Note on the Seismic Stability of the Piers of the Naisha-gawa Railway Bridge, Formosa.

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With Pls. XLII & XLIII.

In connection with the seismic experiments on the fracturing and overturning of columns, described in the "Publications of the Earthquake Investigation Committee," No. 4, I have used for the fracturing the formula

$$a = \frac{IgF}{x_0 fW},$$

in which the different symbols have the following significations:

a = Acceleration of the earthquake motion necessary for fracturing a given column, supposed to be uniform in section or else to have a vertical axis or plane of symmetry.

g = Acceleration due to the gravity = 9,800 mm/sec^2.

F = Tensile strength of the column at the section of fracture.

x_0 = Half width of the section of fracture in direction parallel to the earthquake motion.

f = Height of the centre of gravity of the portion above the section of fracture.

W = Weight of the fractured portion of the column.

In the practical application of the above formula to the calculation of the strength of bridge piers, chimneys, walls, etc., there is always a great uncertainty respecting the value of the tensile strength F; it being impossible that each of such masonry structures should have a perfect homogeneity of strength of material. A column is therefore broken by the earthquake shock at the weakest place near the theoretical section of fracture. Again, a brick structure of large dimensions requires a certain length of time for the hardening of the mortar joints, such that the latter would be a good deal compressed before their conversion into perfectly solid elastic bodies. From this latter circumstance it seems that, at the mortar joints, where the brick work is almost invariably broken, tension will tend to set in immediately with the bending of the column. From these considerations, I have in my former papers simply taken the tensile strength of the brick work into consideration. For certain masonry structures, however, we may more logically take the quantity F in the above equation as denoting the tensile strength of the material increased by the weight per unit area of the section of fracture of the mass above the latter; it being absolutely necessary for the practical applications of the results that the strength of the material should not be over-estimated. Let us now consider, as an example, the seismic stability of the tall piers of the Naisha-*gawa* bridge in Formosa.

The single track Naisha-*gawa* bridge on the Formosa main railway line, consists of nine 60′ plate girders supported by two abutments and eight piers of masonry (Fig. 3), with embedded iron frame. As the ground is of a soft rocky formation, there is no well sinking, the heights of the piers, including the thickness of the foundation, being as follows :—

Northern, or Taihoku-end, Abutment.	27′	0″
No. 1 Pier	70	7
No. 2 „	92	6½
No. 3 „	114	5

No. 4 Pier	114′ 5″
No. 5 „	114 3
No. 6 „	110 3
No. 7 „	105 0.5
No. 8 „	105 0.5
Southern, or Taichu-end, Abutment........	46 9

Thus the six piers Nos. 3 to 8 are each taller than 105′, the construction in masonry of these high piers having been necessitated by the peculiar conditions of climate in Formosa, which cause iron spikes, bolts, etc. to rust quickly, and which render the maintenance in proper manner of high trestle works of iron extremely difficult.

Weakest section. In considering the seismic stability of the high piers of the Naisha-*gawa* bridge, we must first determine the approximate position of the weakest section, or the height where these structures are likely to be broken in case of a violent earthquake. If each of these piers be regarded as a "tall column," it would behave as a high brick chimney and be broken by the earthquake shock at about two-thirds of its height. If the column be, on the other hand, regarded as a "short column," then it would be weakest at, or near, the base. Thus it is first necessary to determine the length of the vibration period, which is proper to each of the columns and on which depends the classification of the latter with respect to the height of the section of fracture. The period, whose exact value can only be found from an actual measurement, may be estimated, so far as the order of magnitude is concerned, from a comparison with other bridge piers whose vibrations have been investigated. Thus for instance, the tallest of the piers of the single track Kizu-*gawa* bridge of Kwansai Railway, has a height of 60′ and supports the ends of a 200′

