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EARTHQUAKE OBSERVATION OF AN EMBEDDED STEEL PLATE CELLULAR BULKHEADS

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SUMMARY

A new aseismic design method for the embedded steel plate cellular bulkhead has been already proposed by authors (Refs.1,2,3), based on shaking table tests. In order to verify the validity of the design method, earthquake observations for an actual structure were performed.Through the observed results, it was confirmed that the design method developed can be applicable to evaluate the earthquake stability of steel plate cellular bulkheads.

INTRODUCTION

The embedded steel plate cellular bulkhead has been developed as a new type of sea wall which is applicable for poor sea bed and deep water sites. For this structure, a new aseismic design method using spring-solid cell model, based on shaking table tests, has been proposed and has been in practical use. For the prevalence of the design method developed, it has been desired to verify the validity of the design method and accumulate the fundamental data on the actual structure under earthquake conditions. Therefore, measurements of the dynamic behavior of the actual structure under earthquake conditions have been performed at Wakayama in Japan from 1984, to investigate the dynamic characteristics of the cell, earth pressure, and effective mass of cell fill. Moreover, in order to obtain the analytical method for evaluating the earthquake behavior of these structures, numerical analysis by finite element model has been performed.

This paper describes the outline of earthquake observation results, and the comparison with the calculated results by the design method proposed.

OUTLINE OF EARTHQUAKE OBSERVATIONS

Embedded steel plate cellular bulkheads were constructed in Wakayama Prefecture, and Fig. 1 shows the outline of the structure. Dimensions of each cell were 19.5 m in diameter and 20 m in height and 57 cells were used. The embedded lengths of cells and arcs were 6 m. The original soil consists of a soft ground made of silty clay down to the depth of 18 to 20 m from the sea bed, whereas the cell foundation ground underwent a soil improvement work.

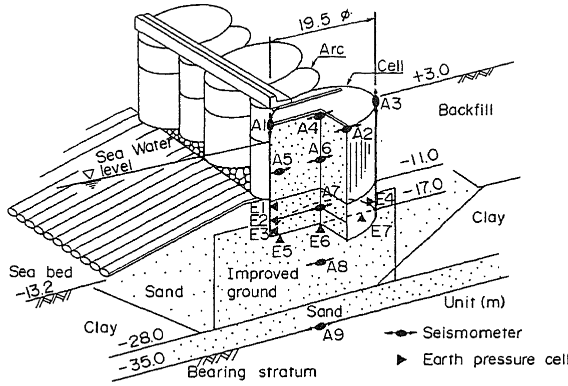


Fig. 1 Outline of embedded steel plate cellular bulkheads

Table 1 Observed earthquake

Record NO.		8	13	17	23	41
Date		1984 6.25	1984 8.7	1984 9.14	1985 1.6	1985 12.9
Epicenter region		Wakayama hokubu	Huyga-nada	Naganoken seibu	Wakayama hokubu	Wakayama hokuseibu
Magnitude		4.4	7.1	6.8	5.5	3.3
Depth (Km)		6	33	2	69	8
Distance (Km)		4	344	284	41	7
Intensity (Wakayama)		III	—	I	III	III
Max. acc. (gal)	Bearing stratum	33	4	2	9	2
	Top of the cell	61	6	5	16	4

Figure 2 shows the soil profile and the S wave velocity. The monitoring items were the acceleration in the ground, the cell fill, and the top of the cell, and earth pressure at the front, the bottom, and the back of the cell. The locations of pick up is shown in Fig.1.

