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Remaining Structural Capacity of Brick-built Piers and Abutments

Capacité portante résiduelle des piles et des culées en maçonnerie

Resttragfähigkeit von Pfeilern und Widerlagern aus dauerhaftem Mauerwerk

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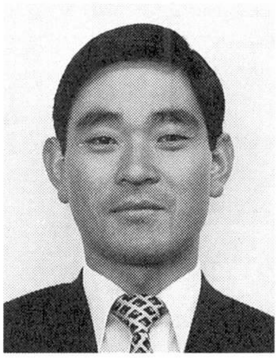

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SUMMARY

The strength of brick piers and abutments of bridges depends on the strength of joints rather than the strength of the bricks themselves. Attention was focused on elastic waves, particularly impulsive waves, as the strength of joints can probably be estimated by measuring the velocity of elastic waves propagating through brick structures. As a result of experiments, a relationship between the velocity of elastic waves propagating through brick structures and the flexural-tensile strength of joints has been derived, allowing a method for evaluating the safety of brick structures under substantial lateral seismic loads to be established. Finally the residual strength of several bridges under the loads of probable major earthquakes was evaluated.

RÉSUMÉ

La résistance des piles et des culées de ponts construites en maçonnerie dépend davantage de celle des joints que de celle des pierres elles-mêmes. Les vérifications se sont concentrées sur les mesures de la vitesse de propagation des ondes élastiques sous excitation par impulsions, en vue de déterminer l'état des joints. A partir d'échantillons de maçonnerie prélevés sur les piles de pont, il a été possible d'établir une corrélation entre la vitesse de propagation des ondes et la résistance à la flexion et à la traction des joints. Une méthode d'évaluation de la sécurité de la maçonnerie sous efforts transversaux dus aux tremblements de terre a pu être mise au point et appliquée à de nombreux ponts.

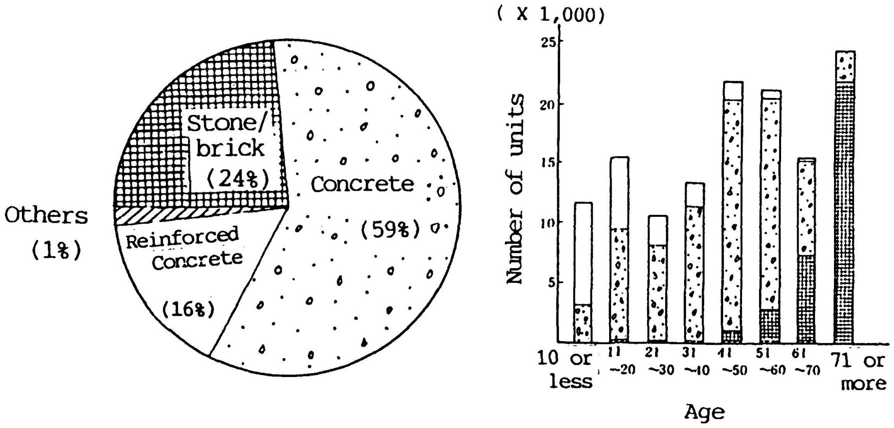
ZUSAMMENFASSUNG

Die Festigkeit von Mauerwerkspfeilern und -widerlagern hängt eher von der Festigkeit der Fugen als der Steine selbst ab. Die Untersuchungen konzentrierten sich deshalb auf die Messungen der Fortpflanzungsgeschwindigkeit elastischer Wellen unter Impulsanregung, um so den Zustand der Fugen zu ermitteln. Anhand von Mauerwerksproben aus Brückenpfeilern konnte eine Beziehung zwischen der Wellengeschwindigkeit und der Biegezugfestigkeit der Fugen hergeleitet werden. Damit konnte eine Methode zur Beurteilung der Sicherheit von Mauerwerk unter hoher Erdbebenquerbelastung entwickelt und auf mehrere Brücken angewendet werden.

1. INTRODUCTION

The number of piers and abutments on the JR lines has reached 132,000 (conventional lines), of which about 110,000 (83%) are made of brick or stone masonry units, or plain concrete [1]. The number of brick or stone masonry piersand abutments reaches about 32,000 (24%).

