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Model Test for Design of Long Span Bridge Foundation

Essai sur modèle des fondations de ponts de grande portée

Modellversuch für die Bemessung von Fundamenten weitgespannter Brücken

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1. Introduction

As the span of bridge is increasing with the progress of technology, its foundation trends to become larger. Especially in the case of long spanned bridges which is constructed on alluvium ground, large multi-cell box caissons are often adopted as their foundation. But the design method for such a large caisson has not been established so far and it used to be designed with excessive safety.

This paper describes the results of study projected to deal with this kind of problem which occurred on the way of designing the caisson foundation of HAMANA-OHHASHI Bridge.

2. Caisson of HAMANA-OHHASHI Bridge

HAMANA-OHHASHI Br. is a prestressed concrete girder bridge with four lanes on two seperate girders. It has five spans and its full length is 631.8 m. Its center span is formed by 120m + 120m cantilevers and as a concrete girder bridge it will be the longest span in the world.

The foundation of the main pier which supports this superstructure is based on alluvium ground. On this foundation 27,000 ton of vertical load always acts and during the earthquake considered in design, moreover 181,000 ton-m of longitudinal moment load caused by horizontal force along to bridge axis, or 188,000 ton-m of transverse moment load caused by transverse force, acts. Therefore, a big reinforced concrete caisson with cells as is shown in Fig. 1 was planned for the foundation of the bridge.

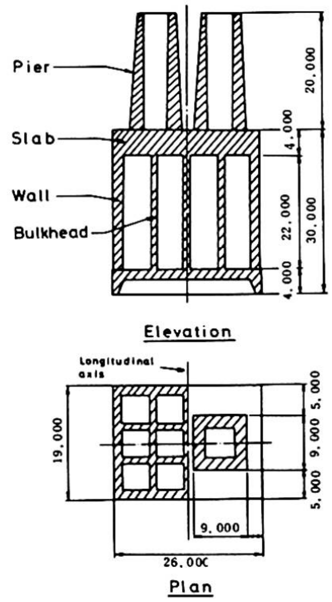


Fig. 1 Caisson of HAMANA-OHHASHI Bridge

However, neither the necessary and sufficient amount of reinforcing steel bar in the top slab or bulkheads could be estimated nor the sufficiency in thickness of the bulkheads could be confirmed. This is because the behavior of slab, the bearing stress in bulkheads, the stress concentration near the corner, the state how the load which is carried through the piers on the slab spreads in the caisson, were not clear.

To solve these problems and to design the caisson rationally, two kinds of model tests were performed. Their results were applied into an actual design.

In this study, furthermore, analytical methods which will be easily applied in designing such a kind of structures were examined.

3. Model Tests

Strictly speaking, tests must be performed on the models which behave nonlinearly, considering that caisson is made of reinforced concrete. But actually this is so difficult that stress was obtained through elastic tests and caisson was designed according to allowable stress method.

Experimental tests are composed of loading test on an acrylic model and three-dimensional photo-elasticity test. Scale factors of these models are 1/50, 3/400 respectively.