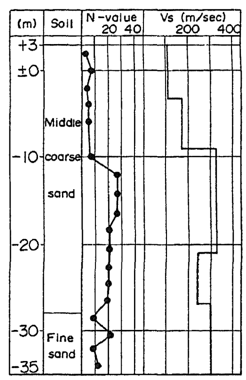
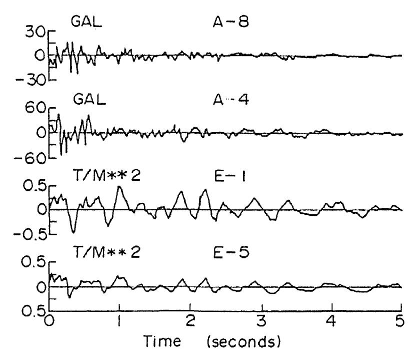
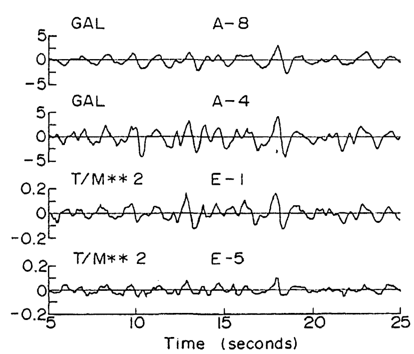


Fig.2 Soil profile



(a) Wakayama-hokubu earthquake (NO.8)



(b) Naganoken-seibu earthquake (NO.17)

Fig.3 Observed waves

OBSERVATION RESULTS

Observed Earthquakes

During past 4 years, 52 earthquakes were recorded although most of their seismic intensities fell within the degrees I and II. Among these earthquakes, 5 earthquakes were shown in Table 1, as examples of those having a comparatively larger acceleration, those having a higher predominant frequency, and those having a lower one. Figure 3 shows a part of accelerations and earth pressures recorded as No. 8 and No. 17. From Table 1 and Fig. 3, it is known that the earthquake having the biggest acceleration was recorded as No. 8 with an epicentral distance of approximately 4 km away from the point of observation. This earthquake was located quite near the observation point , moreover, the earthquake showed a predominant high frequency component. The record No. 17 belongs to a long distance type and has a predominant low frequency component.

Dynamic Characteristics Adding the records No. 13 and No. 23 to the foregoing 2 records, the dynamic characteristics of bulkhead was investigated.

Fourier spectrum of ground A8 is shown in Fig. 4 and the transfer function of the top of the cell A4 with respect to the A8 is shown in Fig. 5.

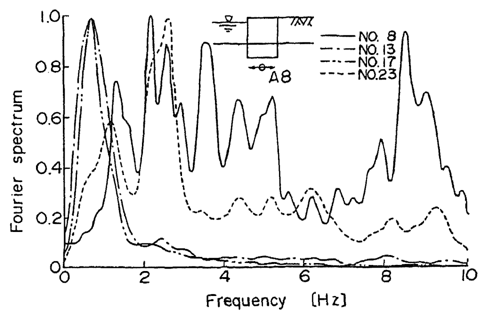


Fig.4 Fourier spectrum of ground (A8)

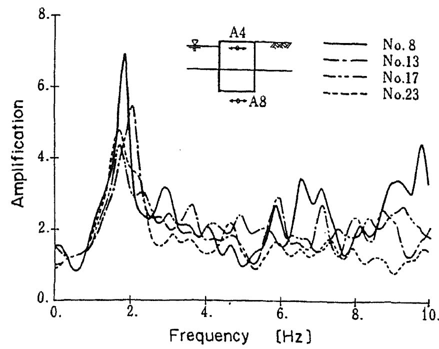


Fig.5 Transfer function of the top of the cell (A4/A8)

From Fig. 4, it is confirmed that the 0.6 to 0.7 Hz component is predominant in the case of earthquakes No. 13 and No. 17 having long epicentral distances, while the 2.1 to 2.5 Hz component is predominant in the cases of earthquakes No. 8 and No. 23 having short epicentral distances. In the case of No. 8, however, the earthquake includes 8.5 Hz, 3.5 Hz, 1.3 Hz, and other many frequency components besides the above-mentioned frequency. Judging from that the peak center is located around approximately 2 Hz in any case of earthquakes in Fig.5, this frequency is considered to be the 1st natural frequency of the cell.

