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THE SURFACE FLOW STRUCTURE OF LARGE SCALE VORTICES AT THE REAR OF A CYLINDRICAL PIER FOR THE FLOW OF TRANSCRITICAL REYNOLDS NUMBER

by

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SYNOPSIS

The surface flow structure of large scale vortices at the rear of a cylindrical pier is studied for the flow of transcritical Reynolds number over 10^8. The field observation around AKASHI KAIKYO OHASHI bridge pier was carried out. Water surface images were taken from top of the main tower using video cameras. And an image analysis method using a correlation method for the calculation of two dimensional velocity distribution of surface was examined. In the rear side of the pier, large scale vortices like Karman vortices were seen by video and MEM spectrum of surface velocity fluctuation.

INTRODUCTION

The study on the surface flow structure around a cylindrical pier has a long history. Leonardo da Vinci sketched a detailed observation record on water surface movement around a pier[1]. Later, based on the study on Karman Vortex Street by Karman, Roshko[2] who directed his attention to the change of resistance against a cylinder in accordance with the value of Reynolds number (hereinafter referred to as R_e), named the region where R_e exceeds 3.8×10^5 as "transcritical" region.

In order to increase R_e, it is necessary to increase the access flow velocity and the diameter of a cylinder. Therefore, R_e remains 10^7 or less in a wind tunnel test. In the region of $R_e=10^7$, the only data available is the value obtained from a field measurement carried out by Sanada et al.[3] where the wind worked on a big chimney at $R_e=1.1$ to 2.8×10^7. Tsuchiya[4] shows that large scale vortices equivalent to Karman vortices were observed in the wake of Cheju Island, using a satellite photo at $R_e=2.0\times10^{10}$. The Karman vortex occurrence at R_e 2.0×10^{10} is due to the turbulent access flow, and if coefficient of eddy viscosity is used instead of kinematic viscosity, the value of R_e becomes around 200, which corresponds to the phenomenon obtained in a laboratory experiment[5].

Ishino et al.[6] carried out the field measurement of the surface flow structure around a cylindrical pier (a main cylindrical pier 3P of the Akashi Kaikyo Ohashi bridge, which is now under construction) in the region of $R_e=10^8$, for the first time in the world, and examined the flow structure. Ishino et al.[6] visually observed the flow pattern around the 3P caisson, and measured the following items with the instruments: (1) velocity of incident flow, (2) water surface configuration on the caisson sidewall, (3) velocity of surface flow 5m below the water surface around the caisson, and (4) velocity of bottom flow 1.5m above the top of riprap around the caisson. The following results were obtained from this measurement: (i) When the velocity of incident flow was at 3.3m/sec, the period of the shed vortex occurrence from the 3P caisson was approximately 30 seconds. (ii) The water level changed with a period four times as large as that of the shed vortex occurrence. (iii) The Strouhal number ($S_t=f\cdot D/u$; where, f : the frequency of the generated vortices, D : diameter of the caisson, u : velocity of incident flow) calculated by using the fourfold period of shed vortex was 0.21, which nearly agreed with the value S_t=0.19 to 0.26, measured by Sanada et al.[3] in the range of R_e=1.1 to 2.8×10^7. From this, it was assumed that large scale vortices with S_t=0.21 in the region of $R_e=10^8$ caused the water level change, though large scale vortices could not be observed at the rear of the 3P caisson. After this, Ishino (one of the authors) got a chance to record by cameras and 8mm video cameras the occurrence of large scale vortices at the rear of the 2P and the 3P caisson from the 300m-high main tower constructed on the 3P caisson. In this study, the authors discussed the occurrence of large scale vortices at the rear of the 2P and the 3P caisson, using pictures and images taken from top of the main tower, as well as using an image analysis technique which Fujita et al.[7] developed by applying a correlation method, for the quantitative discussion.

