A Structural Model Study of a Hydraulic Intake Tower

Etude d'un modèle structurel d'une prise d'eau

Modelluntersuchung eines hydraulischen Einlaufs

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1. Introduction

In the design of any structure which will be subjected to water flow, the magnitude of the hydrodynamic forces may have to be determined, and the dynamic response of the structure predicted. In certain cases there is also a possibility of the hydrodynamic forces being increased by interaction with the vibration of the structure, causing a condition of hydroelastic instability.

A free-standing hydraulic intake tower is one such structure. This kind of tower, commonly used in reservoirs to draw off the water, is often tall and slender and hence liable to vibrate as a vertical cantilever. The section of the tower is commonly circular or square, and is fitted with intake valves at various levels to enable water to be drawn off at any required elevation. In operation the tower is subjected to the dynamic forces caused by water entering at the valves under considerable static head, dissipating much of its energy inside the tower, and flowing out at the base. The magnitude of these forces depends on the valves that are open and on the height of water in the reservoir. Further the tower is standing in water and its dynamic response will be influenced by the water both inside and outside the tower. There has been at least one case of serious vibration in a tower of this kind, a condition that might have led to structural damage if the flow of water had not been cut off.

The purpose of this model study was to establish the stability of a proposed intake tower design under all possible flow conditions, and to determine if any design modifications were required in the design to achieve this stability. As the hydraulic aspects of the tower had also to be studied, a combined hydraulic-structural model study was undertaken to reduce the total cost and time. The tower, to be constructed in Southern California, was also designed for seismic forces,hence it had considerable bending stiffness when considered as a long vertical cantilever. The stability of the design in this regard made it probable that it was also adequately stiff to resist the horizontal hydrodynamic forces, but this had to be established.

2. Description of the Structure

The prototype tower in this study is a 214 ft. high circular tower with an internal diameter of 32 ft., fitted with thirty six 6 ft. diameter butterfly valves arranged in groups of four at nine elevations. Each group of four valves is arranged as two opposing pairs, the groups are spaced at 17 ft. centers vertically and the lowest is 7 ft. above ground. When the reservoir is full the water level will be 158 ft. above ground.

When all valves are finally installed, all four valves at any given level will either be open or closed, one or two levels will be open and these will be fully submerged. The maximum flow with all valves open will be 9600 cub. ft. per sec. During the initial phases of construction there will be only one pair of opposing valves at each level.

The appearance of the tower above ground will be similar to that of the model shown in Plate 1. Below ground the internal diameter tapers from 32 ft. to 19 ft. over a height of 75 ft., and below this there is an elbow section which joins the outlet tunnel which also has a diameter of 19 ft.

The foundation of the tower is interbedded sandstone and shale which will be pressure grouted after construction.

3. Considerations in the Design of the Model

Dynamic forces due to hydraulic flow are inertial forces and drag forces, and these two lead to conflicting similitude requirements. As gravity acts on both model and prototype, accelerations are the same in both, and this in turn gives rise to the velocity ratio $v_r = 1/L_r$ where subscript r denotes a dimensionless ratio between model and prototype, and L = length. Hence the ratio of inertial forces when water is used as the fluid in the model is $F_r = L_r^3$. To keep the drag forces to the same scale the Reynolds Number has to be the same in model and prototype, and this leads to a velocity requirement of $v_r = 1/L_r$. This conflict in velocities cannot be resolved in such a model study and hence a decision has to be made regarding the relative importance of inertial and drag forces. Clearly inertial effects are extremely important, and the only question is whether or not the drag forces are a significant factor. In this case it was decided to neglect the drag forces, but to keep the Reynolds Numbers as close as possible by making the linear scale of the model as large as possible. For the flow condition causing the maximum vibration of the tower the Reynold Numbers were 2.7×10^7 and 1.6×10^5 in prototype and model respectively. The final effect of this decision will not be known until tests are made on the prototype tower.

In using a physical model as part of a design process it is desirable to construct the model so that modifications to the design can be effected on the model with a minimum of difficulty to allow for possible design changes in the prototype. This demands that certain geometrical features be taken as fixed, and in this case it was the internal geometry of the section. The outside geometry was left open to modification, hence the mass and the overall bending and shear stiffnesses of the tower could be modified.

