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Stability of a Stone Arch Bridge against Flood Pressure and its Preservation

Stabilité de ponts arcs en pierre sous la pression des flots lors d'innondations et leur préservation

Stabilität von Steinernen Bogenbrücken bei Hochwasser und deren Instandhaltung

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SUMMARY
Dynamic water pressure caused by the rapid flood water which hit Nagasaki, Japan, in 1982, took away the spandrels and railings of the Momotani, Megane and Fukuro Bridges of stone arch, but their arch stones remained. Six other bridges of a similar type were completely destroyed. To measure the hydrodynamic pressure which caused great damage to the stone arch bridges, two stone arch models of the Fukuro Bridge were tested in a testing channel. Based on the test results, the stability of a stone arch bridge against flood pressure and its preservation are discussed in this paper.

RÉSUMÉ
La pression hydrodynamique, engendrée par le débit de flots rapides, qui frappa Nagasaki au Japon, en 1982, emporta les voûtes et les garde-corps de plusieurs ponts arcs massifs mais leurs pierres d' arche demeurèrent intactes. Six autres ponts du même type furent complètement détruits. Pour mesurer la pression hydrodynamique ayant endommagé les ponts arcs en pierres, deux modèles réduits d' arcs en pierre du pont de Fukuro ont été testes dans un canal d' essai. Sur la base des résultats des tests, la résistance des ponts en arcs pierre contre la pression des flots et sa préservation sont discutés dans ce document.

ZUSAMMENFASSUNG
Die dynamischen Drücke schnell-strömender Hochwasserfluten, von denen Nagasaki, Japan 1982, betroffen wurde, rissen die Bogenfüllungen und die Fahrbahn der Momotani-, Megane- und Fukuro-Brücken weg, liessen aber Steinbögen stehen. Sechs weitere Brücken ähnlichen Typs wurden völlig zerstört. Um die für die Zerstörung der steinernen Bogenbrücken verantwortlichen dynamischen Wasserdrücke zu messen, wurden zwei Modell-Steinbögen der Fukuro Brücke in einem Testkanal getestet. Basierend auf diesen Testergebnissen wird in diesem Beitrag die Stabilität einer Steinbogenbrücke gegen Hochwasserdruck und ihre Instandhaltung diskutiert.

1. OUTLINE

The present paper is related with exceptional conditions due to extreme flood flow, and discusses experimentally the stability of a stone arch bridge against flood pressure and its preservation. A heavy local downpour hit the Nagasaki area of Kyushu Island in Japan on July 23, 1982, causing a sudden increase of water flow in many rivers, so that the flow reached the superstructures of bridges crossing the Uragami, Nakajima, Hachiro and other rivers.[1]

In Kyushu, including Nagasaki, Kumamoto and Kagosima prefectures, there still remain many rivers spanned by stone arch bridges. The stone arch bridges were constructed by a traditional method which was one of the most reliable methods of bridge construction, as well proven by many ancient Roman Bridges still stoutly remaining after some two thousand years.

While such stone bridges are a valuable property in the history of building techniques, they were appointed important cultural assets in Japan. In addition, along the River Nakajima, Nagasaki, there are many other stone bridges like Momotani, Oide, Amigasa, Furumachi, Ichiran, Susukihara, Higasishin and Fukuro bridges, which were rated as the important cultural properties by the City and have formed the sights of the city.

This Nakajima River, running through the center of Nagasaki City, was struck by the aforementioned local downpour and the flooding occurred which submerged the road surfaces of these stone bridges. Dynamic water pressure generated by the fast flood flow (3.5 m/sec to 4.0 m/sec) took away the arch spandrels and upper railings of the Momotani, Megane and Fukuro bridges, but left the arch stones. Six other bridges were completely destroyed and only some of the bridge foundations were left.

Since these bridges provide the City's road network with arteries, they have been playing an important role in the city transportation, especially as escape ways for emergency or as access for the reconstruction works after a disaster.

The combined forces and moments working on the arch stones, caused by drag, lift, yawing moment, pitching moment and rolling moment were measured through an experimentation of the model stone arch bridge. As a result of calculation of the resistance of the stone arch bridge against flood flow, we confirmed that as far as the Fukuro bridge is concerned the arch stones were stable.

Collapse tests of the flood flow pressure on a stone arch bridge model of the same construction as the actual bridge were also carried out.[2]

2. EXPERIMENT ON STONE ARCH BRIDGE MODEL

2.1 Model Dimensions and Experimental Facilities

The experiment was carried out by putting a 1/38.5 scale model of the existing Fukuro bridge into the test water channel with the width of 40 cm and the slop of 1/94.14 to reproduce the flood condition. Fig.1 shows a beam instrument used for measuring the loads and Fig.2 shows the construction of the model stone arch.

