STUDIES ON THE EARTHQUAKE RESISTANT DESIGN OF SUSPENSION BRIDGE TOWER AND PIER SYSTEMS

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Synopsis Further to previous studies(1)(2), dynamic properties and earthquake resistant design of the tower and pier systems of suspension bridges are investigated by theoretical and experimental means in this paper. Especially, the effects of foundation stiffness of the systems to the dynamic properties are discussed, and the importance of coupled vibrations between the tower and the pier on the earthquake resistant design of long span suspension bridges is emphasized.

INTRODUCTION

Methods of analysis of earthquake response of long span suspension bridges were proposed at the previous papers.(1)(2) In these reports, the suspension bridges were simplified to physically analogous systems with finite degrees of freedom, and the fundamental characteristics of the earthquake responses of the suspension bridges were investigated.

Earthquakes act on suspension bridges through two pier bases, and two anchorages. These points, then, are subjected to quite complicated dynamic effects of the earthquakes. For long span suspension bridges, moreover, the combination of deep piers, large anchorages, tall towers, long cables, and large suspended structures, of various rigidities, results in unusual problems in the calculation of earthquake responses.

According to previous studies(1)(2), however, coupling motions between the towers and the cable and suspended structures are not significant for the vibration modes where the displacements of the tower and the pier are predominant. The analysis in which the influences of the cables and suspended structures are replaced by the proper spring stiffness at the top of the tower is approximately possible for earthquake resistant design of the tower and pier systems.

The studies on the pier and tower systems subjected to earthquakes are the most importance for earthquake resistant design of the suspension bridges.

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Dynamic characteristics of the system, the tower and pier system, eminently depend on the dimensions of the pier and the resisting properties of foundation. In this paper, the effects of these factors on earthquake resistant design of long span suspension bridges are discussed by analytical and experimental means.

According to the results given one of the previous papers(3), the maximum responses of the system due to earthquake ground motions remarkably depend on the rotation of the pier, and therefore, the width of the pier and the foundation conditions are important parameters for earthquake resistant design of the considering system.

Effects of the dimentions of the pier are roughly discussed in the previous paper(3), but the dimensions of the pier affect both the inertia and stiffness properties of the system, and the investigations of the results are rather complicated. In the analysis given in this paper, therefore, the investigations are mainly restricted to the effects of foundation conditions which affects only stiffness properties of the system. Same kinds of discussions are also applicable to the effects of the pier dimensions, and these are quite important for the design practice of the systems.

VARIATION OF NATURAL FREQUENCIES AND MODES DUE TO FOUNDATION CONDITIONS

The system to be analysed in this paper is as shown in Fig. 1, and the method of analysis of this system was given in the previous paper(3). The prototype system discussed in this paper has the following dimensions and is shown in Fig. 2.

Main span length of the bridge	1 300 m
Height of towers	200 m
Weight of two towers	30 000 ton
Horizontal component of cable tension due to dead load	19 560 ton/cable
Height of piers	100 m
Width of the piers perpendicular to bridge axis	60 m
Widtn of the pier along bridge axis	45 m

Different values of the width of pier along bridge axis also used in the experimental studies in this paper.

Natural frequencies of the system varies with the foundation conditions, i.e., the elastic constant of the rock foundation and surrounding soil of the pier. Fig. 3 shows the variation of the natural frequencies of the system due to the variation of foundation constant. In Fig. 3, the natural frequencies of the pier alone without tower are given by the dotted line, and the natural frequencies of the tower rigidly supported at its base are shown by chain lines. The natural frequencies of the pier are linearly increasing function with respect to the square root the foundation constant K, horizontal axis of Fig. 3, and the natural frequencies of the tower, the chain lines, are independent with foundation constant.

The natural frequencies of the system are given by bold lines in Fig. 3, and these lines are closely related with the dotted and chain lines. For specific foundation stiffness the natural frequencies of two vibration modes are close with each other while for other regions all vibration frequencies are well separated. No repeated roots, however, are obtained. In this paper, the former regions are denoted as correlated mode regions and the later are, the separated mode regions.

Fig. 4 shows natural modes of the system for different foundation conditions. For the separated mode regions, only a single mode of vibration has predominant amplitudes of the pier and is accompanied by the deflections with small amplitudes of the tower. For the correlated mode regions, however two modes of vibration have predominant amplitudes of the pier, and these modes are accompanied by large tower deflections. The phases between the tower and the pier are inversed for these two modes. As it will be shown in the later investigations, dynamic responses for such systems are relativel complicated, and ordinary methods of analysis, such as root mean square method, may not directly applied to such cases.

