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BEHAVIOUR OF CELLULAR BRIDGE PIERS UNDER DYNAMIC LOADS

A.S. Arya* Ph.D., Anand Prakash M.E.**

Synopsis

In this paper an experimental and theoretical study is made to find the effect of different filling materials in cellular bridge piers on their behaviour under free and forced vibrations. Four different fills, which can be commonly made use of, are tried and their effect on damping and natural frequency of the pier is observed under low water level and high flood level conditions. Some conclusions are drawn as a result of this study which will be useful in practice and for planning further investigation.

1. Introduction

In an earlier paper by the authors(1), the dynamic characteristics of masonry piers and their behaviour under free and forced vibration conditions were discussed. In order to rationalize the aseismic design of the bridge sub-structure, an attempt is made in this paper to study the behaviour of the cellular piers with different fills when subjected to dynamic loads For this purpose an experimental steel model of a reinforced concrete balanced cantilever bridge supported on cellular piers founded on rock was subjected to free and forced vibrations.

2. Details of the Model

Details of the various elements of the model bridge are given below :

2.1. *Super-structure* : Super-structure for the model consisted of one main span of 270 cm length with overhangs of 45 cm length on either side of a box type balanced cantilever bridge. It was made of steel plates welded together as shown in Fig. 1. At the two ends of the main span bearing plates were welded underneath the soffit slab so as to fix the roller and rocker bearings as shown in Fig. 2(a) and 2(b).

2.2. *Piers* : Model piers were chosen of circular cellular cross section made of steel. The main dimensions of the piers were : internal diameter 15 6 cm, height 75 cm, thickness of the steining 0.35 cm. The piers were fixed to a 45 cm × 45 cm × 45 cm size 1:2:4 cement concrete foundation through 4 nos. 16 mm dia anchor bolts and a steel plate as shown in Fig. 1.

2.3. *Bearings* : For supporting the superstructure on top of piers, a rocker steel bearing was provided on top of one pier and a roller steel bearing on top of the other pier. Bearings were made of a shaft with two wheels on either end of it. Ball bearing arrangement was made between the shaft and the wheels so as to allow free rotation of the two bearings.

2.4. *Filling Materials* : The following most commonly used filling materials were used to fill the cellular space in the piers.

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* Professor and Assistant Director, School of Research and Training in Earthquake Engineering, University of Roorkee, U.P.

** Reader, Civil Engineering Department, University of Roorkee, U.P.

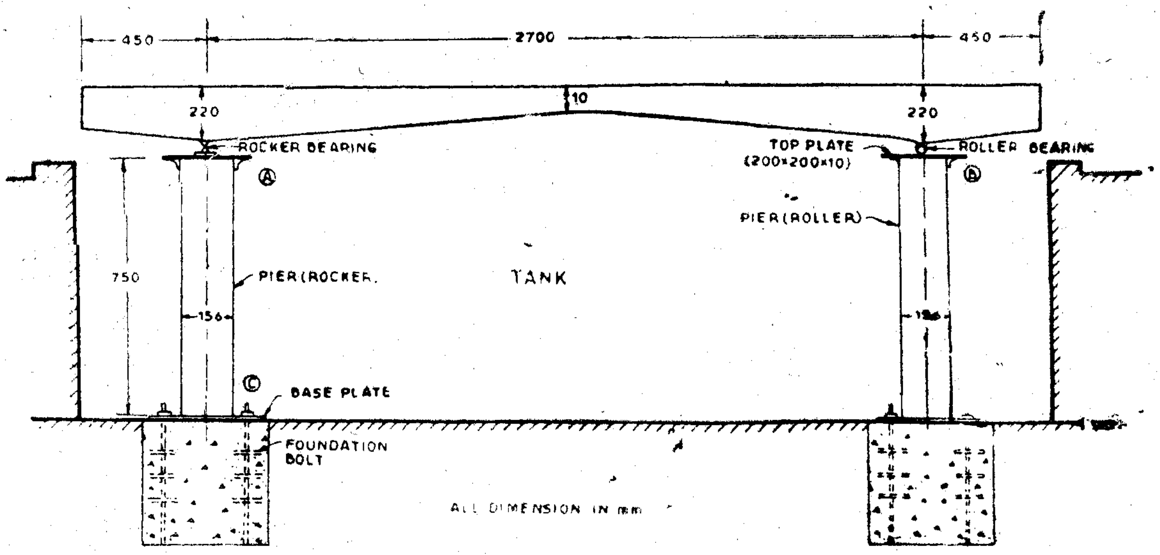

Fig. 1. Model Bridge

(1) Dry sand of density 1.48 gm/cc

(2) Stone ballast of density 1.60 gm/cc

(3) Saturated sand having density of 1.9 gm/cc

(4) Water with density of 1.00 gm/cc

Besides, the piers were also tested with no filling materials inside.