Figure 6 shows the transfer functions of several areas of cell with respect to the record No. 8. The peak of about 2Hz in Fig.6 is caused by the 1st mode of rocking whose center is located lower than the bottom of the cell. The peaks at 6 Hz and over are considered to be caused by the dynamic characteristic of the cell fill.

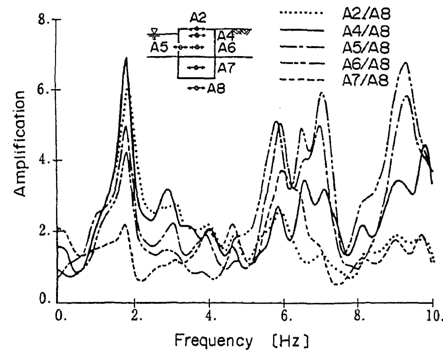


Fig.6 Transfer function (NO.8)

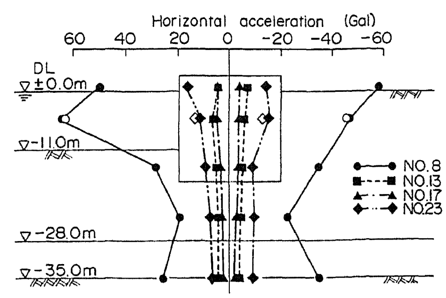
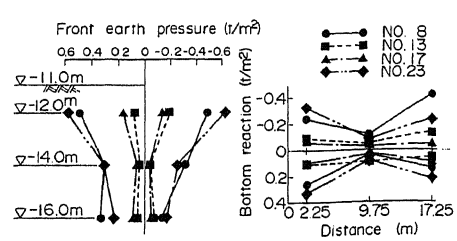


Fig.7 Distribution of maximum acceleration



(a) Front earth pressure (b) Bottom reaction

Fig.8 Distribution of maximum earth pressure

Dynamic Behavior of Ground and Cell during Earthquakes

(1) Distribution of Maximum Values of Acceleration and Earth Pressure

The distribution of maximum acceleration of ground and cell of records No. 8, No. 13, No. 17, and No. 23 are shown in Fig. 7 and distribution of maximum values of earth pressure at the front of the cell and bottom reaction are shown in Fig. 8.

Through Fig. 7 it is confirmed that amplification is not necessarily uniform in the direction of height partly due to high frequency component in the case of No. 8. However, the higher part of the cell tends to show greater acceleration. With respect to No. 13, No. 17, and No. 23, the acceleration grows almost uniformly from the lower part to the upper part of the cell.

Figure 8(a) reveals that distribution of maximum values of the front earth pressure shows the triangle distribution with the largest value near the sea bed. Figure 8(b) shows that the distribution of maximum values of bottom reaction proves to be greater at the front and back sides of cell, and to be similar to that of gravity type quaywalls.

Although maximum acceleration in the case of No. 23 is considerably smaller than that of record No. 8, maximum values of front earth pressure and bottom reaction of both records are almost the same, accordingly, as far as the earth pressure values are concerned, they do not always correspond to acceleration level. As a fact coming from Fig. 4, No. 8 has predominant high frequency components besides 2.1 to 2.5 Hz, whereas No. 23 has a predominant component being similar to the 1st natural frequency of the cell. Therefore, it is considered that the displacement response at No. 23 was almost the same as that of No. 8, although the acceleration level was low.

Since earth pressure can be regarded as subgrade reaction based on relative displacement of the cell and the ground, dynamic characteristics of the cell and the ground will have to be taken into consideration in order to investigate the dynamic earth pressure precisely.