DYNAMIC RESPONSES OF THE SYSTEM

The variations of natural frequencies and modes discussed in the previous section affect the dynamic responses of the system. Three specific foundation conditions, $K = 1.0 \times 10^4$ ton/m^3, $K = 5.0 \times 10^4$ ton/m^3, and $K = 7.0 \times 10^4$ ton/m^3 are used to investigate the dynamic responses. The first foundation stiffness corresponds to the first proximity of the natural frequencies between the 1st and 2nd modes, and the third foundation stiffness corresponds to the second proximity between the 2nd and 3rd modes. The second stiffness corresponds to the case where the all frequencies are well separated.

In order to simplify the analysis the structural damping with the same constants for all vibration modes is assumed in the analysis. This type of damping diagonalize the damping matrix by normal mode coordinates for undamped system. It may be extended to more general cases applying different damping constants for different modes of vibrations. Two other types of damping, damping proportional to mass matrix, damping proportional to stiffness matrix, are also applied in the analysis(4), but the results to these damping are omitted in this report since the types of damping are not the main subject of this report.

In the analysis of dynamic responses of multi-degrees of freedom systems, random vibration theory including non-stationary vibrations are fully applied(4). In this paper only a part of the results of the investigation is utilized.

To investigate the response properties of the systems, responses due to white noise are firstly discussed, although real earthquake are somewhat different from white noise.

Fig. 5 shows root mean square responses of the system obtained from power spectrum due to white noise excitation. Dotted lines in Fig. 5 show the responses where only direct power spectrum of each mode is considered, and solid lines, the responses including cross power spectrum between the vibration modes.

The effects of cross power spectrum to the responses are predominant at the correlated mode regions of the system as shown in the left and the right figures of Fig. 5, and at the separated mode region, the middle figure, the effects of cross power spectrum are negligible.

Fig. 6 shows the maximum responses due to 1940 El Centro Earthquake Record obtained by various computation methods. Modal method of analysis, RMS method, gives good approximation for the separated mode region, middle figure, but does not, for the correlated mode region. The same results are also obtained for the non-stationary random excitations with specific power spectrum modified by specific deterministic functions(4). These results are quite important for practical earthquake resistant design of the complicated structures discussing in this report.

EXPERIMENTAL MODEL

To obtain the effects of foundation stiffness to free and forced vibration properties of the system experimentally, a model was set up. Fig. 7 shows the model used, and the scale factor of the model is approximately 1/200. The top of the model tower is constrained by the cables with proper elastic constants. The pier is a solid mass of steel, and its dimension a ong bridge axis is changeable as 76, 118, and 163 mm. The stiffness of foundation is also controlled by adjusting stiffness, number, and position of the springs under the pier. Photos. 1 and 2 show the model set up.

RESPONSE STUDIES DUE TO STEADY STATE EXCITATION

Resonant frequencies and modes of the model were obtained by steady state sinusoidal excitation. Three kinds of pier dimensions were used and the foundation stiffness were varied almost continuously. Resonant frequencies of the model are obtained as shown in Fig. 8. The dotted lines in these figures show the natural frequencies of the pier without tower, and the chain lines, the tower fixed at the base.

These results fairly agree with the theoretical results shown in Fig. 3. Almost the same results are obtained for different pier dimensions as shown in these figures, but deviation from the dotted and chain lines is large for the pier with small dimension.

Fig. 9 shows the variation of resonant displacement configuration of the system with the various foundation conditions. These shapes are approximately similar with the results shown in Fig. 4.

RESPONSE STUDIES DUE TO GENERAL EXCITATION

Earthquake responses of the model due to 1940 El Centro Earthquake Record were obtained experimentally using general exciting vibration table. (Photos. 1 & 2) The responses of the model were recorded by magnetic tape data recorders and analysed by the high speed digital computer.

Fig. 10 shows maximum response due to the earthquake for different foundation stiffness. For the correlated mode region, relatively large response is obtained. These responses, however, are influenced by the properties of the earthquake record used as well as the foundation properties.

Fig. 11 shows the maximum responses due to band limitted white noise excitation with frequency range 2 to 20 cps. The same tendency as in Fig. 10 is given in Fig. 11.