About 70% of these structures were built 40 or more years ago. Surprisingly, 90% of brick or stone masonry structures are 60 or more years old (see Fig. 1).



Materials Used

Age by Material

Fig. 1 State of Substructure(132,000 units)
(from Journal of Structurel Design Journal,No.9,February 1983)

Some of these old structures have already deteriorated because of years of use. Although they are being replaced with reinforced concrete structures, it takes huge amounts of cost and time to replace all of them. It is inevitable, therefore, to use the old structures until they are replaced.
Japan is one of the most seismically active countries in the world and has suffered many large earthquakes, which have resulted in substantial structural damages.

Recent damage-causing earthquakes include the Nankai Earthquake (M8.1, 1946), Fukui Earthquake (M7.3, 1948), Tokachi-oki Earthquake (M8.1, 1952), Boso-oki Earthquake (M7.5, 1953), Niigata Earthquake (M7.5, 1964), Tokachi-oki Earthquake (M7.9, 1968), Miyagiken-oki Earthquake (M7.4, 1978), Nihonkai Chubu Earthquake (M7.7, 1983), and Chibaken Toho-oki Earthquake (M6.2, 1987) [2].

Joints in brick piers and abutments are often in the deteriorated condition due to years of use. These deteriorated joints are vulnerable particularly to lateral loads like earthquake loads.

It is therefore important to evaluate the soundness, particularly earthquake resistance, of those old structures and take whatever necessary steps accordingly.

In this paper, data obtained from model experiments, which can be used in evaluating the earthquake resistance of brick piers and abutments, is reviewed. It is believed that the data will be found useful in maintaining those old structures.

2. FACT-FINDING SURVEY

2.1 Strengths of Brick Structures [3]

Block samples were taken from an old pier(built in 1889), and the shear strength of the samples was measured. Photo 1 shows a similar brick pier.

2.1.1 Shear Strength

Specimens used in the loading test are cubes measuring about 80cm x 80cm x 80cm, and their surfaces have been chiseled. The loading test was conducted in the form of a double shear test, as shown in Fig. 2. To introduce a stress of 0.19 MPa, which corresponds to the dead load (6374 kN), bearing plates (to cover overall surfaces) were installed on both sides of the specimens, and six ϕ 16mm steel bars were used for tensioning. Shear failures occurred at two joint faces, but the failures at the two faces did not occur simultaneously. Thus the first shear failure and the next one are referred to as the first failure and the second failure, respectively. The results of the shear strength test are shown in Table 1.