To simulate the high flood conditions, water was filled all round upto a height of 65 cm and to represent the low water conditions no water was filled outside.

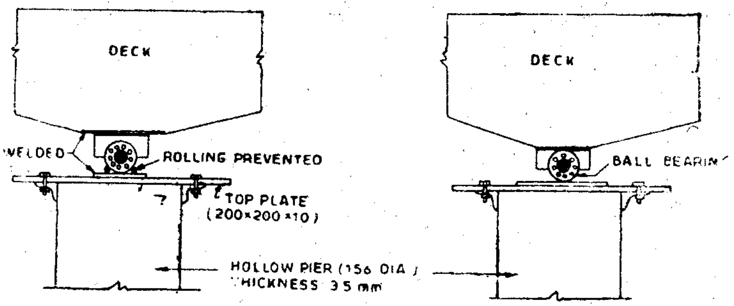

Fig. 2. Details at A,B (*vide* Fig. 1)

3. Tests

The following tests were carried out on the model :—

3.1 *Pull test* : In order to determine the degree of fixity at the base and the effect of the various filling materials on the stiffness of a pier, static horizontal load was applied at the top of the pier. The deflections at top were measured for different horizontal pulls under different conditions of fill material. The load deflection curves are plotted in Fig. 3. It is observed that there is only a slight effect of the various fills on the stiffness of the piers and that the deflections in each case are in excess than those obtained theoretically by considering the pier to be rigidly fixed at the base. It is found from the curve of empty tank that the base is having a stiffness against rotation equal to 21.5×10^6 kg–cm/radian in place of being completely rigid. Subtracting the effect of the base rotation from the deflection the stiffness of the pier under various filling conditions is obtained as follows :

(a) Empty or with water	2550 kg/cm
(b) Dry sand or ballast	2670 kg/cm (about 5% increase)
(c) Saturated sand	2840 kg/cm (about 11% increase)

1	2	3	4	5
17	XX XX	23.6	12.872	45.50
18	——— ———	2.71	2.469	8.90
19	—X— ———	3.18	2.936	7.68
20	—XX ———	3.36	2.978	11.39
21	XXX ———	3.47	2.995	13.70
22	——— —X—	4.81	3.957	17.72
23	—X— —X—	9.61	9.476	1.39
24	——X —X—	9.25	9.069	1.96
25	—XX —X—	13.10	9.277	29.20
26	—X— X—X	15.80	11.038	30.20
27	—X— —XX	15.38	10.479	32.00
28	—XX —XX	17.05	11.765	31.00
29	—XX XX—	17.60	13.846	21.35
30	XXX —XX	18.10	13.093	27.60
31	—X— XXX	15.80	11.926	24.50
32	—XX XXX	18.65	15.669	16.00
33	XXX XXX	20.05	17.037	15.00

Note : (minus sign indicates that the measured frequency is lower than the corresponding computed frequency).

Acknowledgements

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3.2 *Free Vibration tests* : For carrying out free vibration test a known horizontal pull was applied along the axis of the bridge at the top of the pier and released suddenly by clutch-plate arrangement as shown in Fig. 4(a) and (b). The vibrations were recorded by making use of an acceleration pick-up fixed at 16 cm height from the base along the axis of the pier. The records were obtained on Brush ink-writing oscillograph by connecting the pick-up with D. C. amplifier and recorder as shown in Fig. 4. The following observations were recorded :—

(1) Vibration of pier along axis of the bridge.

(2) Horizontal vibration of the deck.

(3) Vertical vibration at the centre of the deck.

The values of natural fundamental frequencies and average damping over 5 cycles for the same maximum first amplitude of 10 mm are given in Table 1 for various filling materials and water conditions.