Pratt truss and a 100′ Warren girder. This pier stands directly on native rocks, and therefore its motion may be regarded as that due to its whole height; the periods of the transverse and longitudinal vibrations being respectively between 0.30 and 0.15 sec., and between 0.31 and 0.14 sec.* As now the bed of the Formosa river in question is rocky in nature, and not muddy, the piers of the Naisha-*gawa* bridge are to be regarded as vibrating approximately with their bases as centres; the period being, when inferred from the case of the Kizu-*gawa* bridge, probably 0.5 sec. or so., that is to say, much shorter than the period of the large destructive earthquake motion. From these considerations we may conclude that each of the high piers of the Naisha-*gawa* bridge would behave on the occasion of a destructive earthquake, not as a tall brick chimney, but is to be regarded as a "short column," and is weakest at the base.

Stability of the piers. Let us consider the stability against the earthquake motion of the two tallest piers, Nos. 3 and 4, of the Naisha-*gawa* bridge. As shown in Fig. 4, each of these two piers, rectangular in section, is 114′ 5″ in height, and is 10′×6′ at the top, and 22′ 11″×20′ 0″ at the base or the ground level; there being at the foot on the up-stream side a buttress 19′ 3½″ in height. The foundation, constructed to suit the nature of the ground, is 14′ 5″ in thickness. Further, the metal frame embedded in each of the piers consists of 8 iron rods, 1½″ in diameter, reaching from a few feet below the top down to the middle of the foundation, joined by horizontal iron bars forming a rectangle at every 10′ distance of the vertical.

Now a body of the dimensions like those of the pier under consideration can never be overturned as a whole, even when the

* See the "Publications of the Earthquake Investigation Committee," No. 12.

structure simply rests on, and not fixed to, the ground.* Hence, the question of the seismic stability of the pier reduces itself to that of the fracture, which is, when the earthquake is sufficiently violent, most likely to take place at or near the base, as before explained.

(i) Let us first calculate the strength of the pier at its base, or the section B, supposing the direction of the shock to be parallel to the length of the bridge. (See Figs. 1 and 4.)

Fig. 1.
(Section B)

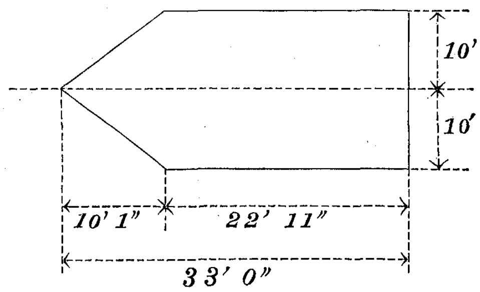
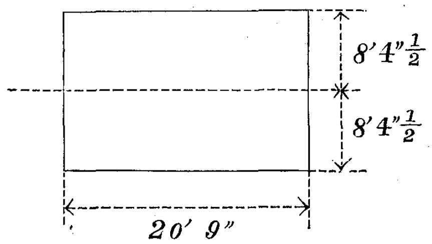


Fig. 2.
(Section A)



The values of the different factors in the fracture-formula for the section B are as follows**:—

I = Moment of the area of fracture about its middle axis
=351,360,000 (unit in inches).

W = Weight of Pier above Foundation (=1524.8 tons)
+Weight of Girder and Track system (=21.1 tons)
= Total Sum = 1545.9 tons = 3,463,000 lbs.

f = Height of Centre of Gravity of the whole structure above Foundation = $38' \ 9'' = 465''$.

$x = 120''$.

For the tensile strength of the brick work, let us adopt a value

* The "Publications," No. 12.