Load magnitudes on each arch stone ②, ③ . . . . ⑫ were measured by detecting strains with a strain meter on load converters tied by piano wires of 0.5mm to the lift measurement points ①, ②, ③ and ④ and the drag measurement points ⑤, ⑥, ⑦, and ⑧. An alienating paper is inserted in 2mm gap between arch stones illustrated in Fig.1 in order to plug water flow to avoid hydraulic stress and to lower frictional coefficient between stones. The magnitudes and application points of resultant flow forces working on each

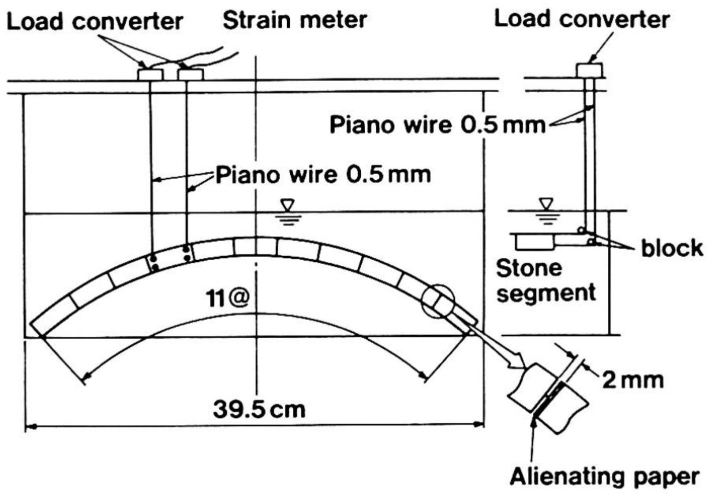

Fig. 1 Illustration of model experimental facilities

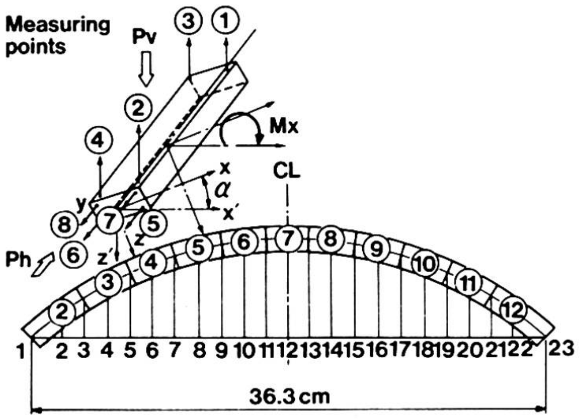

Fig. 2 Fukuro bridge model

arch stone were thus measured, and such external forces determining the limiting hydrodynamic fracture stress on the stone arch bridge as flow pressure, drag, lift (static water pressure + lift), horizontal pressure, yawing moment, rolling moment and pitching moment were computed from the measured values.

Table 1. shows the averge values Fm of the resultant forces measured about fifty times at the measuring points ①~⑧ for the eleven arch stones ② to ⑫ . In Table 2, the drag Ph(g), the lift + static water pressure Pv(g), the pitching moment Mx(g-cm), the drag coefficient Cd, the lift coefficient Cl and the static water pressure Ps(g), and the average flow velocity at 90cm of the upper stream U(cm/sec), are given as the values calculated by the three kinds of stresses and the three kinds of moments mentioned above. Although the actual measurement values in Table 1 and Table 2 were in fact not necessarily symmetrical, these were averaged for the convenience of the calculation.

Table 1. Values of Fm

Stone number \ Measuuring point	1	2	3	4	5	6	7	8
2	7.38	43.7	2.4	7.0	4.98	6.06	3.97	6.17
3	9.03	33.4	3.0	15.8	8.50	3.22	6.02	7.76
4	16.27	24.7	7.5	16.2	5.53	4.12	7.17	7.05
5	15.21	16.3	11.5	13.0	5.80	3.85	7.57	5.34
6	8.29	9.4	5.3	12.1	3.71	3.84	6.12	6.69
7	7.21	15.7	6.4	12.9	4.15	4.50	2.44	4.35
7A	4.58	13.3	6.0	13.8	1.16	1.29	1.49	2.79
8	4.89	18.2	9.3	16.2	3.54	3.11	4.32	4.35
9	9.84	11.5	14.3	17.0	5.44	8.60	4.62	6.62
10	6.50	17.4	21.0	22.5	4.22	8.16	4.86	8.10
11	0.80	9.1	13.7	37.2	2.42	4.10	11.54	8.64
12	4.59	9.1	8.9	40.2	6.32	4.58	6.00	5.33

3. STABILITY OF STONE ARCH BRIDGES AGAINST FLOOD FLOW

3.1 Experimental Results and Structural Analysis

A three-dimensional construction illustrated in Fig.2 was analyzed by F.E.M. using the measurement values of the drag Ph(g), the lift + static water