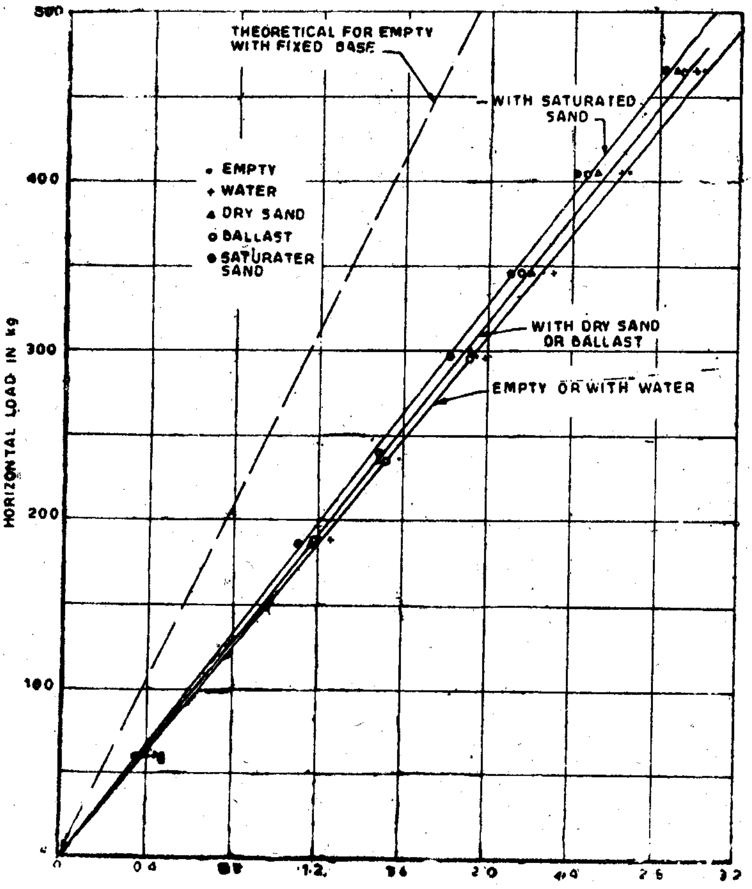


Fig. 3. Static load deflection curves

The values of maximum horizontal acceleration at the end of the super-structure and maximum vertical acceleration at the centre of the deck are given in Fig. 5 for various cases.

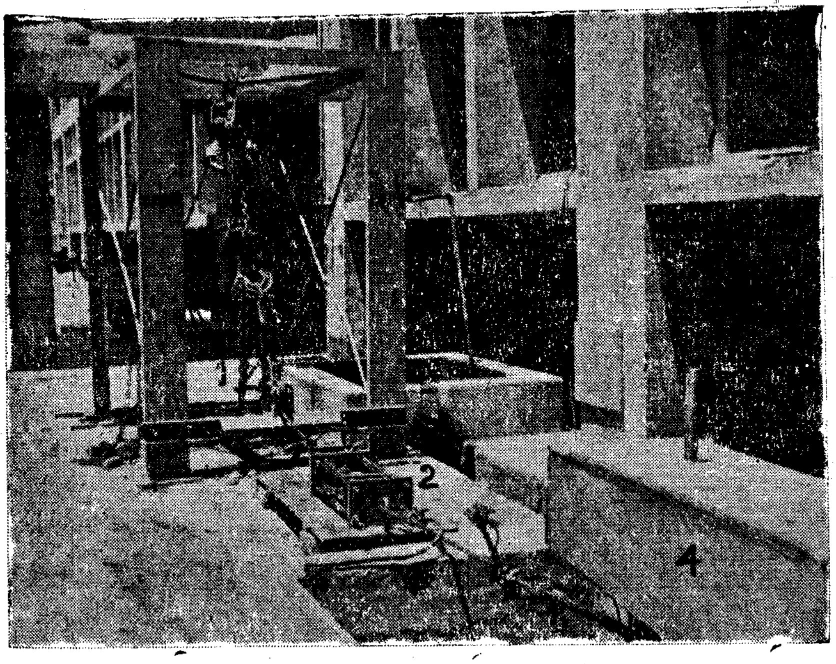
3 3 *Forced Vibration tests* : The forced vibration tests have been conducted by imparting horizontal accelerations to the deck by means of a mechanical oscillator mounted over the deck as shown in Fig. 4 (c) The speed of the motor was controlled at the desired rate with the help of a speed control unit so that a sinusoidal periodic force of various desired frequencies and amplitudes could be imparted at the top of the bridge model. The horizontal motion was applied along the longitudinal axis of the bridge and records were obtained for the vibration of pier with the help of a strain gauge fixed at 15 cm height from the base and horizontal acceleration of the deck with the help of an acceleration pick-up fixed on top.

