthquake).

A pier also suffers a displacement or an inclination when the pier is pushed longitudinally at the top of the pier by the girder, which in turn is pushed by the abutment.

Photo. 8 shows an inclination of a pier caused by an unequal settlement of the foundation, the right side of which rests on piles and the left side on the footing.

5. The Failures of the Masonry Piers

With the intensity of the Kishodai scale VI, many masonry piers suffer cracks, which extends all around the pier. When the height of the pier above the groundsurface is taller than about 8m, a pier is often cut off in more than one section.

The upper part of the pier is often shifted as seen in Photo. 10, 11, or is rotated as seen in Photo. 9. The bridge in Photo. 10 was under construction at the time of earthquake and the girders were not yet erected. If the upper part of the pier in Photo. 11 would move further to the right, it would turn over as seen in Photo. 12.

We can suppose from these photographs, that when the pier is cut-off, the upper part of the pier begins to walk or rotate over the lower part during the earthquake. At the same time the edge stone of the lower part is damaged and when the displacement becomes larger the upper part will easily fall down.

6. The Damage to the Abutment

Most of the abutments which suffered horizontal displacement during earthquakes, were situated on soft ground. When the displacement of the top of the abutment exceed certain amount, the girder acts as a strut as seen in Photo. 13 or 14. The parapet is cut-off by the strut action of the girder as seen in Photo. 13. In many cases the anchor-bolts are cut-off by the similar action. In Photo. 14 we see that the foundation moved forward and the movement of the top of the abutment was restricted by the girders.

Photo. 15 shows a most typical failure of the abutment on soft ground.

When the bridge is situated on soft ground and has only one span, a box-culvert is recommended as a most suitable construction. When the girder is strong enough against axial compression force, the strut action of the girder may be considered in the aseismic design of the abutment.

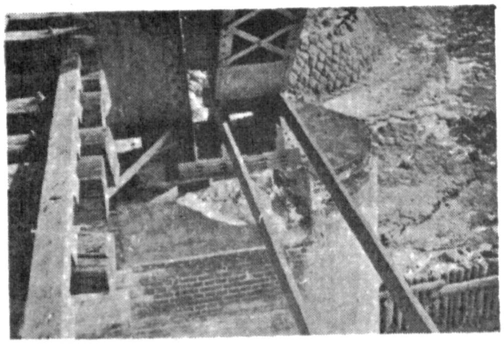
7. The Settlement of the Foundation

During a strong earthquake the ground itself suffers vertical and horizontal displacement. The settlement considered in this article is the relative settlement of the foundation against the ground.

Fig. 4 shows the distribution of the substructures of the railway bridge which settled during the Kanto earthquake. We see in this figure that more substructures settled near Tokyo where the ground is very soft, than in the coastal area near the epicenter where the ground is comparatively hard. One of the most severe damage in foundations happened at the Arakawa Bridge near Tokyo. The piers on the right bank of the Arakawa River, where the foundation rests on a layer of pure sand(see the curve A in Fig. 5) settled 50 to 150cm. On the other hand, the piers on the left bank where the sand is not so pure(see the curve B in Fig. 5) settled about 10cm.

Fig. 6 shows the relation between the settlement of pile foundations near Tokyo during the Kanto earthquake and the safety factor $\nu = Py/Pd$, in which Py is the ultimate bearing load of a pile and Pd is the dead load acting on a pile. Py is estimated from the test at the site. We see that no settlement has happened when $\nu > 3$.

All the well foundations, which settled during the earthquake, did not rest on a firm layer but on a soft layers such as clay, silt or silty sand. For example, the well foundation on clay settled about 10 to 30cm, and on silty or clayey sand 2 to 6cm. The well foundations, which settled about 2 to 10cm or suffered an inclination of 1/1000 to 1/100 radius during the earthquake could be used normally after the earthquake.



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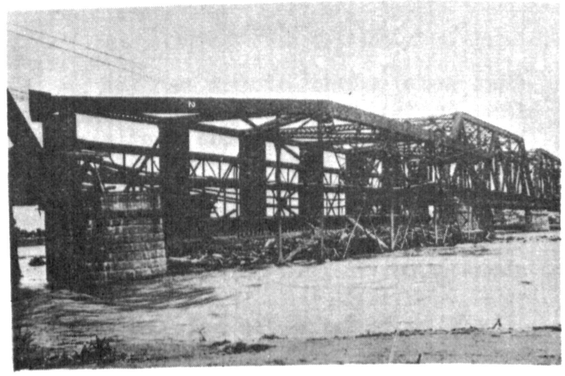