It was assumed that the important structural properties for this study were those associated with the vibration of the tower considered as a long vertical cantilever, hence the overall flexural and shear stiffnesses of the tower section and its mass distribution had to be correctly simulated. Those modes of vibration associated with the local deformation of the cross section corresponded with frequencies that were considered too high to be significant.

The tower was considered fixed at ground level, and the model supported in such a way that there was an effectively rigid connection at this elevation. The prototype design included an access bridge to the tower, but this was not to be considered unless the response of the model called for design modifications.

The interaction between the vibrating tower and the surrounding water was assumed to be correctly simulated by the model. The interaction effect is discussed below. There is some data available for this effect at model scale (1), but little at prototype scale and it is recognised that the effect may be velocity dependent. As any scale effect would likely influence the magnitude of the coupled mass of water vibrating with the tower, once this scale effect is known it can be allowed for by the designed mass of the model. In this study as no information of this kind was available, it was assumed that there was no scale effect influencing the virtual coupled mass of water.

4. Design of the Model

The stiffness requirements and frequencies of the model were fixed from the values of F_r and v_r discussed above. To make the model true scale and in prototype material would have made it too stiff by a factor of L_r the geometric scale, and as a scale of $L_r = 1/30$ was used this would have meant a model 30 times too stiff. The stiffness could have been reduced in two ways: (a) by reducing the wall thickness as local deformation was not being studied, and (b) by using a more flexible material. The first of these would have resulted in a model with extremely thin walls and difficult to construct; the second would have required a lower value of E than can be found in suitable materials. Hence a combination of the two was used. Acrylic resin in the form of Plexiglas sheet was selected for the model material, and as this has an effective dynamic E approximately 1/5th that of concrete, the further 6 times reduction is stiffness had to be effected by reducing the wall thickness of the model to approximately 1/6th of its true-scale value.

There are two properties associated with model material that must be considered in an elastic dynamic study, stiffness and damping. The value of E is the dynamic modulus associated with the frequencies expected in the study. Tests on certain plastics show E to be frequency dependent, and if E varies significantly over the expected range of frequencies, such a material may be unsuitable. Dynamic tests on Plexiglas showed that E is effectively constant at 6.5×10^5 psi above 6 Hz, and as the first natural frequency of the model in water was approximately 6.5 Hz this was considered suitable. Material damping presents problems when using certain plastics for dynamic modeling. The damping of Plexiglas is in the order of 4% critical, and this is somewhat higher than would be expected in an uncracked concrete tower. Provided that there is no interaction between the dynamic forces and the vibration of the structure, the effect of higher damping can be allowed for; if a feed-back phenomenon is present, this is not possible. It was decided to use Plexiglas and to recognise the problem of higher damping in the model.

Having decided on a distorted model, it was found convenient to make the basic model understiff and to bring it up to the design stiffness with detachable external ribs. Hence it was possible to increase the stiffness further if redesign was called for.

The natural weight of the model was approximately 100 lb., whereas the simulation of inertia forces called for a weight of 550 lb. This was achieved by adding external lead weight rings, bolted to the model in such a way that they held the section geometry on two normal diagonals (Plate 2). By this means the problem of the reduced local bending stiffness of the walls was overcome. The weights were designed not to interfere with the flow pattern external to the tube, and they could also be increased in value if design modifications required it.

The valves were modeled in Plexiglas (Plate 3), and were installed with the axis of the vane vertical. Open and closed valves were modeled and these were installed according to the required operational conditions. The situation arising during the opening or closing of the valves was not studied. The model above ground without valves or weight rings is shown in Plate 1.

Three large tanks were used, a constant head tank and a weir tank to control and measure the water flow, and an 8 ft. diameter tank (Fig. 1) in which the model was tested.

5. Instrumentation

Horizontal accelerations were monitored at six points in the tower, two accelerometers at each of three elevations (Fig. 1). The locations were selected to monitor the vibration of the tower simultaneously about two orthogonal axes and at elevations suited to measuring experimental mode shapes for the first three natural modes. Samll piezoelectric accelerometers were used with a frequency range down to 1 Hz and a sensitivity of 0.01g. Dynamic stresses were measured by resistance strain gages mounted in opposing pairs at the base of the tower.