CONCLUSION FOR DESIGN PRACTICE

For earthquake resistant design of suspension bridges dynamic considerations are fully required. From the results of this paper and of the previous studies the following points must be emphasized for the dynamic design of suspension bridge tower and pier systems against earthquakes.

1. Earthquake resistant design of the tower and pier systems is one of the most importance in suspension bridges, and it is approximately possible to analyse the part separated from the whole structure.

2. Rotation of the pier on the foundation has significant effects on the earthquake resistant design of the system.

3. Estimation of the foundation properties of the structural site is quite important for the design of complicated structures such as disscussed in this investigation.

4. If accurate estimation of the foundation properties is difficult from field investigation, some ranges of these values must be considered in the design practice.

5. For some range of foundation condition, two modes of vibrations are close with each other, and specific consideration for dynamic design in these cases are required.

6. For some demensions of the pier, the same condition as the case of foundation properties occures.

7. Assumption on vibration damping affects the earthquake responses significantly. (Refer Bibliography (4)). Investigations on damping properties are, therefore, important for dynamic design of the complicated structures.

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(4) Yoshikazu Yamada and Hirokazu Takemiya, Studies on the Responses of Multi-degrees of Freedom Systems Subjected to Random Excitation with Application to the Tower and Pier Systems of Long Span Suspension Bridges, Memoirs of Faculty of Engineering, Kyoto University, Vol. 30, Part 4, 1968

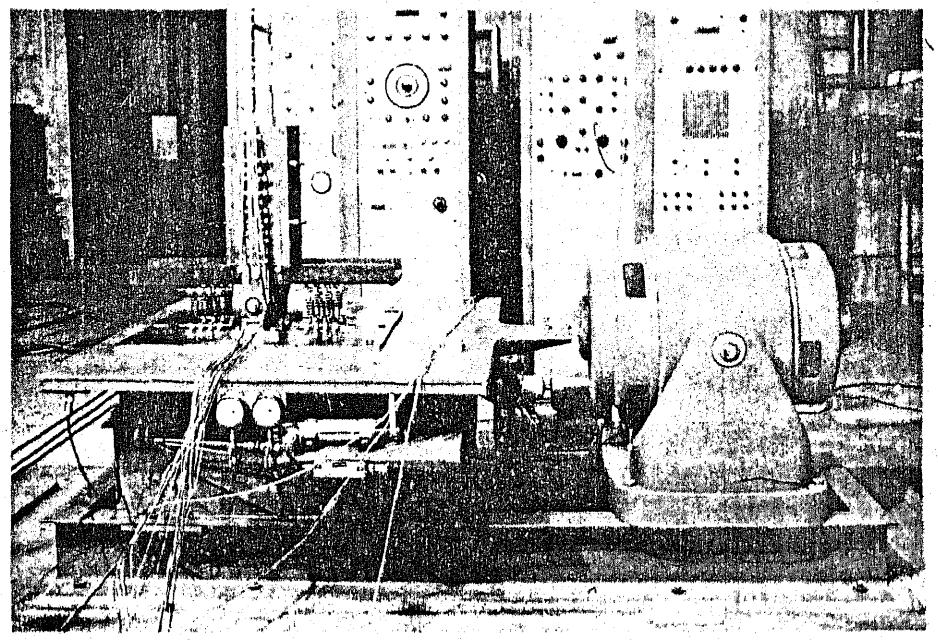
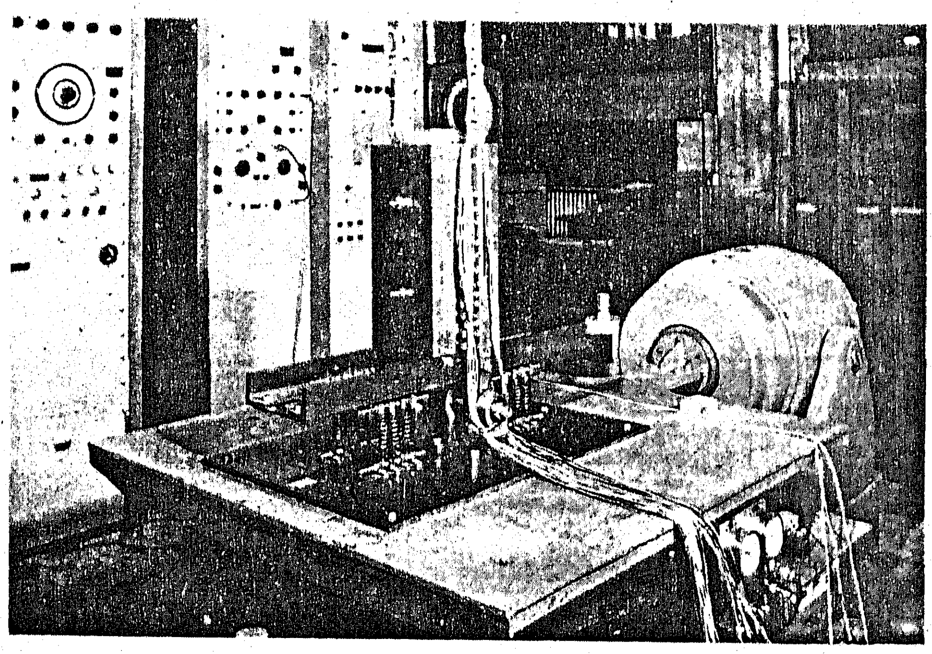