Table 2. P_h, P_v and other parameters (symmetrically rearranged)

Stone number	Ph (g)	Pv (g)	Mx (g-cm)	Cd	Cl	Static water pressure (g)	U (cm/s)
2	21.7	61.6	180.6	1.14	2.01	214.2	85.8
3	26.1	61.0	160.4	1.21	1.15	166.9	90.9
4	24.6	66.0	69.2	1.12	0.59	124.4	87.7
5	23.9	54.4	16.4	0.73	0.23	88.6	106.5
6	17.8	41.9	62.8	0.51	0.16	66.4	111.1
7	11.0	40.0	76.6	0.25	0.13	61.0	111.7

pressure Pv(g) and the pitching moment Mx (g-cm).

Elastic coefficients of the arch stones used for the model arch bridge were measured as follows:

$E=5.76\times10^4$ kg/cm^2, Poisson's ratio $\nu=0.18$, $G=2.43\times10^4$ kg/cm^2.

The weight of each stone segment was 2.23 g/cm^3 and the underwater coefficient of friction between the arch stones was 0.67. Through the structural analysis it was observed that the axial force Fx(g), the shearing stress Fz(g) and the flexural moment My(g-cm) due to the in-plane arch action, and the shearing stress Fy(g), the torque T(g-cm) and the flexural moment Mz(g-cm) due to the out-of-plane arch action, occurred as indicated in Table 3.

Table 3. Three-dimensional stresses and moments on arch bridge

Number of panel point	Axial load Fx (g)	Shearing stress (out-of-plane) Fy (g)	Shearing stress (in-plane) Fz (g)	Torque T (g-cm)	Flexure in-plane My (g-cm)	Flexure out-of-plane Mz (g-cm)
1	-897.3	119.7	4.2	-163.7	-102.7	-218.2
3	-832.8	98.0	40.5	-25.4	-130.3	115.1
5	-778.1	71.9	50.3	74.0	-54.1	366.7
7	-735.2	47.3	37.6	73.2	23.1	564.4
9	-710.2	23.4	27.4	7.9	61.2	686.4
11	-699.3	5.5	23.5	-16.4	76.7	728.4
13	-699.4	-5.5	18.3	-27.0	76.7	728.4

3.2 Calculation of Stability of Stone Arch Bridges against Hydrodynamic Pressures

Bridge stability against shearing stress τ_1 generated by torque τ_2 due to the in-plane arch action and the shearing stress τ_3 due to the out-of-plane arch action, can be maintained by frictional stress due to the arch thrust. The allowable shearing stress due to the friction is denoted by τ_a. When the resultant stress of τ_1, τ_2, and τ_3 becomes larger than τ_a the stability of sealing material between arch stones is lost so that they may start rotating or slipping, and finally the bridge will collapse. Fig.3 shows the calculated results, proving that the stability was maintained in the model arch.

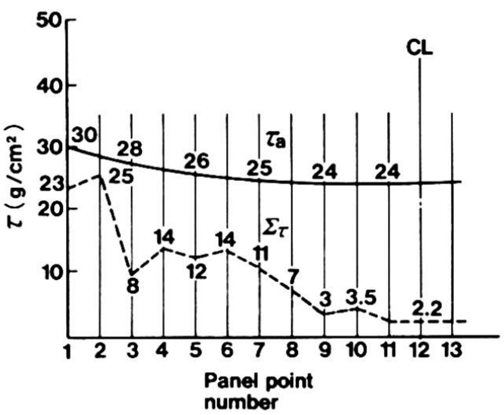

Fig. 3 Results of stability calculation with experimental values

4. COLLAPSE TEST OF MODEL STONE ARCH BRIDGE

For the collapse test under flood flow a model stone arch bridge using the same number of stones as the existing bridge and scaled down to 1/38.5, was installed in the experimental water channel with the 1/94.14 flow slope. The process of collapse was filmed on a video camera.

The road surface and spandrel of the arch bridge were washed away soon after the bridge was submerged, but the arch stones did not collapse. However, after being flooded for a long time, the seal started gradually to slip out and the arch stones to move. Finally, the sealant gap became larger and then the bridge collapsed. The details are shown in Photos 1-3.