Provision was made for processing the data in either digital or analog form. For digital processing the data could be stored on magnetic tape. For diaplay in analog form the data could be fed to a storage oscilloscope and photographed. It was found that the latter procedure was ideally suited to the entire program as it had two advantages: the instantaneous display of dynamic response is essential in any study where there is a possibility of resonance causing damage; also it was useful in the preliminary stages for studying the constructional problems associated with the dynamic characteristics of the supporting tank system. Two devices were used in connection with data display. The first was an operational amplifier which displayed the log of the acceleration vertically against time horizontally. This was used for damping studies (Plate 6). The second was a harmonic analyzer which displayed the intensity of any quantity against frequency, and was used to monitor the harmonic contents of the horizontal accelerations at the top of the tower (Plate 5).

A digital counter was used to measure natural periods, and this period could be measured at any preselected interval after initial excitation by the use of a specially designed zero-crossing counter.

6. Tower-Water Interaction

The principle effect of submergence on the dynamic response of the tower is the coupled virtual mass of water which lowers the natural frequencies of the tower as compared with the frequencies in air. This was studied extensively on a series of small models (2) as well as on the tower model, and the coupled mass of water determined from interaction graphs of the kind drawn in Fig. 2 for the tower model. In this graph m_o = mass/unit length of the tower in air, m = required coupled mass of water/unit length, f_o = first natural frequency of the tower in air, and f = frequency of the tower in water. The theoretical curves are based on a Rayleigh solution which assumes a constant mode shape and a coupled mass of water taken as a constant mass m per unit depth.

The mass coupling due to water outside the tower is expressed as a percentage of the mass per unit depth of the water displaced by the tower. From a series of tests conducted on tubes of different external diameters ranging from 1.0 in. to 13.44 in. (the latter being the tower model), the coupled mass factor was found to be sensibly constant at 75%. 100% of the mass of the water inside the tower was coupled with the vibrating tower.

Fig. 2 shows the results of tests conducted on the model tower with water rising simultaneously inside and outside. The form of the experimental curve, which closely follows the theoretical interaction curves, indicates that the simple interaction concept provides an accurate procedure for computing the first natural frequency of a vertical tube standing in water whose surface is at any elevation below the top of the tube.

The damping, as measured from decay curves, was not measureably increased by submergence in still water, even when the water level was at its maximum and all valves were open.

7. Experimental Results

Data was taken for a wide variety of valve operational conditions; single valves open at various levels of submergence, two adjacent valves open, two opposing valves open, all four valves open, and these combinations for more than one level at a time up to and including all valves being open for the maximum flow condition.

The vibration of the tower appeared to be random in form and occurred simultaneously about both horizontal axes. The form of movement of the top of the tower as viewed in plan can be seen in Plate 4, which is the trace formed by the signals from the two accelerometers at the top of the tower being fed to the X and Y plates of the oscilloscope. The most useful display of the acceleration data was by taking the signal from one accelerometer, passing it through a spectral analyzer, and recording the resulting acceleration-frequency plot on a storage oscilloscope. Plate 5 shows the spectral analysis of the accelerations at the top of the tower about one axis. It was due to two adjacent valves being open at level 4 with all other valves closed, and the water level outside the tower being at its maximum elevation. This was the valve condition that produced the maximum vibration in the tower. It will be noted that the important dynamic response of the system was associated with the natural frequencies of the tower in water, the two major peaks in this particular diagram corresponding to the second and third natural frequencies. In all cases the maximum acceleration intensity was associated with the second mode, but the largest displacement amplitude was associated with the first mode. The acceleration response curves were all of the general form shown in Plate 5, and it appeared that within the range of frequencies under study the hydrodynamic forces produced something in the nature of a white noise excitation, the dynamic magnification at the natural frequencies causing the response peaks. It will be noted that the projected prototype displacements at the top of the tower are not large, the maximum amplitude in the first mode for any valve condition being 0.4 in., and this is considerably less than the design seismic displacements. Displacements in the higher modes were much smaller.