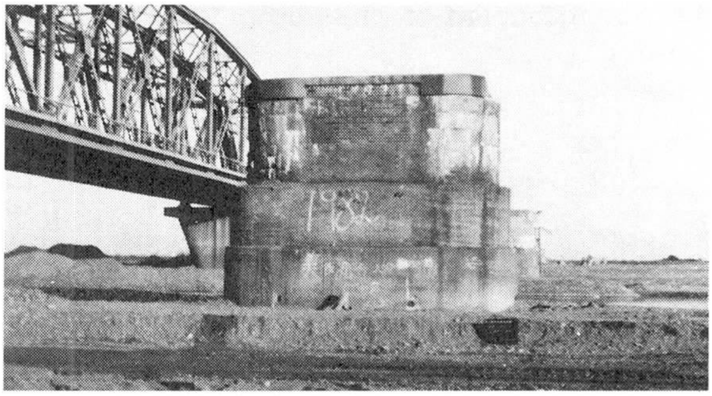


Photo 1 An Example of Brick Pier

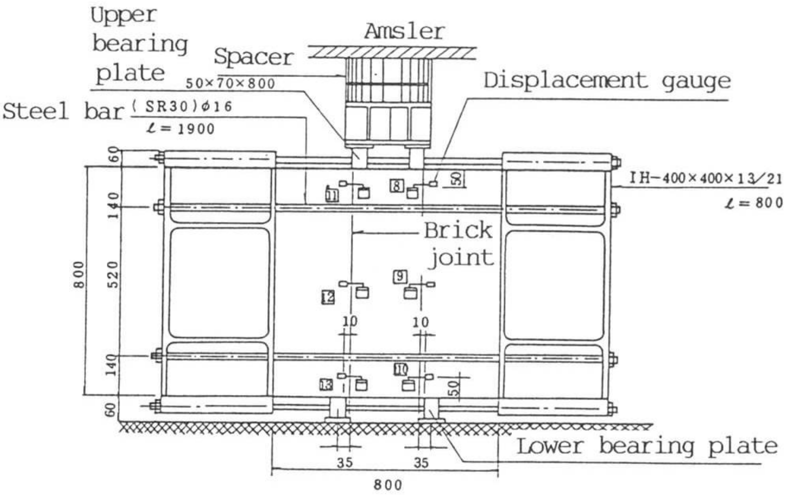


Fig. 2 Shear Test (unit: mm)

	Specimen 1		Specimen 2	
Stage of failure	First failure	Second failure	First failure	Second failure
Load 2P	1167 kN	1238 kN	1348 kN	1079 kN
Shear Stress	0.88 Mpa	0.93 Mpa	0.99 Mpa	0.86 Mpa

Table 1 Results of Shear Strength Test

2.2 Nondestructive Test Using Elastic Waves Propagating in Brick Structures

2.2.1 Configuration of the Setup for the Nondestructive Test

The strength of brick piers and abutments depends on the strength of joints rather than the strength of bricks, and there has been no method to estimate the strength of structures consisting of bricks.

As a tool for determining the compressive strength of concrete nondestructively, ultrasonic waves are in general use. The currently used ultrasonic wave methods, however, are hardly applicable to such partly hollow, mortar-jointed structures as brick structures because of considerable attenuation of sound waves. Therefore, a method using elastic waves (which in this paper refer to waves caused by hammering, though they generally refer to waves propagating through elastic bodies) with high levels of propagated energy caused by hammering was employed [4].

The configuration of the setup for elastic wave measurement is illustrated in Fig.3.

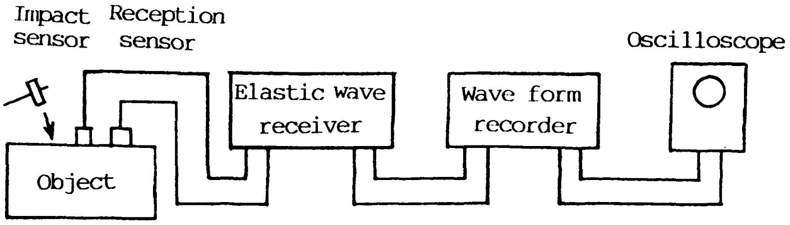
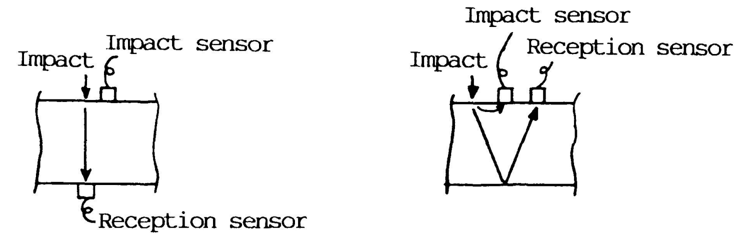


Fig. 3 Standard Configuration of Elastic Wave Measurement System [4]

Two sensors were used for the detection of elastic waves: an impact sensor and a reception sensor. The impact sensor detects surface vibration and converts it into signals representing the occurrence of waves. The reception sensor detects waves propagated through an elastic body. In the test, the signal for the initiation of waves and an elastic wave signal were chosen at the elastic wave receiver and stored in the wave form recorder. The recorded wave forms were then displayed on the oscilloscope.

2.2.2 Method for Measurement of Elastic Waves

The concepts of two standard methods for measuring elastic waves are shown in Fig. 4. Usually the transmission method is used to measure the velocity of elastic waves transmitted through media, and the reflection method is used to determine the locations and sizes of discontinuities in horizontal joints. Often these methods are used in combination.