** The evaluation of the quantities I, W, and f for the two sections A and B have been made by Mr. Inagaki of the Railway Department of the Formosa Government-General.

of 50 lbs per sq. in., which is a little smaller than that obtained from the test pieces of the masonry of the Kiso-*gawa* railway bridge destroyed by the great Mino-Owari earthquake of 1891.* The strength of the iron rods, supposed to be uniformly distributed over the section under consideration, is equivalent to the reinforcing the masonry by 10.5 lbs per sq. in. of the area, assuming the ultimate strength of the iron rods to be 60,000 lbs per sq. in. Again, supposing the total weight of the pier and the girder and track system ($=W$) to be uniformly distributed over the base plane B, we obtain a pressure of 43.0 lbs. per sq. in. of the sectional area. Taking together the strength of the masonry, that of the iron rods, and the compressional effect, the effective tensile strength of the column will be

$$F = 50+10.5+43.0 \text{ lbs} = 103.5 \text{ lbs.}$$

The seismic stability of the pier then becomes

$$\alpha_1 = \frac{9800 \times 351,360,000 \times 103.5}{120 \times 456 \times 3,463,000} = 1844 \text{ mm/sec}^2.$$

(ii) Let us next take the section A, whose height corresponds to the top of the buttress. (Figs. 2 and 4.) We have :—

$I = 168,502,500$ (unit in inches)

$W = \begin{cases} \text{Weight of Pier above Section } A \ (=902.1 \text{ tons}) \\ +\text{Weight of Girder and Track system } (=21.1 \text{ tons}) \\ =\text{Total Sum} = 923.2 \text{ tons} = 2,068,000 \text{ lbs.} \end{cases}$

$f =$ Height of Centre of Gravity of the structure above Section A
$= 29'\ 10'' = 358''$.

$x_0 = \frac{1}{2} \times 16'\ 9'' = 100''\frac{1}{2}$.

The effect on the strength of the brick work of the iron rods is equivalent in this case to an increase of 16.9 lbs per sq. in. of

* The "Publications," No. 4.

the sectional area ; while the pressure of the mass above the plane of fracture is 41.3 lbs per sq. in. of it. The effective tensile strength is $F=50+16.9+41.3=108.2$ lbs per sq. in. Hence the seismic stability of the pier at the section A is

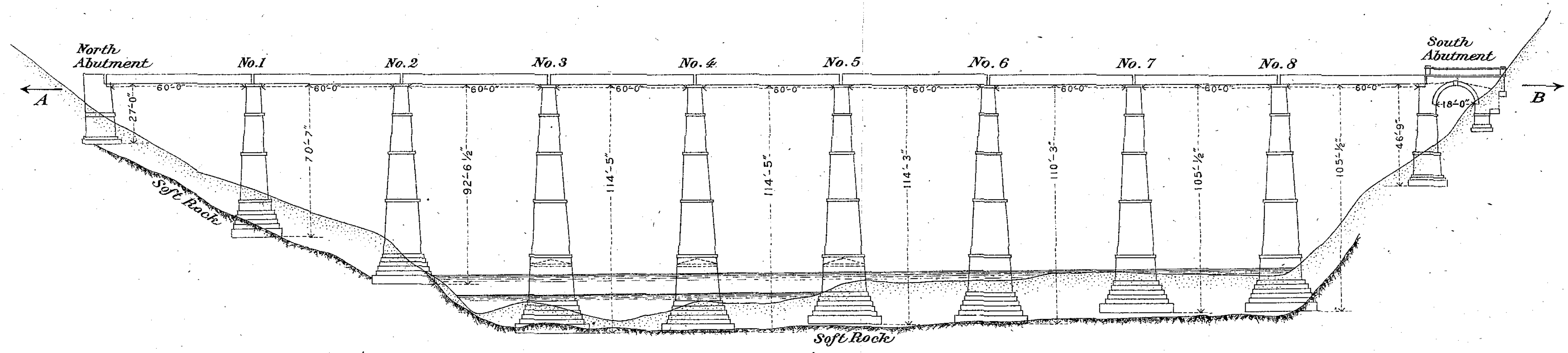
$$\alpha_2 = \frac{9800 \times 168{,}502{,}500 \times 108.2}{2{,}068{,}000 \times 358 \times 100.5} = 2404 \text{ mm/sec}^2.$$

Thus α_2 is greater than α_1 in the ratio of about 4 : 3, and the pier, which is strengthened by a buttress, is still weakest at the base, its seismic stability being $\alpha_1=1844$ mm/sec^2. As this is nearly equal to the intensity of motion in the destructive earthquakes likely to disturbe the western part of Formosa, the pier in question may be considered, when the work is properly executed, to be fairly good from the seismological point of view.