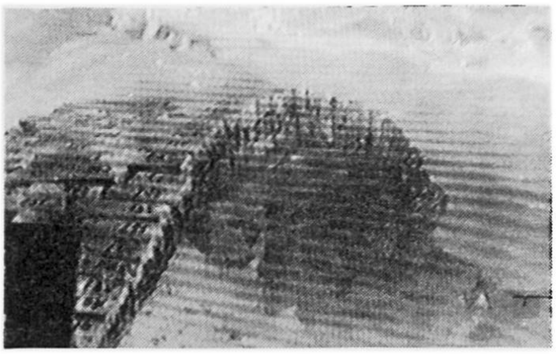

Photo 1 Collase of arch stones

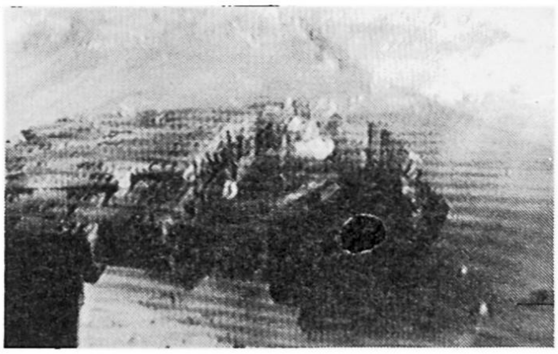

Photo 2 Collase of arch stones

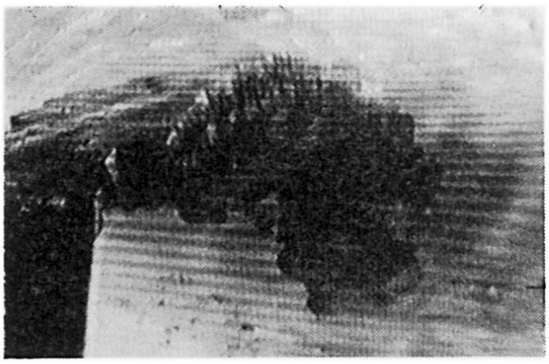

Photo 3 Collase of arch stones

Then, providing with an adhesive between arch stone segments, and making a continuous structure the arch stones may not collapse, and these stone arch bridge as the cultural properties will be able to be preserved against flood pressure.

The Fukuro bridge, only using an epoxy adhesive at the joint of the stones of arch spandrel and of pavemant of the road surface, could maintain the stability of the stone arch bridge against flood pressure. Photos. 4 and 5 show the appearance of Fukuro bridge.

5. CONCLUSIONS

The following conclusions were obtained.

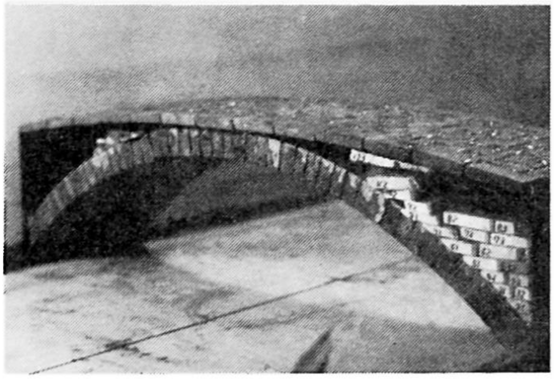

Photo 4 Collapse of arch spandrel of downstream side.

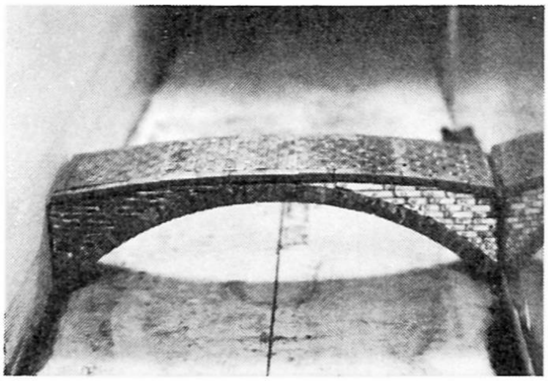

Photo 5 Non collapse of arch spandrel

(1) The experimental flow volume was calculated to be 216 m^3/sec for the actual bridge and this corresponds to 68 % of the flow of 320 m^3/ sec estimated for the flood.
(2) In the test, to measure the resultant hydrodynamic forces acting on the arch stones by putting a model stone arch bridge in a reproduced flood flow, a substantial amount of standard deviation was recorded due to the jet stream and due to the existence of cavitation down-stream from the arch stones.
(3) Due to the hydrodynamic forces mentioned above, when the shearing stress caused by torque due to the out-of-plane arch action, the shearing stress due to the in-plane arch action and the shearing stress due to the out-of-plane arch action, exceed the frictional resistance produced by the axial torque of the arch sealing, the sealing between the arch stones will lose the stability, so that they start rotating or slipping and finally the collapse will take place. In the experiment, however, such a collapse did not occur and the arch stones stayed safe.
(4) The arch spandrel of the model stone arch bridge using the same number of stones as the actual bridge was immediately carried away in the collapse test, though the arch stones were not destroyed. However, when left in the flow for a long time, the sealant slipped away, the stone segments also dropped off and the bridge collapsed.
(5) By providing with an adhesive at the joint of the arch stone segments, stone arch bridges will be preserved against flood flow.

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