Transmission Method

Reflection Method

Fig. 4 Standard Measuring Method [4]

2.3 Nondestructive and Destructive Tests on Brick Specimens [5]

2.3.1 Relationship between Elastic Wave Velocity and Flexural-Tensile Strength

As shown in Fig. 5, specimens were taken from a pier of a bridge on a railway line that went out of operation, and were dressed manually. Using these specimens, a nondestructive test as shown in Fig. 6 and a flexural failure test as shown in Fig. 7 were conducted.

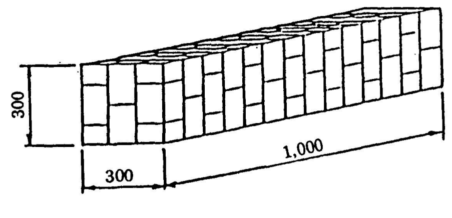
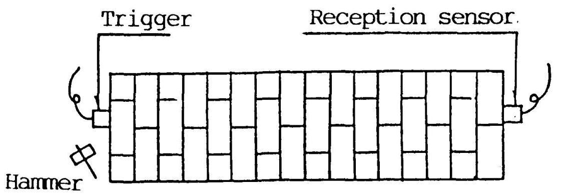


Fig. 5 Dimensions of Brick Specimen (unit: mm)



In measuring reflected waves, the trigger and the reception sensor are positioned at the corresponding points on the opposite faces.

Fig. 6 Nondestructive Test

Fig. 8 is a plot of the results of the tests, with the axis of ordinates measuring the flexural-tensile strength and the axis of abscissas the elastic wave velocity (where the dotted line represents a multiple regression formula). As a practical formula for the relationship between the elastic wave velocity and the flexural-tensile strength based on engineering judgments, the following equation is proposed:

$$\sigma_{ctu} = 2.65 \times 10^{-4}\ V \qquad (1)$$

where

σ_{ctu} :flexural-tensile strength(MPa)

V :velocity of elastic wave(m/sec)

2.3.2 Estimation of Residual Strength and the Locations of Defective Regions [4]

When the velocity of elastic waves in an actual pier or abutment is to be measured, transmission velocities are measured at multiple points as shown in Fig. 9 (a), and the average value of measurements is taken as the transmission velocity for the structure. Then, the flexural-tensile strength σ_{ctu} is calculated using Eq. (1).

The locations of defective regions can be determined by use of a time-distance curve as shown in Fig. 9(b). A time-distance curve shows the time elastic waves require to travel a certain distance. Since the gradient of the time-distance curve represents velocity, a greater gradient of the curve means a lower velocity. The lower velocity shown by the steep gradient in the section b-d in Fig. 9(b) suggests the possibility of disconnected joints.

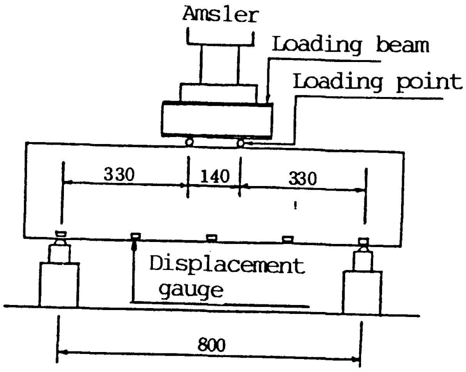


Fig. 7 Loading Device and Loading Points (unit: mm)