Photo. 1



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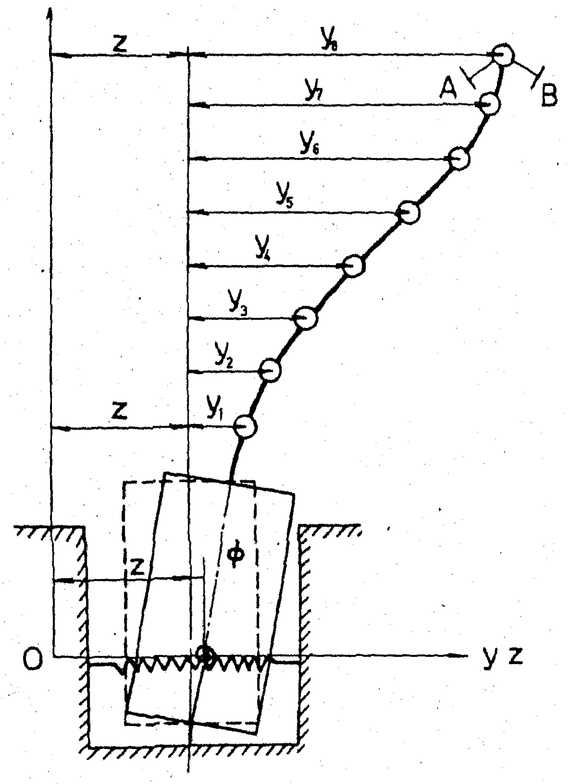