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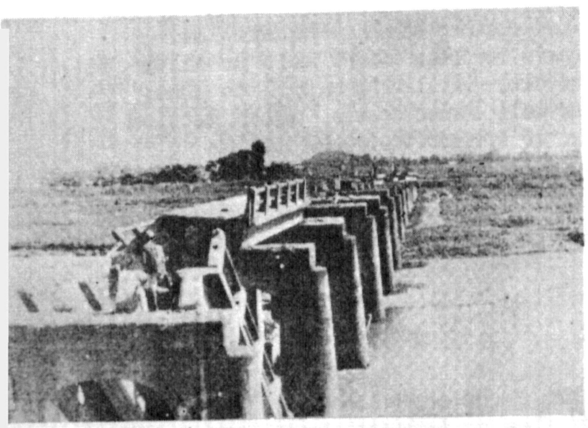

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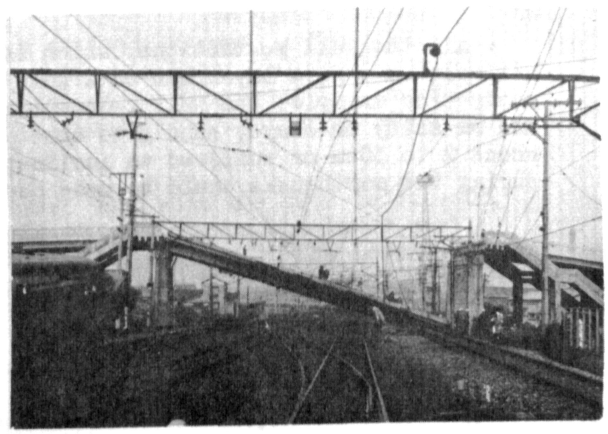

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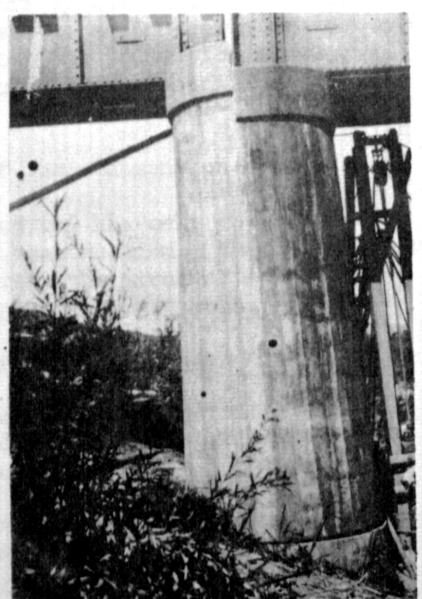

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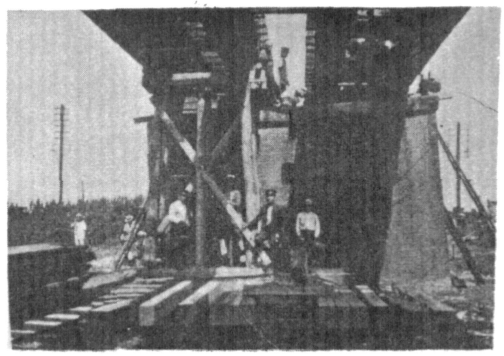

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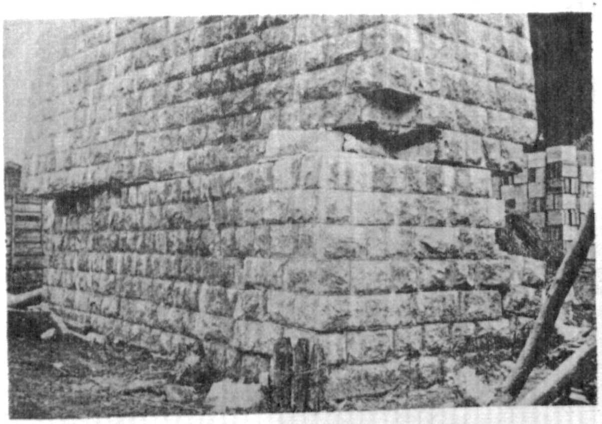

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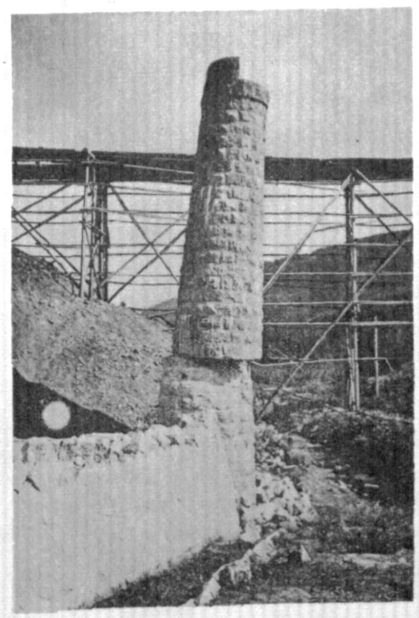