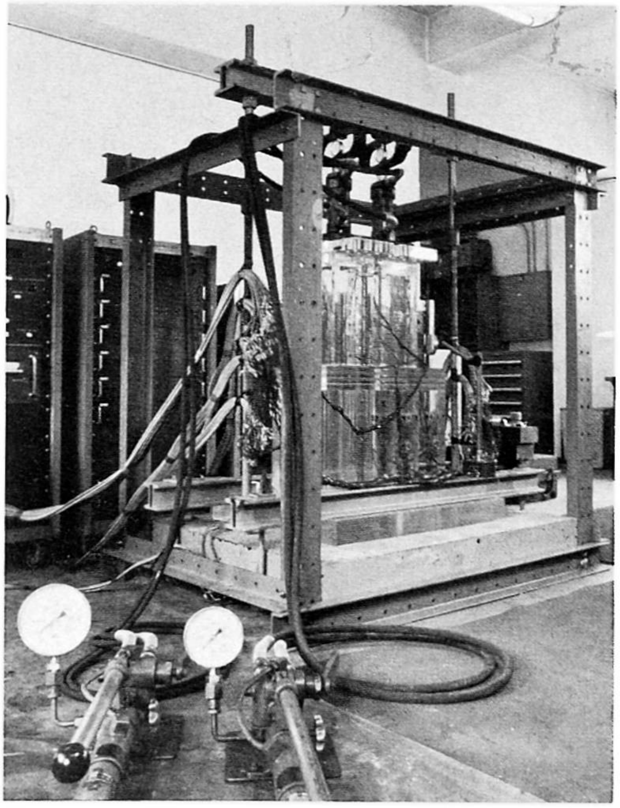


Photo. 1 View of Acrylic Model Test

1) Loading Test on an Acrylic Model

The material of model is acrylic resin, not only because it can be processed without difficulty but also it has low Young's modulus ($E=29,000$ kg/cm^2) which leads to larger strain with small loads. This model was made by assembling acrylic plates which were installed with strain-gages. Most of them were affixed to 1/4 part of the model, considering the symmetry of the caisson.

Loads were vertical load, longitudinal moment load and transverse moment load. They were controlled by hydraulic jacks or loading rods, and made to act step by step to confirm that the stress or strain is within the elastic region. Photo. 1 shows the view of experiment.

The strains detected by strain-gages were immediately digitalized into a paper tape and stresses were calculated by the computer off-line.

2) Three-dimensional Photo-elasticity Test

By the acrylic model test the strains or stresses at discrete points on the surface can be obtained, but those at other parts or inside the caisson are unknown yet. This photo-elasticity test was made to treat these problems. In other words this test was performed in order to know the stress flow, the stress distribution inside the slab, stress concentration near the corner and to fill up the stress between those obtained by the acrylic model test.

The model was vertically loaded at 130 °C in the hearth and gradually cooled. Stress was obtained by examining the thin slices which were cut out of the model.

4. Experimental Results and Considerations

The stresses under the loading condition considered in design were calculated from the experimental results by applying the law of superposition and the law of similarity. Concerning these model tests, the law of similarity is written as the followings, for vertical load $\frac{\sigma_m L_m^2}{P_m} = \frac{\sigma_p L_p^2}{P_p}$, $\nu_m=\nu_p$

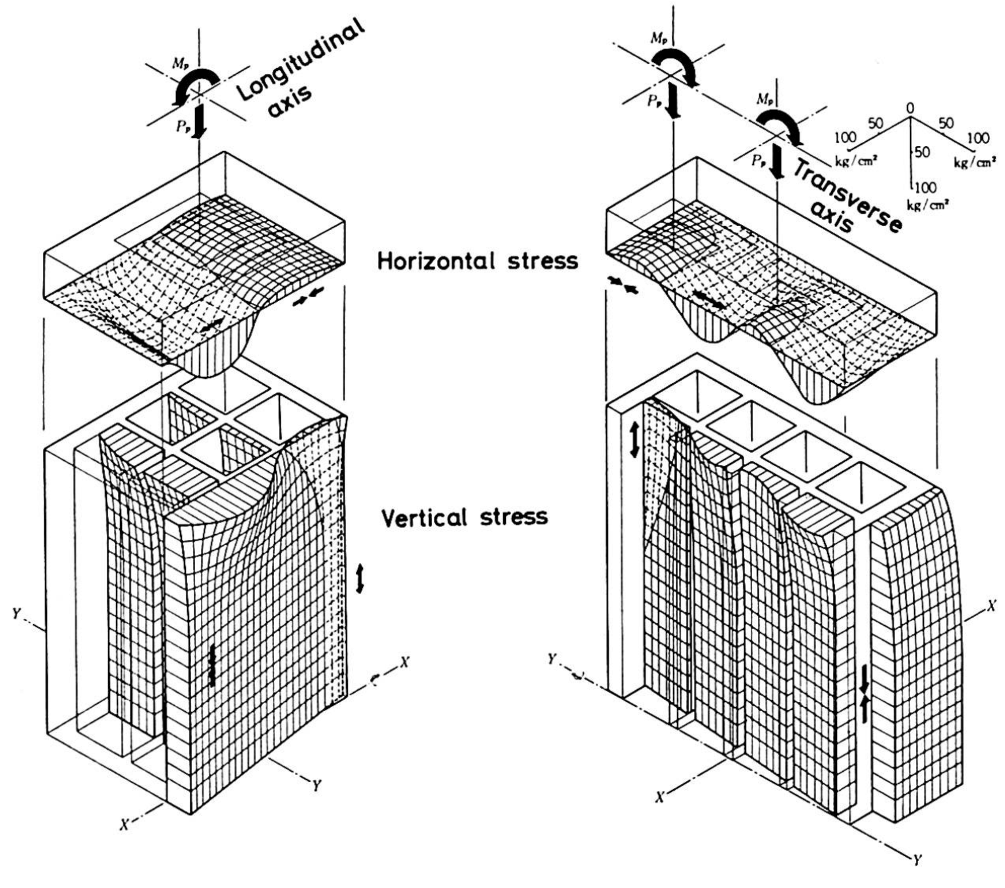
for moment load $\frac{\sigma_m L_m^3}{M_m} = \frac{\sigma_p L_p^3}{M_p}$, $\nu_m=\nu_p$