Fig. 1

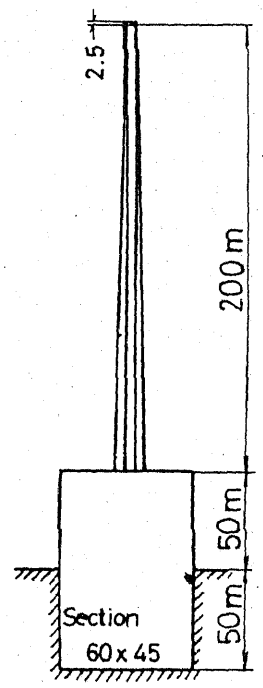

Fig. 2

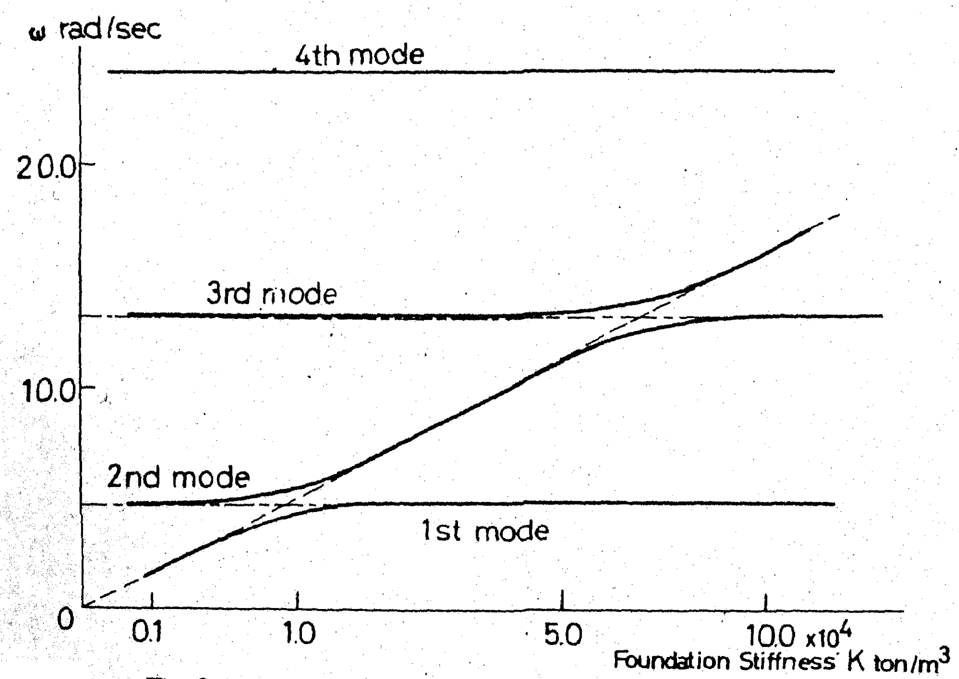

Fig. 3 Natural Frequencies of the System

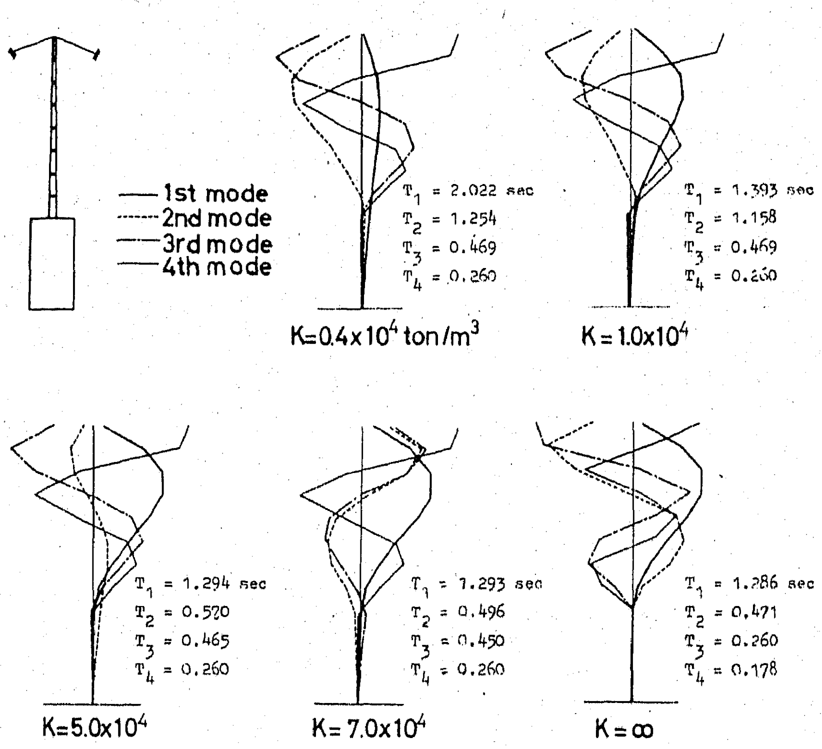

Fig. 4 Free Vibration Modes