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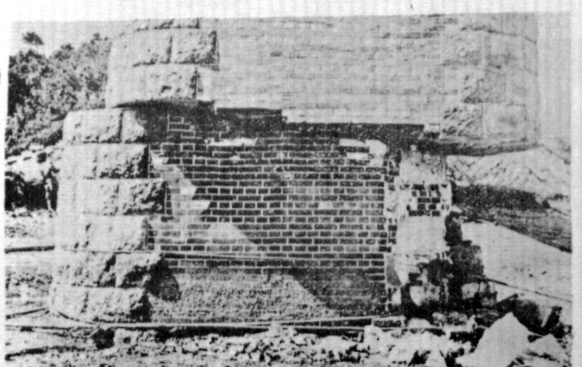

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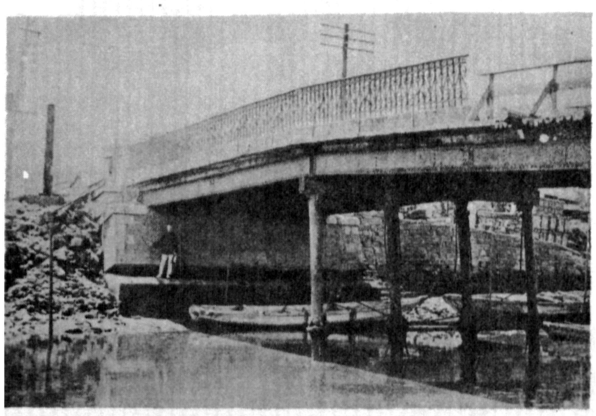

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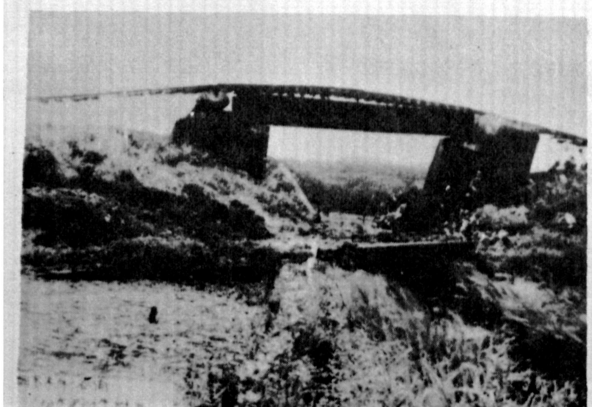

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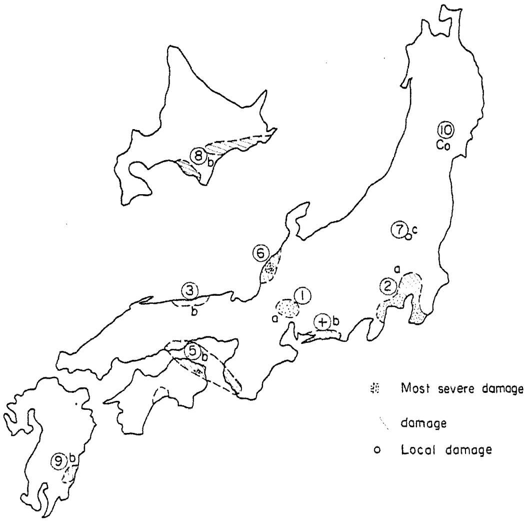


Fig. 1 The distribution of the earthquake damage of the railway bridges in Japan

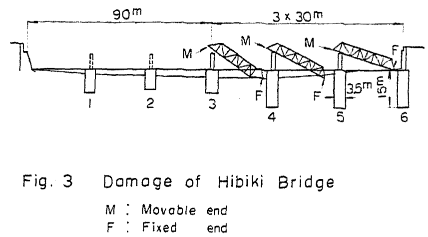


Fig. 3 Damage of Hibiki Bridge

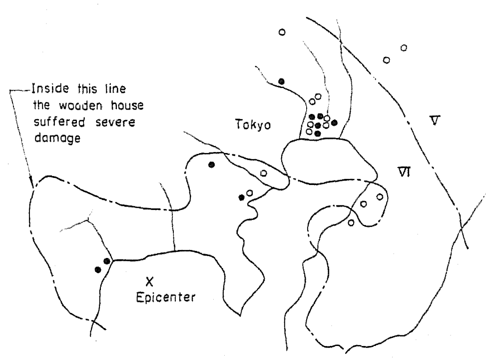


Fig. 4.1. Distribution of the Abutments which settled during kanto Earthquake

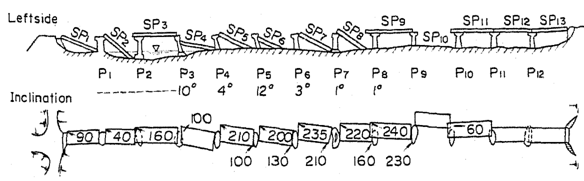


Fig. 2 Damage of Itagaki Bridge

(the figure shows the horizontal displacement of the girders in cm).