Fig. 1. The Naisha-*gawa* Bridge, Formosa Railway.

Scale 1:1,000

A....Taihoku End. *B*....Taichu End.



Pl. XLIII.

Piers Nos. 3 and 4. The Naisha-*gawa* Bridge, Formosa Railway.

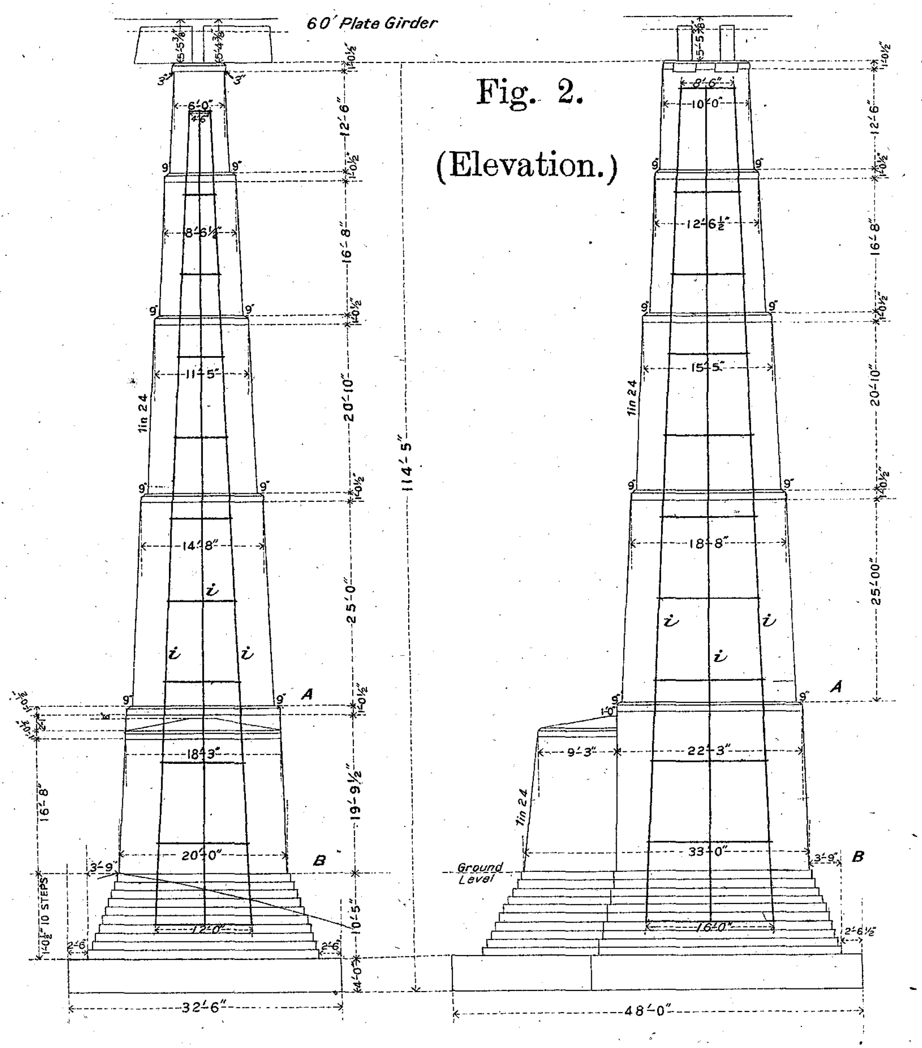


Fig. 2.

(Elevation.)

Thick lines, *i*, are iron rods.

Scale 1 : 220.