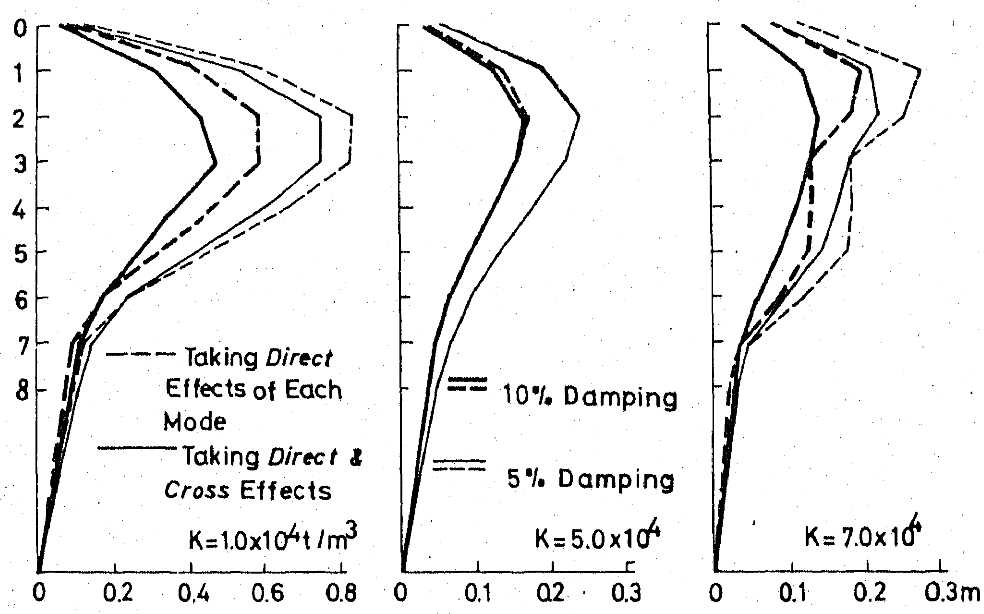

Fig. 5 Root Mean Square Response (White Noise)

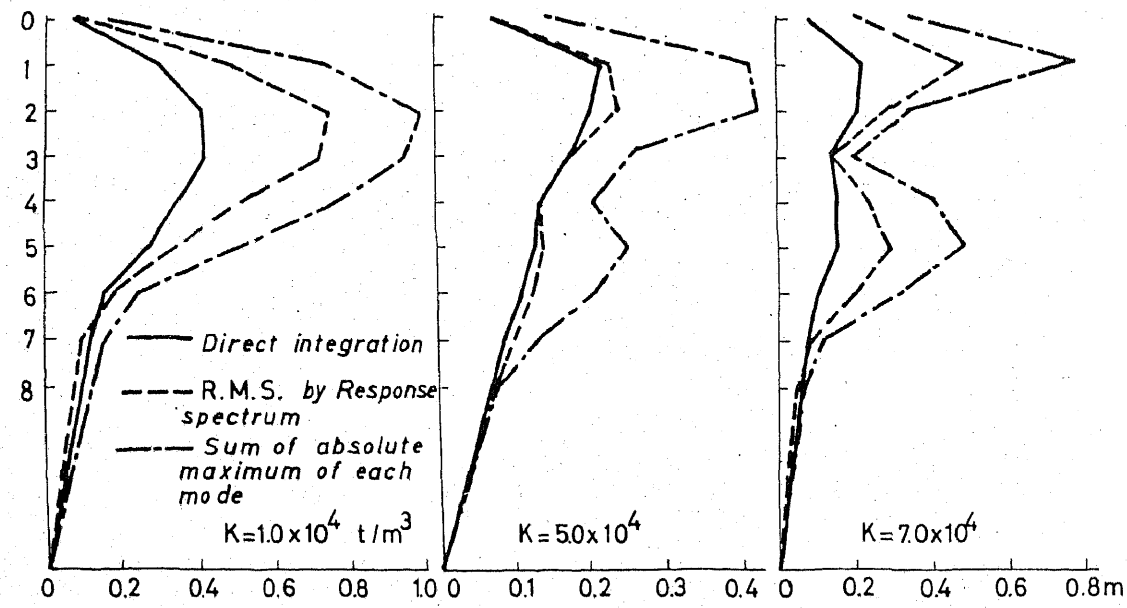

Fig. 6 Earthquake Responses due to 1940 El Centro Earthquake Record (10% Structural Damping)