where σ, L, P, M, ν indicate stress, representative length, vertical load, moment load and Poisson's ratio respectively, subscripts m, p also indicate model and prototype respectively.

About Poisson's ratio ν, the law of similarity generally can't be satisfied in this kind of model tests. Because the Poisson's ratio of concrete ν_p=0.17, though that of acryl is ν_m=0.39 . But in this study the influence of Poisson's ratio could be made clear by the numerical analysis as is mentioned later.

Fig. 2-(a) shows the distribution of horizontal stress at the bottom of slab and that of vertical stress at bulkheads and walls during longitudinal earthquake. Fig. 2-(b) shows those during transverse earthquake.

From these figures it is considered that some portion of the load, which comes through two piers, is carried to walls by the bending of slab, but the remains are directly transferred to bulkheads beneath the piers and carried toward walls by the shear force of bulkheads. This horizontal movement of stress occurs above the level of 2/3 of the height of caisson. Under this level the stress distribution is similar to that of a cantilever beam where the caisson is regarded as a cantilever rigidly embedded. This means that bulkheads must be designed strongly enough to resist shear force as well as bearing stress and the top slab must resist the bending moment.



(a) Longitudinal Earthquake (b) Transverse Earthquake

Fig. 2 Stress Distribution During Earthquake

By the results of the three-dimensional photo-elasticity test, the stress distribution inside the slab was obtained as shown in Fig. 3. This figure indicates that the stress distribution inside the top slab is similar to what is acquired according to Bernoulli's hypothesis on the whole, though it has a little tendency as a deep beam. Therefore, it can be mentioned that the slab strongly has the property of a thin plate as far as the horozontal stress concerned.

Furthermore, Fig. 2 shows that the bulkheads located as a grid are not so stiff that the slab bends as one body. So it is more rational to design the slab as a plate on elastic supports i.e. bulkheads, rather than to design seperately its each section, four sides of which are rigidly supported by the bulkheads or the walls of caisson.