Resonance curves are drawn taking A/ω^2 as ordinate and ω/p as abscissa for empty and ballast filled conditions where ω is the circular frequency of the oscillator, p is the natural frequency and A is the strain in micro cm/per cm. These are shown in Fig. 6 (a) and (b).

Table 1

Natural Frequencies and Damping from Free Vibration Test (Rocker Pier with Superstructure)
Horizontal pull = 238 kg.

Type of filling	Frequencies of pier in cps		Damping % of critical		Horizontal frequencies of deck in cps.		Vertical frequencies at centre of the deck in cps.	
	No water outside	Water outside	No water outside	Water outside	No water outside	Water outside	No water outside	Water outside
Empty	11.25	11.00	2.60	2.75	11.25	11.00	32.0	30
Dry sand	11.25	11.00	3.00	2.98	11.25	11.00	31.5	30
Ballast	11.25	10.50	2.96	3.10	11.25	10.50	30.0	31
Saturated sand	11.00	10.25	2.70	2.90	11.00	10.25	31.0	32
Water	11.25	10.75	2.65	2.83	11.25	10.75	28.5	29

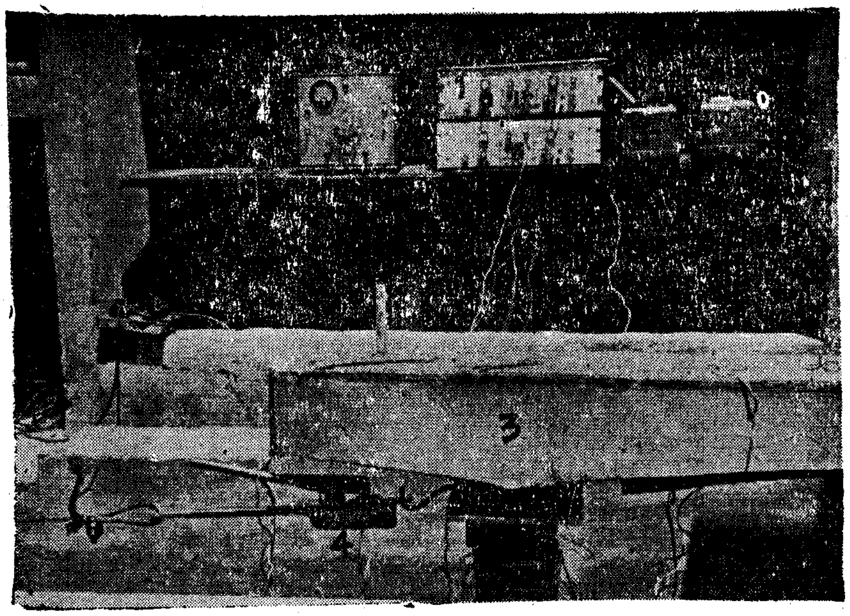


(a) Load Application

1. Chain pulley, 2. Tension Proving Ring
3. Release Cluth, 4. Bridge Deck

(c) Forced Vibration Test

1. Speed Control Unit
2. Universal Amplifiers
3 Motor
4 Lazan Oscillator
5 Bridge Deck



(b) Measuring Equipment

1. Universal Amplifiers, 2. Recording Oscillograph
3. Bridge Deck, 4. Release Clutch