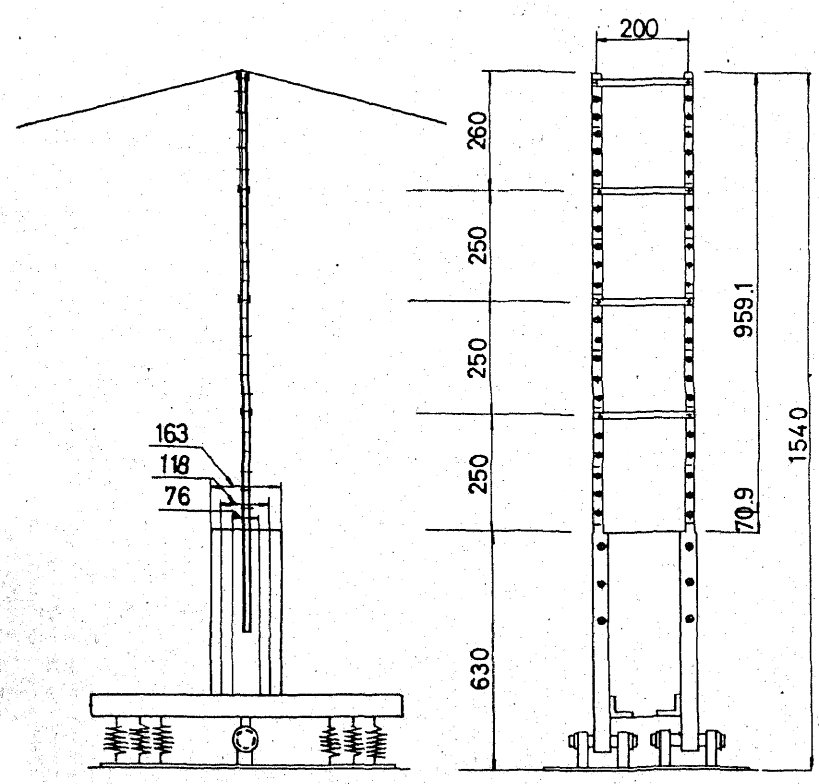

Fig. 7

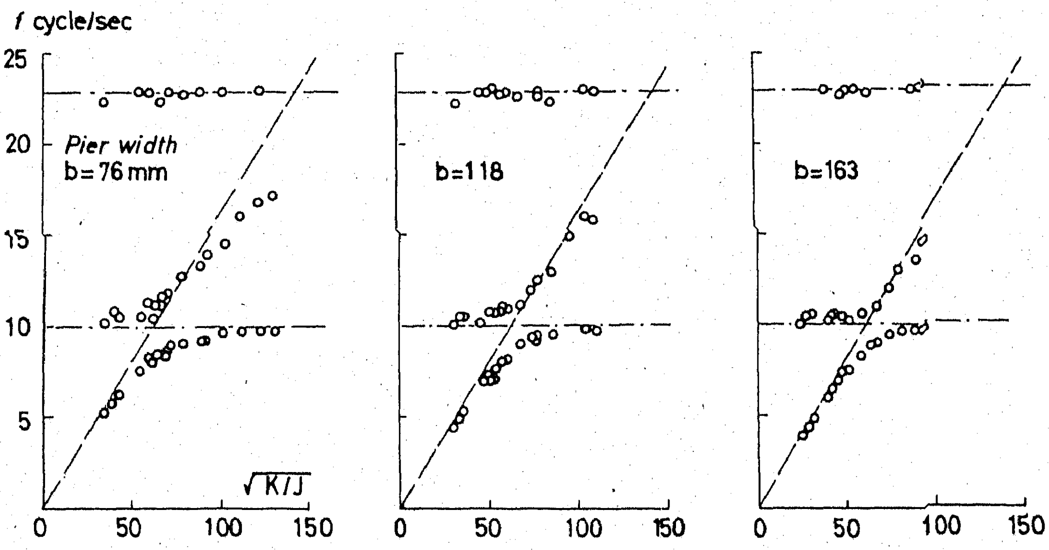

Fig. 8 Resonant Frequencies

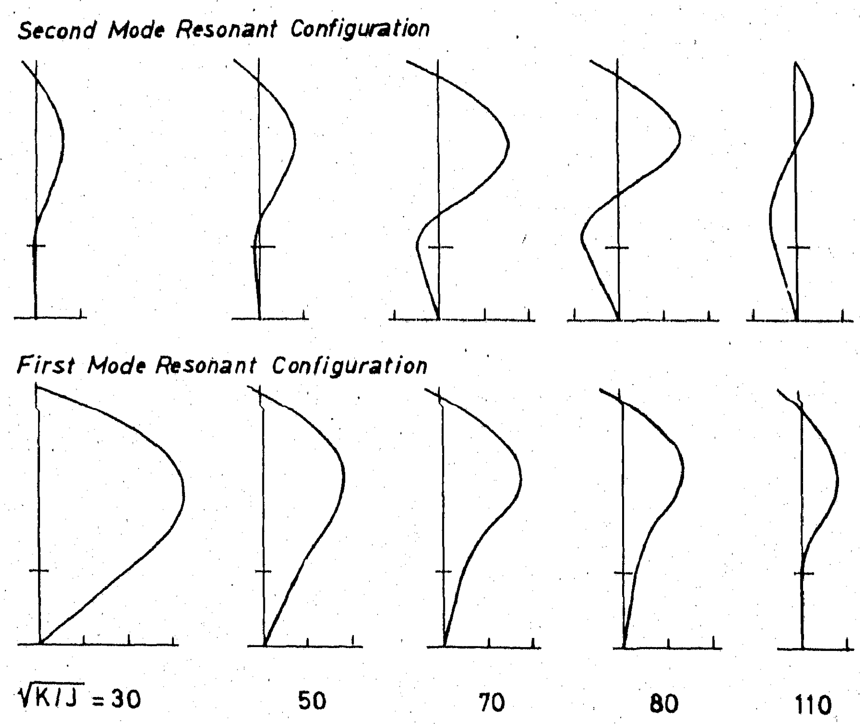

Fig.9 Resonant Configuration for Various Foundation