THE MAIN PIER FOUNDATION 3P CAISSON AND THE MAIN TOWER AT THE AKASHI KAIKYO OHASHI BRIDGE

As shown in Figs. 1 and 2, the Akashi Kaikyo Ohashi bridge is a 3910m-long suspension bridge between Tarumi-ku, Kobe City and Awajishima Island with the center span of 1990m. The main pier foundation is the 3P caisson, a 62m-high steel caisson of diameter 78m, which was installed on the sea bed of 57m deep, as shown in Fig. 3. The sea bed was originally 37m deep and was excavated 20m deep.

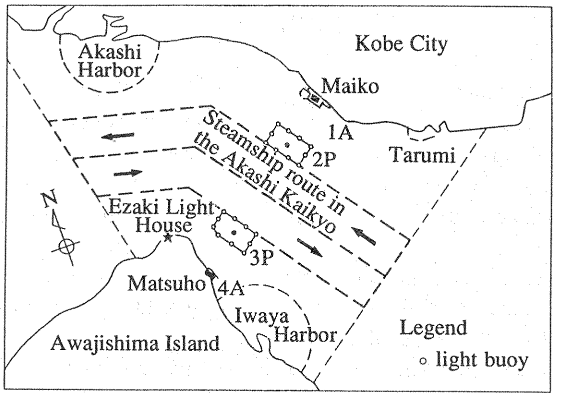


Fig. 1. Location of the Akashi Kaikyo Ohashi bridge

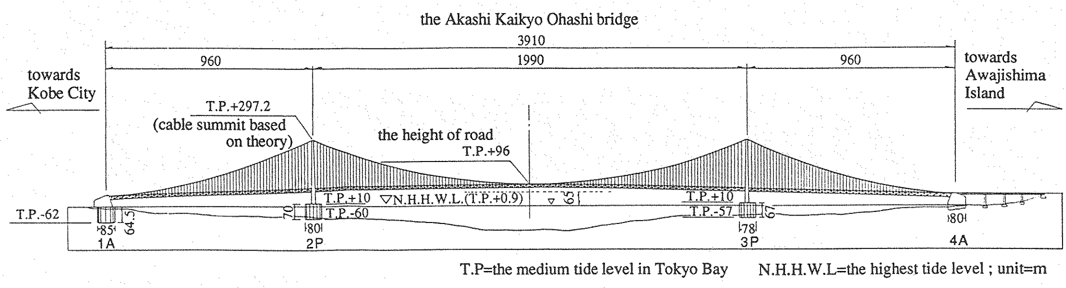


Fig. 2. Vertical cross sections of the Akashi Kaikyo Ohashi bridge

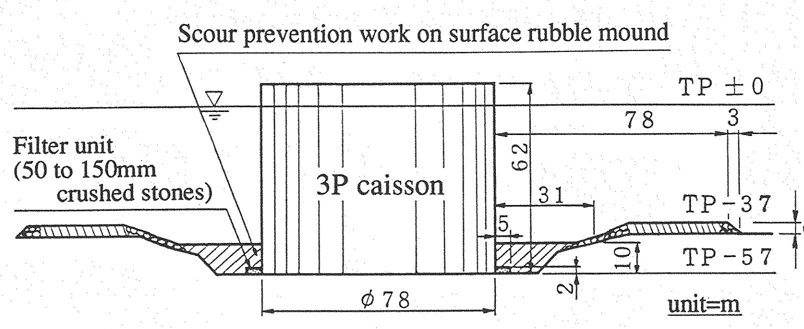


Fig. 3. The 3P caisson and scour prevention work

Since the maximum velocity of tidal currents at the Akashi Kaikyo Strait was observed as high as 8kt (4.1m/sec), scour prevention work was carried out on the sea bed around the pier foundation. The scour prevention work consisted of two methods: one was using a filter unit, a net filled with 1-ton bags of 50 to 150mm crushed stones, and the other was using riprap of 1 to 2 tons. The filter unit was placed 2m thick from the excavated sea bed and 5m wide around the 3P caisson. Rubble mound was placed on the filter unit with a thickness of 8m, which backfilled the excavated hole halfway[8]. As shown in Fig. 2, the overall height of the main tower is 283m, whose top is TP + 297.2m above the sea level.