Fig. 4. Details of Testing Arrangement

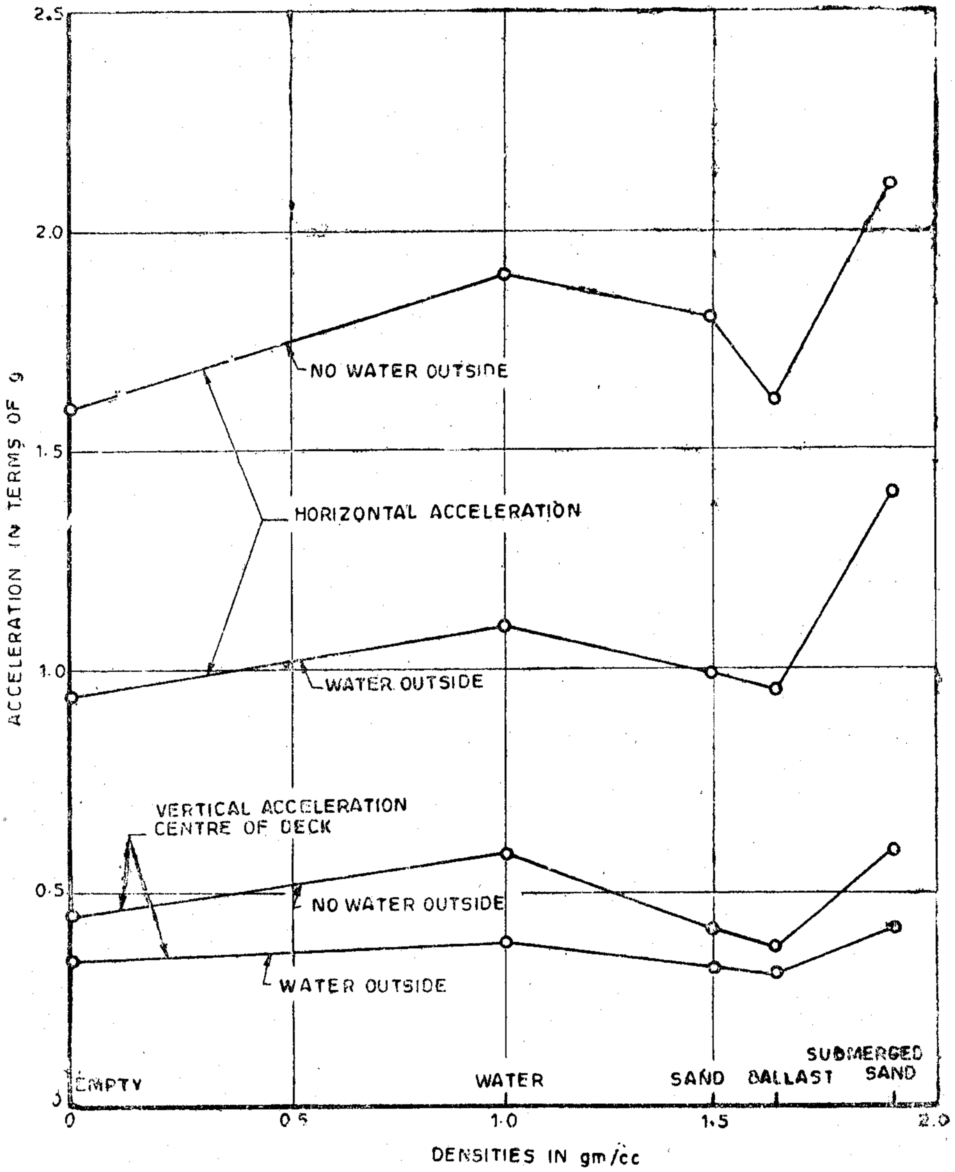


Fig. 5. Accelerations of Deck VS Density of Filling Material

4. Discussion of the Test Results

From the free vibration test results given in Table 1, it is observed that the fundamental frequency of the rocker pier is very little affected by the presence of the various filling materials. It is because of no appreciable change taking place either in the effective mass or stiffness of the pier due to the presence of various fills. In the case of saturated sand fill, the reduction in frequency is rather contrary to the increase in stiffness observed earlier. It appears that the dynamic pressures in the pore-water may have decreased the stiffness observed in static tests. The damping values are found to be maximum in case of dry sand and ballast. The natural frequency is decreased and damping is increased when water is filled outside as compared with the case when no such water was present. The decrease in frequency in water may be attributed to the virtual mass of water vibrating with the pier since there in no change in stiffness. Natural frequency for the vertical acceleration of the deck is almost the same in all conditions and equal to the fundamental frequency of the deck.