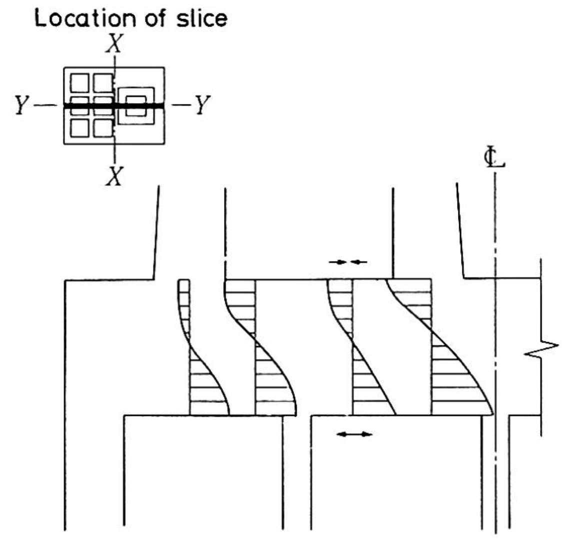


Fig. 3 Stress Distribution inside the Slab under Vertical Load

The caisson of HAMANA-OHHASHI Br. was mainly designed to resist these stress distribution. And the corner between the pier and the slab was reinforced to resist the stress concentration that was made clear by the photo-elasticity test.

5. Numerical Analysis

The caisson of HAMANA-OHHASHI Br. was designed as mentioned above, in this study, numerical analyses were also conducted in order to find out a convenient analytical method that can be easily applied to the design of such a kind of structures.

If three-dimensional finite element method (i.e. F.E.M.) were able to be easily applied to solve these problems, it would be helpful for establishing reasonable design method. But, in general, three-dimensional F.E.M. analysis requires a great amount of computation, therefore, it cannot be considered convenient.

In this study, more convenient F.E.M. was applied to solve these problems, considering the behavior of each member of the caisson. It is the F.E.M. programmed to analyze shell structures which are fabricated with thin plates. In this analytical method, the wall of pier was divided into two plates located at the inner and outer surfaces of the wall in order to take the thickness of the wall of pier into the consideration.

The direct object of this analysis is the acrylic model used in the loading test, and Poisson's ratio $\nu=0.39$. The numerically analyzed stress distribution at the bottom of slab is shown by solid lines in Fig. 4, compared with experimental results which are shown by —o discretely, where the load is vertical.

It is easily pointed out from this figure that analytical result shows good agreement with the experimental one. This shows not only the propriety of this analytical method, but also the high precision of the experiments. Also in the case of moment load, the results of analytical study and experimental one are sufficiently coincide , though they are not shown in this paper. Hereafter this analytical method, which is often used to solve the problem of shell structure, can be successfully applied to this kind of structures.

Through numerical analysis the influence of the difference of Poisson's ratio was investigated, which cannot be examined by model tests. The dotted lines in Fig. 4 show the computed stress distribution when Poisson's ratio

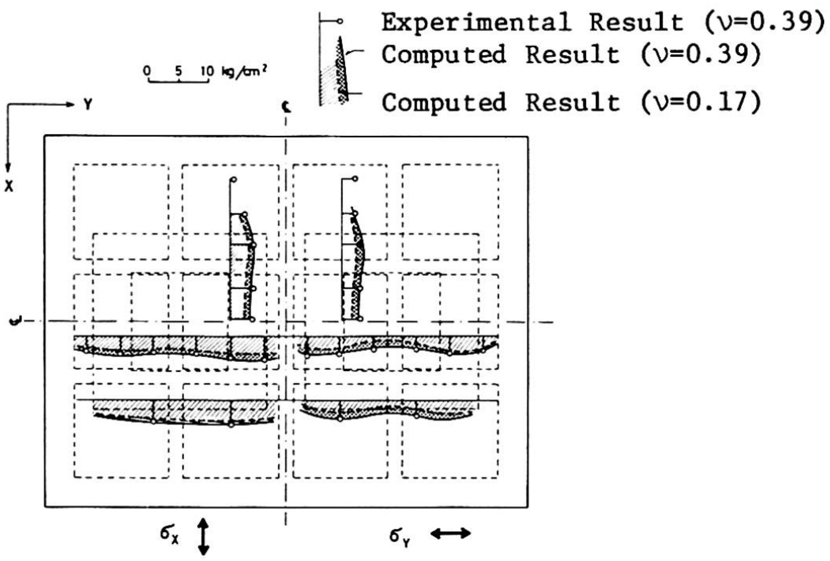


Fig. 4 Stress Distribution at the Bottom of Slab under Vertical Load of 1,000 ton