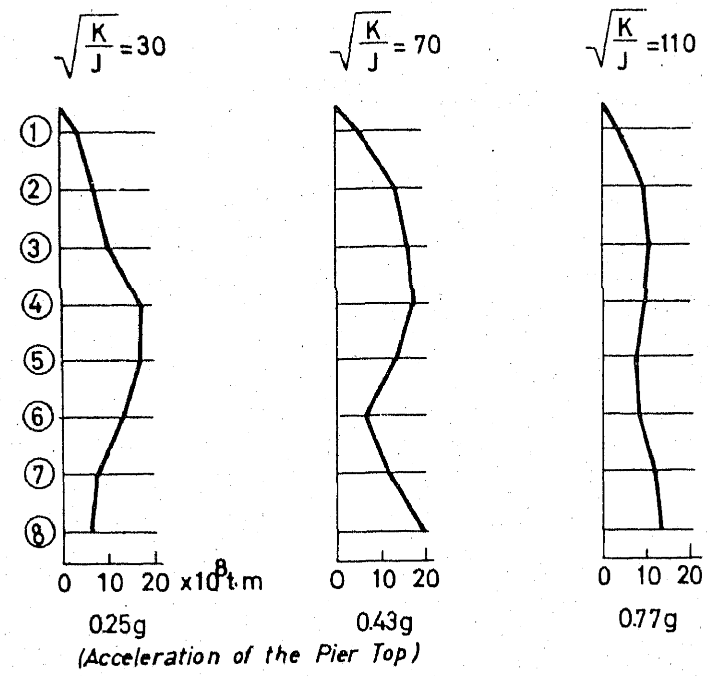

Fig. 10 Maximum Moment due to 1940 ElCentro Earthquake Record

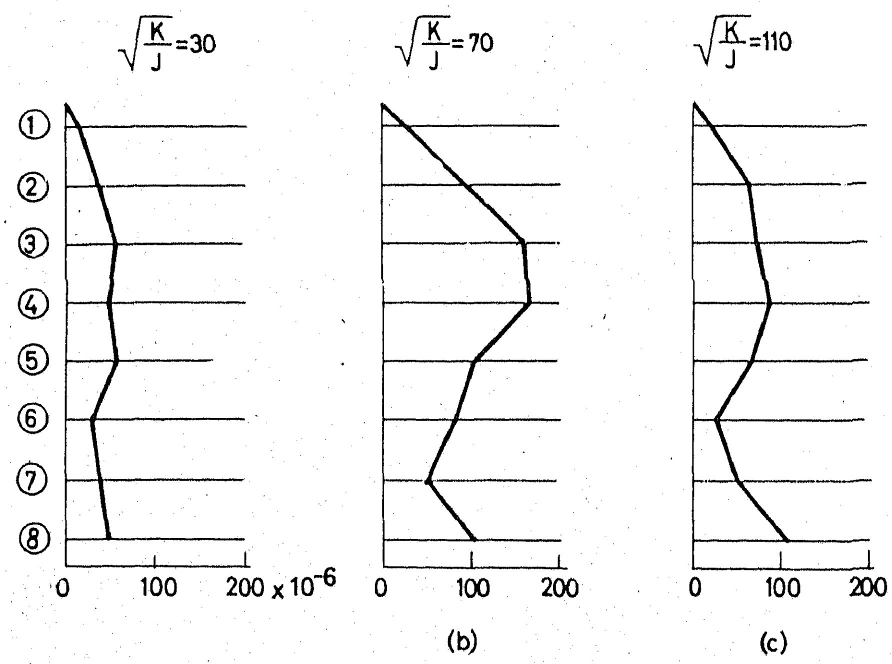

Fig. 11 Maximam Strains due to Random Excitation