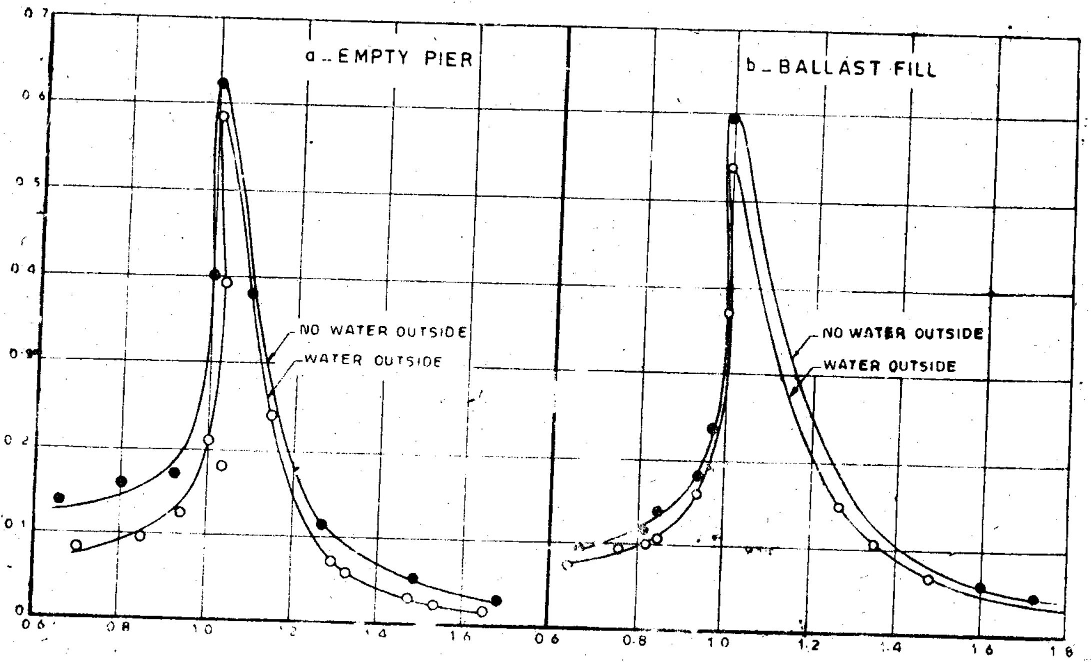


Fig. 6. Resonance test results for empty and ballast filled pier

From Fig. 5, it is obvious that the horizontal and vertical accelerations are minimum when ballast is used as a filling material. The accelerations are considerably reduced in each case when water is present outside. The average reduction in the horizontal accelerations is 37% and in the vertical accelerations of the deck 24%.

From forced vibration test results presented in Fig. 6 (a and b) it is obvious that resonant amplitude is less in case of water outside condition than that obtained in no water outside condition.

During forced vibration tests, it was observed that the superstructure got considerably accelerated in the vertical direction as well although the forced vibrations were imparted along the longitudinal axis of the bridge. At resonance the whole deck along with the oscillator tended to jump on the piers.

5. Theoretical Analysis

For the purpose of theoretical analysis, the pier is treated as a vertical cantilever either fixed or having some flexibility at the base. Depending upon the ratio of height to diameter of the pier both bending and shearing deformations may be significant. Therefore, natural frequencies are calculated considering both types of deformations. But the rotatory inertia is neglected since it will be small in such stiff structures The frequencies for the rocker pier have been computed numerically by Myklested—Prohl method (2,3,4) and are given in Table 2 for various values of rotational spring stiffness at the base. It is observed that the experimental and theoretical values of the fundamental frequencies are in agreement with each other for a value of rotational spring constant at base equal to 13.0 × 10^6 kg cm/radian. It will be recalled that the rotational spring constant was earlier found as 21.5 × 10^6 kg cm/radian by the static pull test. The dynamic value is perhaps reduced due to the mass of the foundation that may also be vibrating with the pier causing a reduction of the observed frequency so that it became equal to the calculated value with a smaller base spring stiffness.

Table 2

Natural Frequencies for Rocker Pier

Rotational Spring Stiffness × 10^6 kg. cm	Frequency in First Mode c/s	Frequency in Second Mode c/s	Frequency in Third Mode c/s
5.0	7.551	726.1	2206
10.0	10.117	742.1	2214
13.0	11.197	750.4	2218
16.0	12.078	758.0	2222
20.0	13.037	767.3	2227
25.0	13.993	777.65	2233
35.0	15.993	794.9	2243
50.0	16.776	814.9	2255

Natural frequencies for the rocker pier have also been computed when the cellular space is filled with various filling materials and for both 'water outside' and 'no water outside' conditions. The rotational stiffness of the base is considered equal to 13.0 × 10^6kg-cm/rad. as obtained above. While calculating the natural frequencies of vibration with water condition outside it is assumed that an equivalent mass of water of the enveloping cylinder is added to the mass of the pier upto the height of water outside(5). In the circular section the enveloping cylinder has its diameter equal to the external diameter of the vibrating system. The values of the frequencies so calculated are given in Table 3. It is observed that there is no appreciable change in the fundamental frequency of the rocker pier with different filling materials. The fundamental frequency is slightly less when water outside condition exists. This is also confirmed by experimental test results. However, the higher mode frequencies are very much reduced by the presence of the various filling materials. Furthermore, at high flood level condition, the frequencies are considerably reduced.