FIELD OBSERVATION

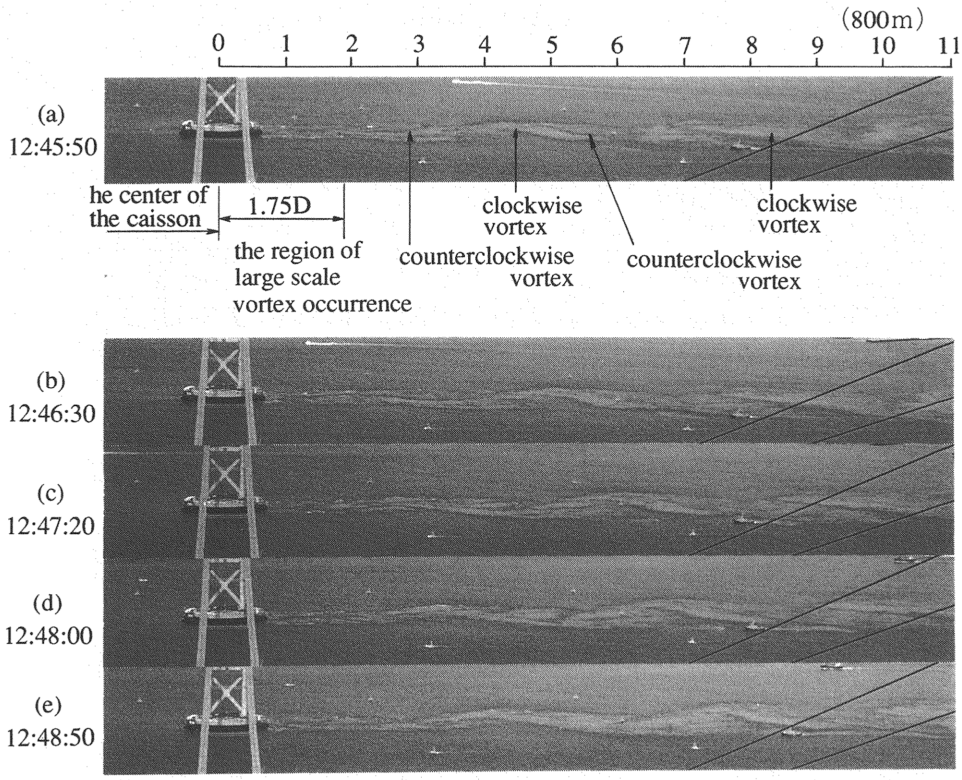
The field observation was carried out at the spring tide on May 24, 1994, from 10:30 to 14:45. The tidal current was flowing eastward into Osaka Bay, and according to the predicted tidal table, the peak flow velocity of 3.2m / sec (6.2kt) was obtained around 12:32.

From the top of the main tower of the 3P caisson, the surface flow structure at the rear of the 3P caisson was recorded by cameras and 8mm video cameras, while the surface flow structure at the rear of the 2P caisson was recorded only by cameras.

DISCUSSION ON THE SURFACE FLOW STRUCTURE RECORDED BY CAMERA AND VIDEO CAMERA

Surface flow structure at the rear of the 2P caisson

Pictures 1 (a), (b), (c), (d), and (e) show the surface flow structure at the rear of the 2P caisson observed from the main tower of the 3P caisson. These pictures indicute the followings:



Picture 1. Surface flow structure at the rear of the 2P caisson observed from the main tower of the 3P caisson