is equal to that of concrete (=0.17). This figure shows that the bending stress of the slab decreases 20% on the average while Poisson's ratio decreases from 0.39 to 0.17 . The reason is thought that when Poisson's ratio decreases, the resisting force against shearing deformation in the bulkheads increases because of the increase in the shearing modulus $G=E/2(1+\nu)$, consequently the portion of load which the slab must carry to the walls decreases. Concerning the vertical bearing stress at the upper part of the bulkheads, it must increase when Poisson's ratio decreases. The difference, however, is little and able to be ignored. Because the bearing stress for $\nu=0.39$ is so large in itself that its increase at $\nu=0.17$ is relatively small. Therefore it may be concluded that in this type of caisson the bending stress in the top slab is considerably influenced, while the stress in bulkheads is influenced very little by the difference of Poisson's ratio.

Through the numerical analysis, it was also found that horizontal compression occurs in the lower part of pier and horizontal tension but not so strong occurs in the upper part of bulkheads in the case of vertical load. This shows that the piers and bulkheads act as stiffening ribs in regard to the bending of slab.

6. Conclusion

As mentioned above, this study was planned to solve the problems which occurred in designing the multi-cell box caisson of the HAMANA-OHHASHI Br. and two kinds of model tests and numerical analysis were performed to know the behavior of this caisson. The results of this study are summerized as the followings.

1) Though the top slab of caisson is very thick, it behaves as a thin plate and the stress distribution inside the slab yields to Bernoulli's hypothesis.
2) The load, which comes through the piers, is carried toward walls by the bending of top slab on the one side and also carried by the shear of the bulkheads on the other side.
3) Finite element method for shell structures was found to be conveniently applicable to this kind of structures. However, the thickness of the wall of pier must be considered in the analytical model as mentioned previously.

4) The decrease of Poisson's ratio results in the decrease in the bending stress of the slab. But the increase in the bearing stress of the bulkheads is little. These changes also mean that the shearing deformation in the bulkheads, upon which the Poisson's ratio has influence, contributes the distribution of load.

These results were applied to the design of HAMANA-OHHASHI Bridge. But, in order to design this type of caisson more rationally, the problem of optimum design and the problem of non-linear behavior should be investigated in future.

Finally the authors appreciate the contribution of Mr. C.Mimura, Mr. T. Fujita and Dr. Y.Morimitsu of Kajima Institute of Construction Technology.

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SUMMARY

In order to design multi-cell box caisson of HAMANA-OHHASHI Bridge, which is made of reinforced concrete, two kinds of model tests were performed. One is a loading test on an acrylic model and the other is a three-dimensional photo-elasticity test. Through these investigations the behaviour of the caisson was made clear. Furthermore, a finite element method which is conveniently applicable to this kind of structures, was proposed.

RESUME

Pour dimensionner les caissons multicellulaires en béton armé des fondations du pont, HAMANA-OHHASHI, nous avons fait deux essais: un modèle en acryl, et un essai de photo-élasticité. Ces recherches ont permis de déterminer le comportement du caisson. Nous avons enfin proposé une méthode des éléments finis applicables à ce genre de structures.

ZUSAMMENFASSUNG

Für die Bemessung der vielzelligen Senkkästen der HAMANA-OHHASHI Brücke wurden zwei Modellversuche durchgeführt. Der erste war ein Belastungsversuch an einem Acryl-Modell und der andere ein dreidimensionaler spannungoptischer Versuch. Durch diese Untersuchungen wurde das Tragverhalten der Senkkästen geklärt. Vorgeschlagen wird weiter eine Methode auf der Basis Finiter Elemente, welche auf derartige Tragwerke leicht anwendbar ist.