Table 3

Theoretical Natural Frequencies

Type of filling	First mode		Second mode		Third mode	
	No water outside c/s	Water outside c/s	No water outside c/s	Water outside c/s	No water outside c/s	Water outside c/s
Empty	11.197	11.134	750	482	2218	1465
Dry sand	11.109	11.064	426	354	1257	1058
Ballast	11.084	11.059	408	343	1201	1024
Submerged sand	11.063	11.029	383	328	1128	978
Water	11.126	11.092	475	380	1402	1140

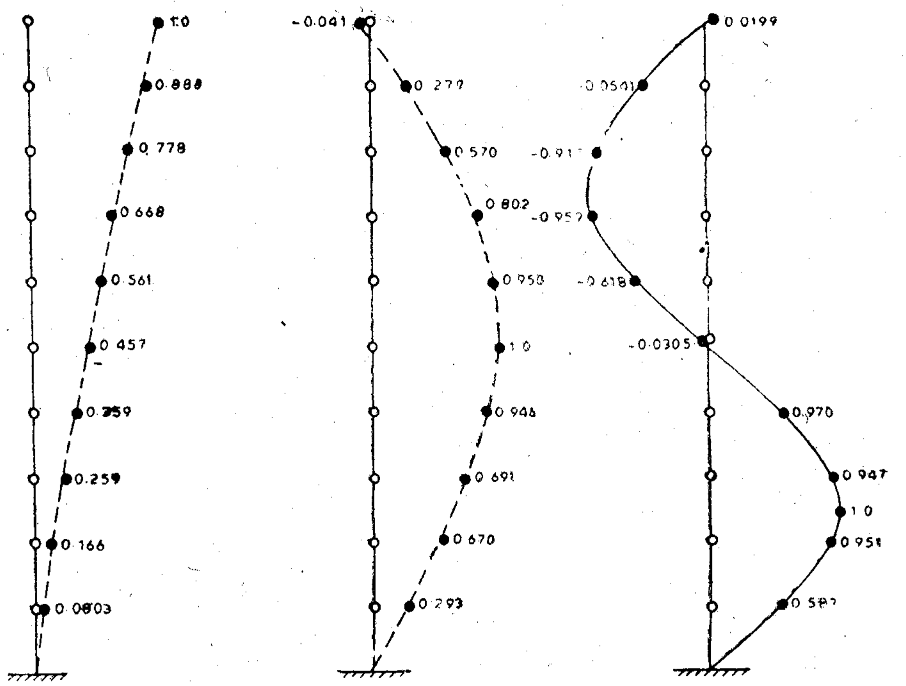


Fig. 7. Mode shapes for rocker pier in empty condition

It may also be noticed that higher mode frequencies are far removed from the fundamental. In fact because of heavy mass at the top, the pier tends to develop a node at its top as observed from the mode shapes shown in Fig. 7. Therefore, in dynamic response of the rocker pier, the fundamental mode only will be of significance.

6. Conclusions

The tests are not exhaustive enough to permit general conclusions. The pier model tested was rather stiff having fundamental frequency of about 11 cps. The conclusions as presented hereunder are therefore of qualitative nature and must be verified for flexible piers :

(1) Presence of the filling material in the cellular space of the pier has only a small effect on the stiffness of the pier and no noticeable influence on the fundamental frequency of the rocker pier. The damping is however slightly increased.

(2) For reducing the dynamic response of the pier and superstructure, ballast turns out as the best material for filling when choice is from amongst dry sand, ballast, saturated sand and water.

(3) The pier has exhibited better response to dynamic loading when water is present outside representing highest flood level condition. There is slight reduction in frequency indicating addition of virtual mass and increase in the damping value over those obtained under 'no water condition'. The actual amount of virtual mass remains to be determined.

(4) The base of the pier is found apparently more flexible in case of dynamic test than the static pull test perhaps due to the vibration of mass of foundation. This effect will be significant in design and must be investigated further.

(5) For the rocker pier, the higher mode frequencies are rather far removed from the fundamental. Therefore, for dynamic calculations, the fundamental mode only is of significance.

Acknowledgement

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