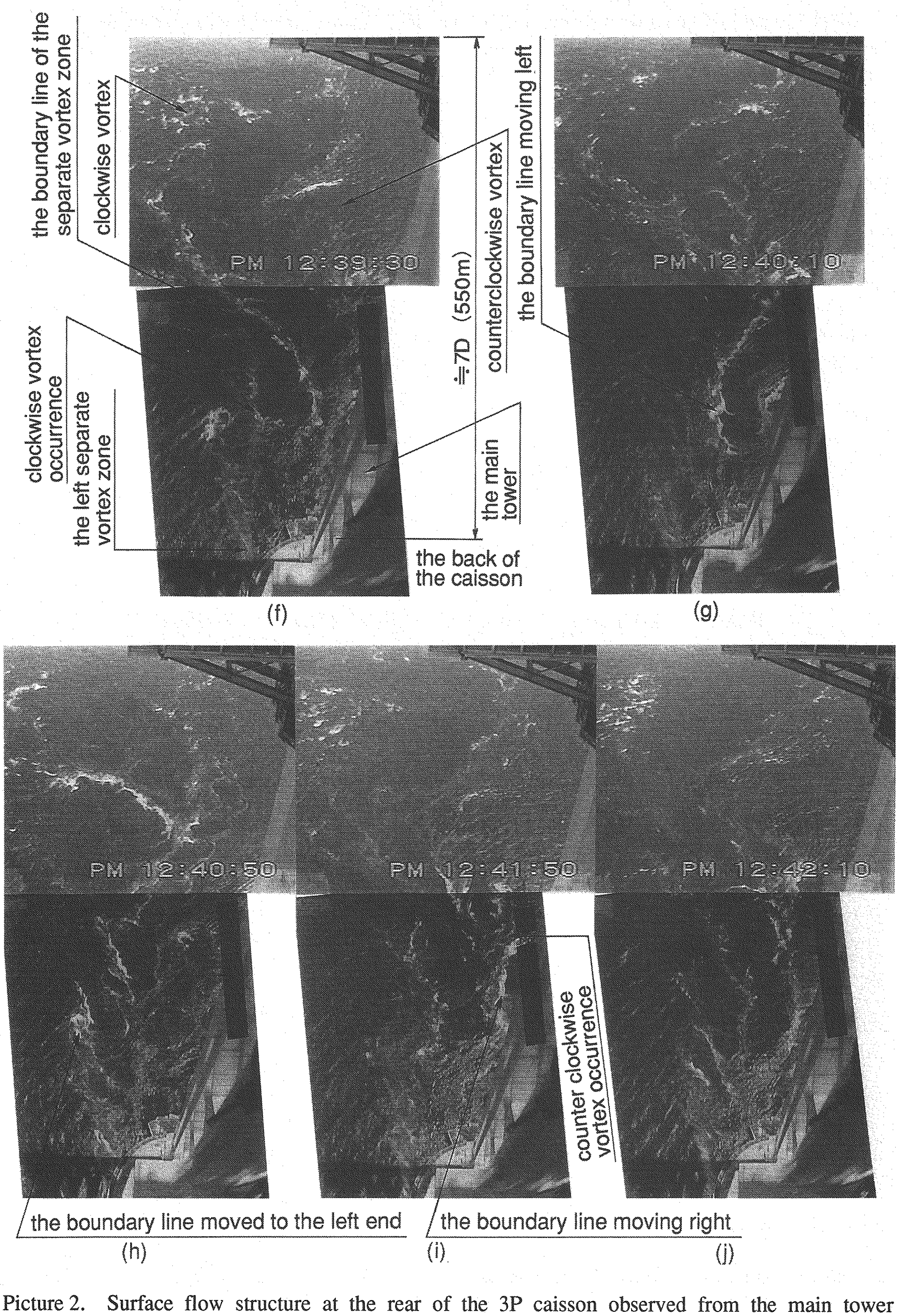
- in Picture (a), the large scale vortices with counterclockwise rotation, equivalent to Karman vortices, were distinct in the region between 1.75D to 3.5D downstream from the center of the caisson.
- in Picture (b), 40 seconds after (a), the counterclockwise vortices were flowing downward and the clockwise vortices occurred.
- in Picture (c), 90 seconds after (a), the clockwise vortices were distinct.
- in Picture (d), 130 seconds after (a), the clockwise vortices were also flowing down and the new counterclockwise vortices occurred.
- in Picture (e), 180 seconds after (a), the counterclockwise vortices similar to those in Picture (a) occurred again.