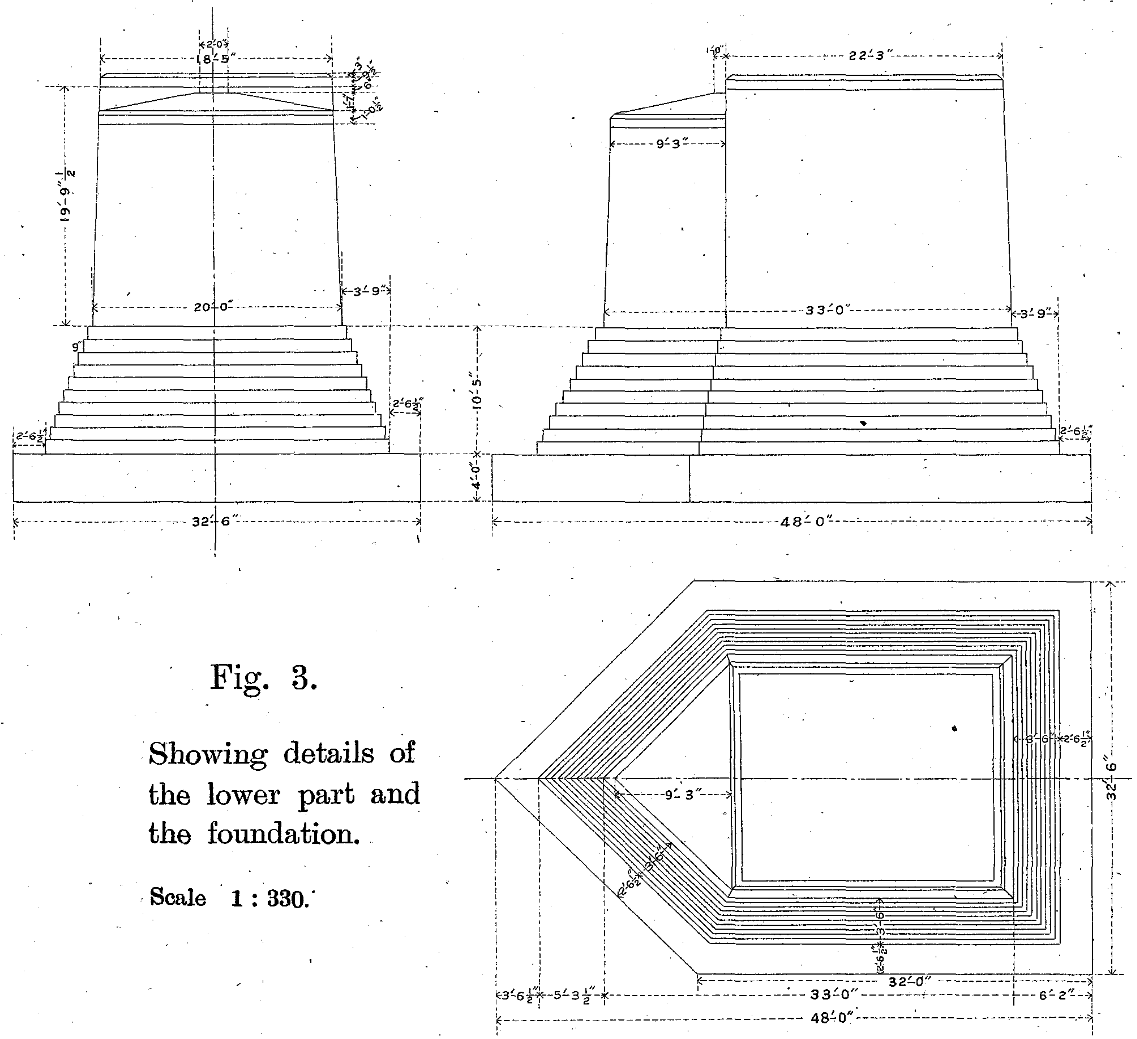


Fig. 3.

Showing details of the lower part and the foundation.

Scale 1 : 330.