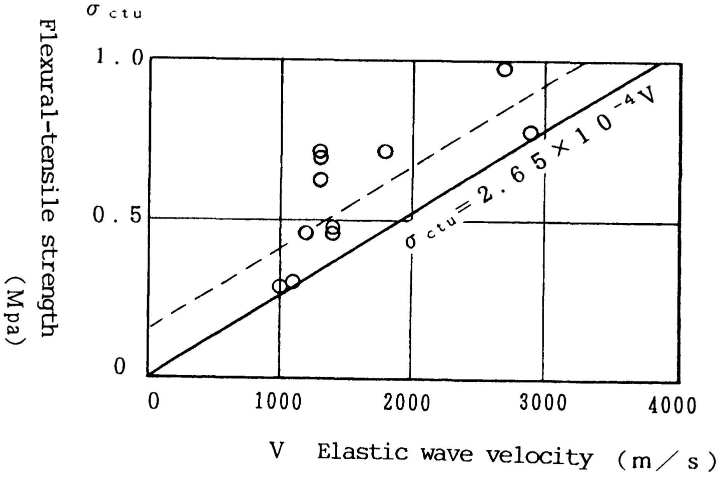
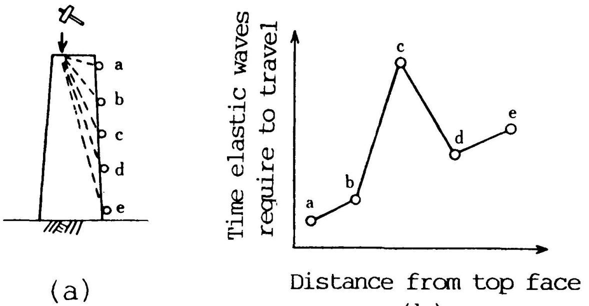


Fig. 8 Relationship between Elastic Wave Velocity and Flexural-Tensile Strength



(a) (b)

Fig. 9 Time-Distance Curve

2.3.3 Estimation of the Embedment Depth of Existing Structures

It is not unusual that design drawings of aged structures such as brick piers and abutments have been lost during the wars or for some other reasons. In such cases it is necessary to determine the embedment depth in order to evaluate the soundness of particular structures.

The embedment depth of a particular structure can be determined by estimating the velocity of elastic waves transmitted through the structure and finding bottom reflection from reflected waves [4]. Photo 2 and Photo 3 show examples of transmitted wave forms and reflected wave forms, respectively.

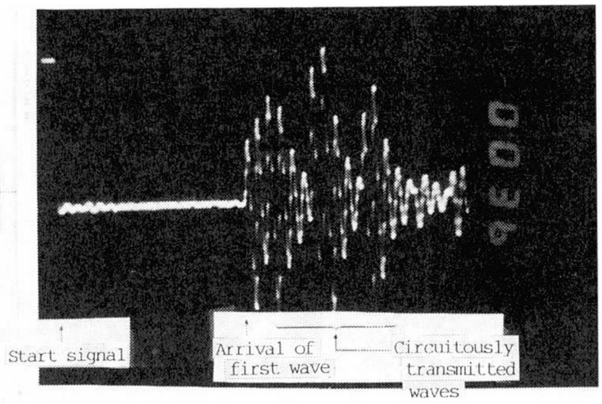


Photo 2 Transmitted Wave Forms

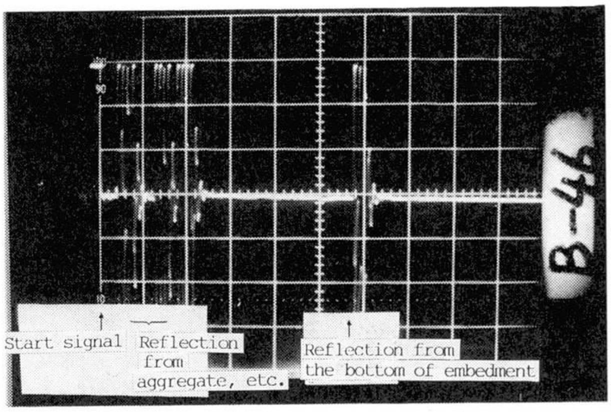


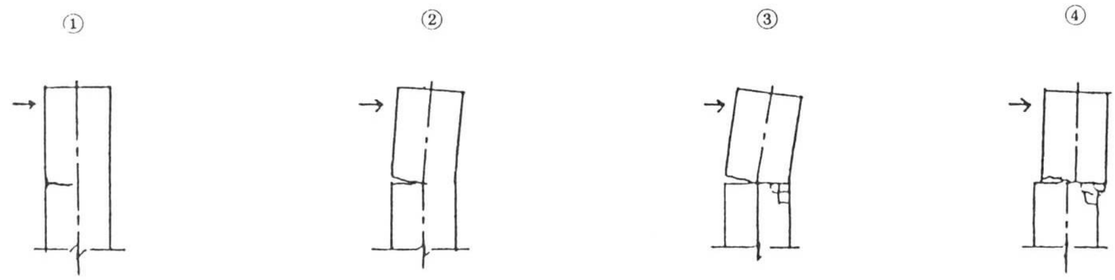
Photo 3 Reflected Wave Forms

3. JUDGMENT OF SOUNDNESS (MAINLY EARTHQUAKE RESISTANCE)

3.1 Failure Due to Lateral Seismic Loads or Other Lateral Loads

From data on brick piers damaged by earthquakes and the results of loading tests on abandoned brick piers, the failure process has been estimated as follows:

First, disconnection between joint mortar and bricks occurs where bond is weakest, resulting in decreases in the area of joint face (bonding surface). Thus, shear stresses acting on the joint face increases rapidly, causing slip along the horizontal plane. This failure process is illustrated in Fig. 10 [5].



A crack occurs under flexural-tensile stress.

The crack grows.

A crack occurs under flexural-compressive stress.

Shear failure occurs.

Fig.10 Failure Process [5]

3.2 Earthquake Resistance

If the flexural-tensile strength of a joint can be calculated using Eq. (1), earthquake resistance, that is, whether the joint is disconnected or not can be judged from such factors as bedrock acceleration, the type of ground, the natural period of a particular structure, and the acceleration magnification factor.

4. AN EXAMPLE EVALUATING THE EARTHQUAKE RESISTANCE OF AN ACTUAL PIER

4.1 Pier

The earthquake resistance of several piers has been evaluated. In this section, a pier (8P) of the former Fuji River Bridge on the Tokaido Line is considered.

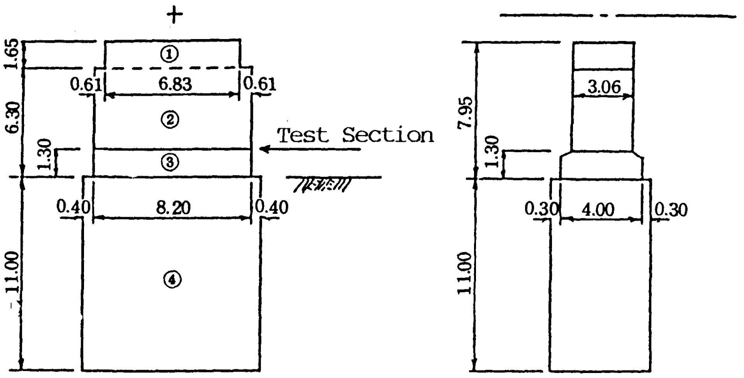


Fig.11 Fuji River Bridge on the Tokaido Line
(out-of-use brick pier, 8P; unit:m)
Superstructure:Theodore truss W=1433KN

4.2 Results of Earthquake Resistance Evaluation

Tables 2 and 3 show the results of the earthquake resistance evaluation. The shear strength used here is as per ACI's shear friction theory, and $\mu=1.0$ is assumed.

Bridge name	Ground surface acceleration α(gal)	Natural period (sec)	Response acceleration at structure's center of gravity $\beta\alpha$(gal)	Response acceleration at center of gravity in test section $\beta'\ \alpha$(gal)	Equivalent seismic intensity $K=\beta'\ \alpha/g$	Average elastic wave velocity (m/s)
Former Fuji River bridge	221	0.3	508	566	0.578	2500

Table 2 Evaluation Data

Bridge name	Bending stress (Mpa)			Shear stress (Mpa)		
	Occurrence	Tolerance	Judgment	Occurrence	Tolerance	Judgment
Former Fuji River bridge	-0.69	-0.66	×	0.10	0.18	○

Table 3 Calculated Stresses

5. CONCLUSION

Findings from this study can be summarized as follows:

(1) A method for estimating the flexural-tensile strength of joints in brick structures like piers has been developed on the basis of the results of a nondestructive test using impulsive elastic waves.
(2) The embedment depths of existing structures can be estimated by use of the transmission method and the reflection method using impulsive elastic waves.
(3) The earthquake resistance of brick structures like bridge piers can be evaluated by the combined use of (1) and (2) above.

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