Considerable time was spent in searching for a more serious resonant condition, without result. There appeared to be no significant feed-back phenomenon between the excitation forces and the vibration of the tower. It was concluded from the model study that this particular design was dynamically stable for all possible conditions of hydraulic flow, within the limitations of the model study.

The effect of water depth on two different valve operational conditions can be seen in Figs. 3 and 4. Fig. 3 shows the effect of the water level outside the tower on the dynamic response when two adjacent valves were open at level 4 (see also Plate 5). The variation of vibration amplitudes in the first two modes was approximately linear with water level. This could be expected as the static pressure at the intake valves increases linearly. However, when valves were open at more than one level the effect was different. Fig. 4 shows the influence of water depth on dynamic response when all valves were open. In this case there was a critical depth of water associated with maximum vibration amplitudes, and this was not the maximum possible depth. As the water level outside the tower was raised above this critical elevation the water flowing into the tower through the higher valves either interfered with the excitation caused at the lower valves, or the random nature of the excitations at the different levels tended to cancel each other, and there was a resulting reduction in dynamic response.

Similar data was taken for the bending stresses at the base of the tower, and it was found that the spectral analysis of bending stresses correlated closely with the values predicted from the modal displacements at the top of the tower derived from the accelerometer readings.

As a further check on the stability of the tower, effective damping tests were done both in still water and also during those flow conditions showing maximum vibration. These were done by externally exciting the tower during the flow condition and observing the decay curve while the flow was maintained. Plate 6 is an example using the signal from the top accelerometer. The system damping can be deduced from the envelope of the first part of the curve which represents the decay after the removal of the external excitation. The residual signal after the initial decay represents the dynamic response of the tower to the hydrodynamic forces. In all such tests the change in system damping caused by the hydraulic flow condition was minimal.

8. Conclusion

This particular model of a hydraulic intake tower was completely stable under all possible flow conditions. In using the experimental data to predict prototype response the limitations of the model are recognized, namely the effects of drag forces and system damping.

At the time of writing the prototype tower has not yet been constructed. It is hoped that the structure will be tested under conditions equivalent to those simulated by the model. Thus it should be possible to study the correlation between model and prototype dynamic behavior and to determine the extent to which dynamic model studies of this kind can be used in the design of hydraulic structures.

9. Acknowledgments

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10. References

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2. Godden, W.G., Tuncag, M., and Wasley, D.L., "Model Analysis of the Castaic Reservoir Intake Tower," Report No. 70-15, Structural Engineering Laboratory, University of California, Berkeley, U.S.A.

11. Summary

Experimental data is presented on the dynamic response of a structural model of a hydraulic intake tower. The effects of submergence on the natural frequencies are given together with the response of the system to the hydrodynamic forces associated with certain valve operational conditions. Using a combined structural-hydraulic model an attempt has been made to establish the structural adequacy of a proposed design.