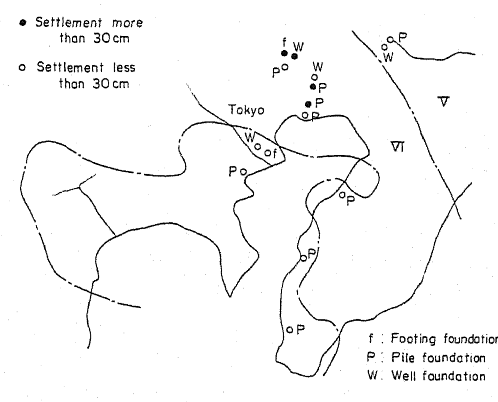
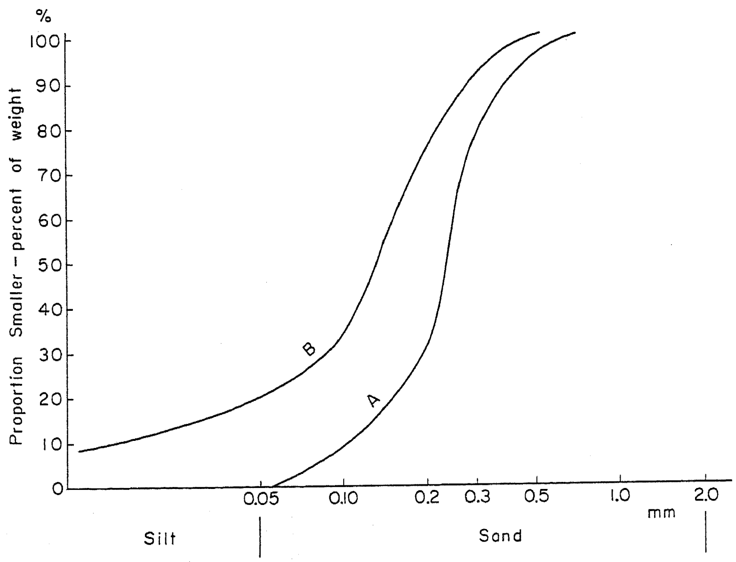


Fig. 4.2. Distribution of the piers which settled during kanto Earthquake

Fig. 5 Size Distribution of the Sand Layer at Arakawa



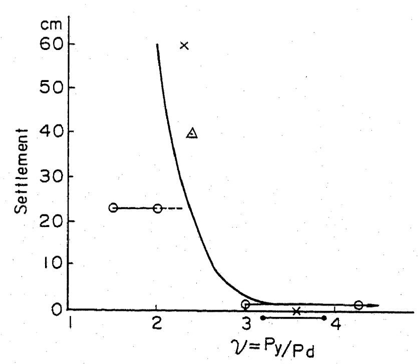


Fig. 6 The relation between the amount of settlement and ν
(Pile foundation)

SOME TENDENCIES IN THE FAILURES OF BRIDGES AND THEIR FOUNDATIONS DURING EARTHQUAKES

BY J. KODERA

QUESTION BY: V.A. MURPHY - NEW ZEALAND

Would the author please comment on engineering methods which would tend to minimise the failure shown in his slides of bridges and which methods Japanese engineers have found to be effective.

AUTHOR'S REPLY: As there are different opinions even inside Japan concerning the aseismic design of the bridges, I will refer to my private opinion, some of which is mentioned in the paper.

1. To prevent a large displacement of the girders, the methods described in the paper in paragraph 3 seem to be very efficient besides strengthening the shoe at the fixed end of a girder. Those methods seem also to be efficient in preventing other damage to bridges, such as inclination or displacement of substructures.

2. If possible we should avoid the construction of piers or abutments in such a slope, which could become unstable during earthquakes. If it is not possible, the resistance of the foundation against horizontal movement should be strengthened, for example, by battered piles.

3. Horizontal struts between the foundation of the two abutments will prevent the displacement of the foundation. The concrete girder between the abutments could be also sometimes regarded as a strut, as described in paragraph 6 in the paper.

4. If possible, it is desirable to connect each foundation on soft ground to avoid relative displacement of each foundation.