(2) Distribution of Acceleration and Earth Pressure at One Simultaneous Time

The distribution of acceleration and dynamic earth pressure in records No. 17 and No. 8 are shown in Fig. 9. In the case of No. 17 in Fig. 9(a), the distribution of acceleration becomes greater in the higher part of the bulkhead, and the distribution of dynamic component of front earth pressure becomes greater in the vicinity of the sea bed. Furthermore, the distribution of dynamic component of bottom reaction is similar to that of gravity type quaywalls. Judging from these distributions and Fig. 5, the predominant mode of cell is rocking having the natural frequency 2 Hz. The accelerations at the measuring point A5 and A6 of the same height have almost the same phases and values.

On the other hand, in the case of No. 8 in Fig. 9(b), acceleration distribution in the vertical direction is not uniform, accordingly, both phases and values at the measuring points A5 and A6 with the same height differ from each other. It is considered that this difference based on high frequency components in the case of No. 8. However, since the distribution of front earth pressure and bottom reaction shows the same tendency as Fig. 9(a), it is considered that the overall behavior of cell is rocking mode at about 2 Hz.

Judging from the foregoing, both cell behavior and earth pressure distribution correspond

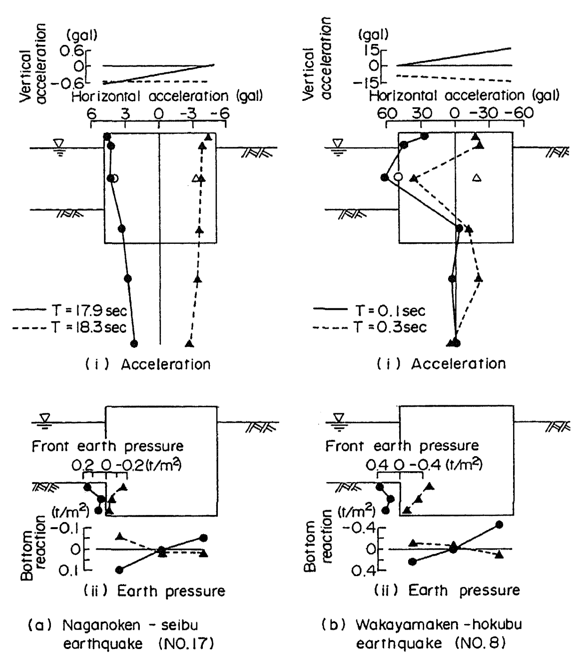


Fig.9 Distribution of acceleration and earth pressure

qualitatively to the results of shaking table test(Ref.1). Consequently, it is confirmed that a proposed design method based on shaking table tests is appropriate.

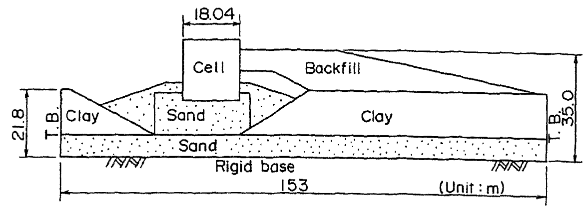


Fig.10 Analytical model

RESPONSE CALCULATION BY FEM

In order to obtain an analytical method capable of expressing behavior of embedded steel plate cellular bulkheads during earthquake, the calculated results by the FEM were compared with the observed results. The computer program employed is the modified FLUSH(Ref.4). Calculation model is illustrated in Fig. 10. With respect to No. 23, the comparison between the waves of acceleration and earth pressure observed and the waves calculated by FEM are shown in Fig. 11. From the figure, it is obvious that the calculated values of acceleration agree with observed values, and with respect to earth pressure, a similar tendency is recognized although there are a few differences between the observed waves and the calculated waves. Therefore, it is considered that cell behavior during earthquake can be predicted by FLUSH.