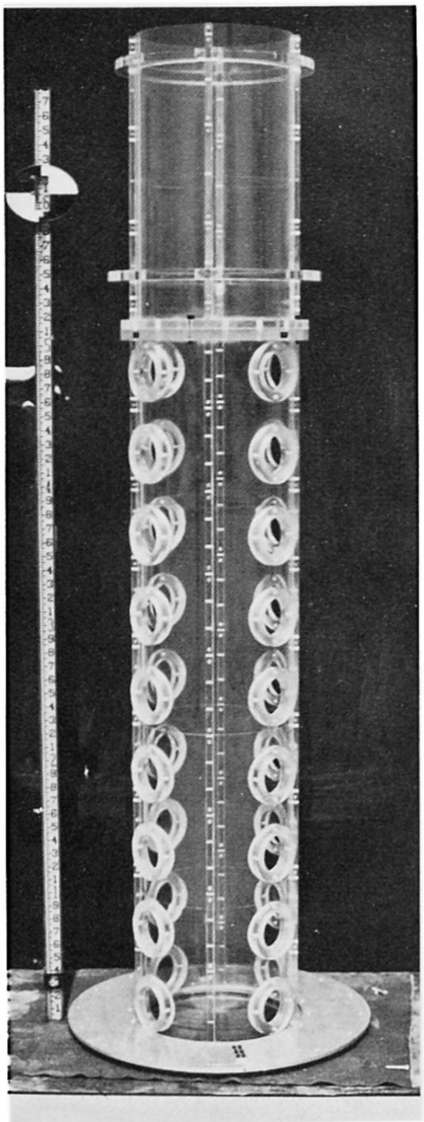

Plate 1. Model Tower without Valves or Weights

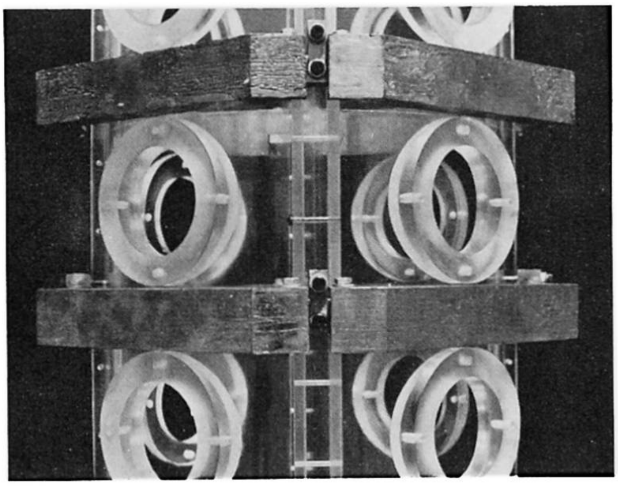

Plate 2. Fitted Weight Rings

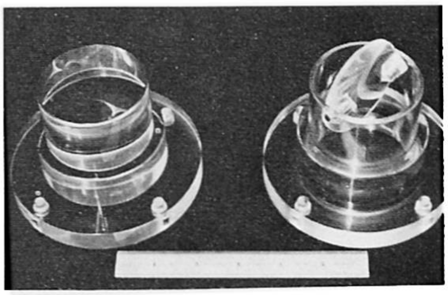

Plate 3. Valves Closed and Open

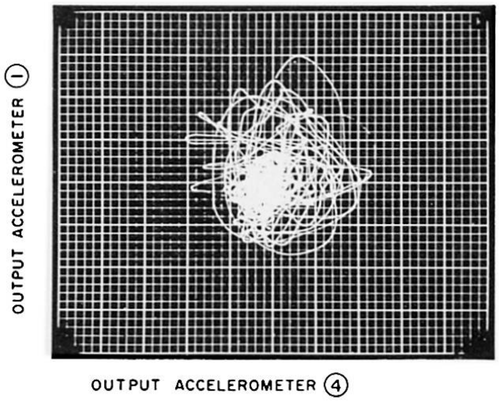

Plate 4. Response of Top of Tower

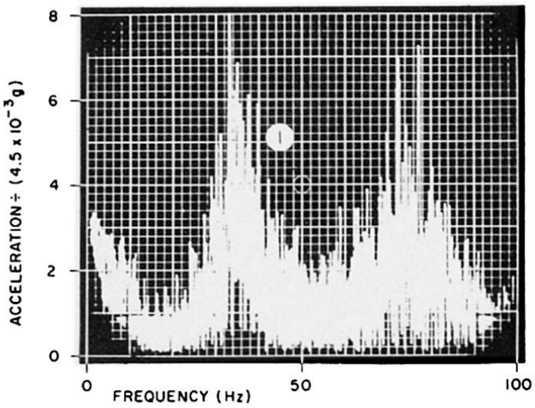

Plate 5. Spectral Analysis of Response

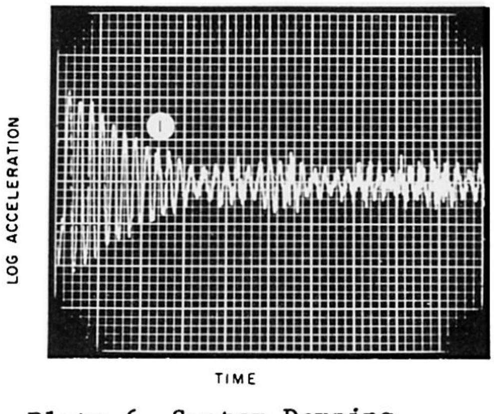

Plate 6. System Damping

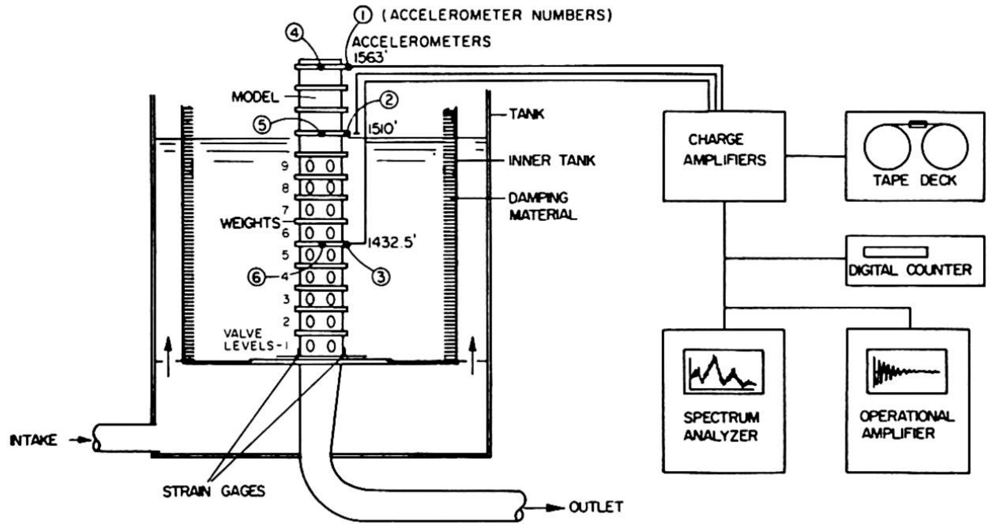

Fig. 1. Test Set-up and Instrumentation

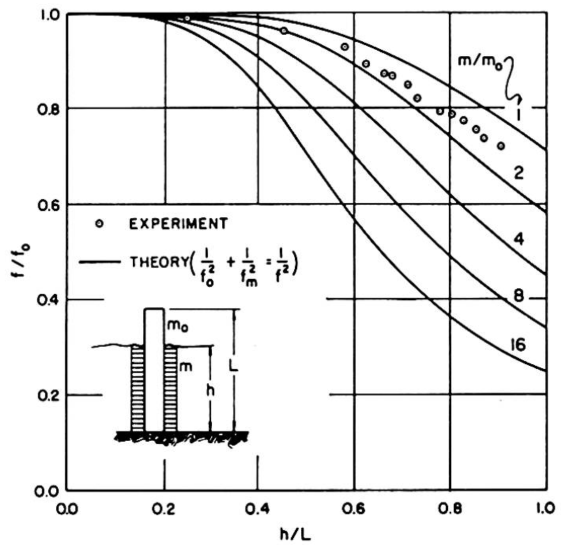

Fig. 2. Effect of Submergence on Natural Frequency

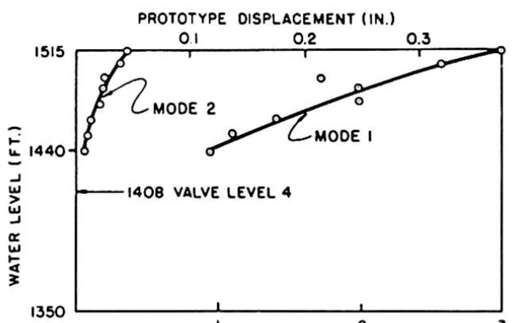

Fig. 3. Effect of Water Level
Two Valves Open at Level 4

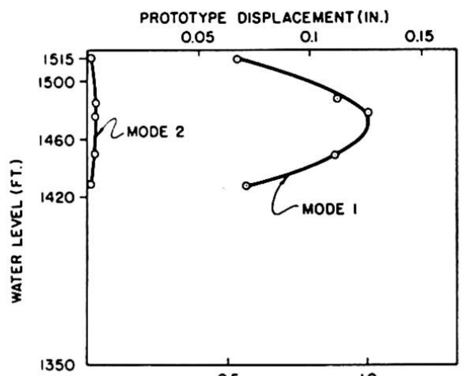

Fig. 4. Effect of Water Level
All Valves Open