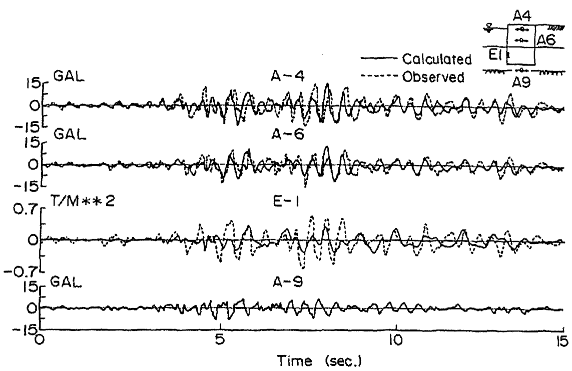


Fig.11 Comparison of waves between observed and calculated by FLUSH (NO.23)

STABILITY CALCULATION BY THE NEW DESIGN METHOD

The new design method was applied to the cell and the calculated result was compared with observed values of earth pressure, where design seismic coefficients were assumed to be values obtained by dividing maximum acceleration at the A7 with gravity acceleration.

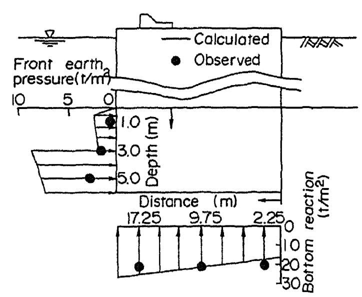


Fig.12 Distribution of earth pressure compared with results calculated by the new design method

With respect to the record No. 8 (33 gal) whose ground acceleration is the largest, the comparison of observed values with calculation values concerning the front earth pressure and bottom reaction is shown in Fig. 12. The observed values of the front earth pressure and bottom reaction given here are the additions of maximum values of dynamic components and earth pressures at rest calculated by $\Sigma 1/2 \gamma h$ and $\Sigma \gamma h$, respectively.

The same design calculations were applied to other earthquake records, and the comparisons were made with respect to the observed values of the front earth pressure E1 and bottom reaction E5 which are considered to remarkably reflect the cell behavior during earthquake. The results of comparison of these earth pressures with accelerations at the bearing stratum A7 are shown in Fig. 13 and Fig. 14 respectively.

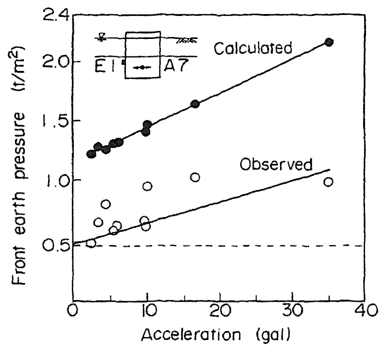


Fig.13 Comparison of front earth pressure between observed and calculated by the new design method

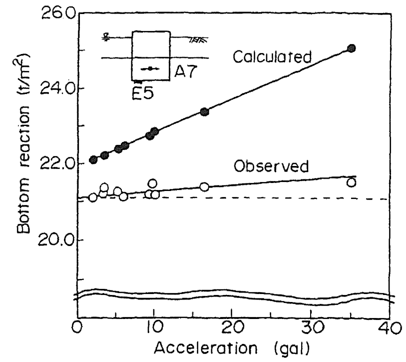


Fig.14 Comparison of bottom reaction between observed and calculated by the new design method

From Figs. 12 through 14, the calculated values are slightly greater than observed values. The new design method can give its result on the safety side.

CONCLUSIONS

(1) During earthquakes, the predominant mode of the cell is rocking as was observed in shaking table tests, and its first natural frequency is about 2Hz.
(2) The distributions of the front earth pressure and bottom reaction measured during earthquakes were close to those of the rocking mode of the cell. These facts assure the appropriateness of the fundamental assumption of the new design method.
(3) Earth pressure of the actual structure calculated by the new design method gives safety side values comparing with measured values. Along with the results described in (2), it is confirmed that the design method is applicable for evaluating the earthquake stability of steel plate cellular bulkhead.
(4) The analytical method using the modified "FLUSH"gives good agreement with measured results. Therefore, this analytical method is effective for evaluating the earthquake behavior of these structures.

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