From these pictures, it was concluded that the period of the large scale vortex occurrence was approximately 180 seconds.

As shown in Picture 1, the counterclockwise vortices were more distinct than the clockwise vortices, which will be explained by the Coriolis effect pointed out by Nishimura et al.[9].

Surface flow structure at the rear of the 3P caisson

Pictures 2 (f), (g), (h), (i) and (j) show the surface flow structure at the rear of the 3P caisson at a distance of 7D from its center, observed from the main tower of the 3P caisson. Pictures 2 and the video images indicate the followings:
- in Picture (f), a clockwise vortex occurred downstream and to the left of the caisson, the



Picture 2. Surface flow structure at the rear of the 3P caisson observed from the main tower of the 3P caisson

counterclockwise vortices were observed in the shed vortex zone and the downstream, and another clockwise vortex was observed further downstream. In the center of the picture, a boundary line between the right and left shed vortex zones (hereinafter referred to as boundary line) at the rear of the caisson was clearly visualized by white bubbles.
- in Picture (g), 40 seconds after (f), the boundary line at the rear of the caisson started to move left. Meanwhile, a shed vortex from the caisson was flowing down at 20-second intervals.
- in Picture (h), 80 seconds after (f), while the boundary line was moving left, a counterclockwise vortex occurred on the right of the boundary line. A clockwise vortex occurred where a counterclockwise vortex had been in Picture (f), and about four shed vortices were confined in the left shed vortex zone.
- in Picture (i), 120 seconds after (f), as the energy in the left separate vortex zone was confined into a smaller area compared to the right zone at the rear of the caisson, the boundary line started to move right due to the repulsion of this energy.
- in Picture (j), 160 seconds after (f), flow structure similar to that in Picture (f) was formed again.

From the above observation, it can be summarized as follows:
- within the region 1.75D from the center of the caisson, the energy of shed vortices occurred from the caisson at 20-second intervals became imbalanced between the right and left zones. Then, the shed vortices were converged at 160-second intervals in the region further than 1.75D downstream, forming large scale clockwise and counterclockwise vortices, which were as large as Karman vortices.

IMAGE ANALYSIS OF LARGE SCALE VORTEX OCCURRENCE

Outline of an image analysis technique

As shown in Picture 2, the boundary line (white bubbles) was developed on the water surface along with the large scale vortex occurrence. The changes in the vortex occurrence were described in '*Surface flow structure at the rear of the 3P caisson*'. Here, regarding the pattern of white bubbles as a tracer of the changes in the large scale vortex shedding process, the quantitative time series analysis was carried out, by applying a correlation method, one of the image analysis technique. Images taken by a video camera were quantized into graphic data with 512×512 picture element with 256 gradation monochrome, using image processing board (produced by DETECT) installed in a personal computer (NEC, PC9801RA21). The images for 30 minutes starting from 12:30:00 were analyzed and quantized at 2-second intervals, resulting in about 1,000 frame pictures. Then, each frame picture was divided into an odd number field and an even number field, and about 2,000 pictures at one-second intervals were adjusted to be the same size as a frame picture. In other words, in the analysis the velocity vectors of 1,000 pictures at a sampling frequency 1Hz were used.

The pictures of the rear of the 3P caisson and the back of the 3P caisson were taken by a video camera. Though the picture of the rear of the 3P caisson was taken at a diagonal angle, it was not corrected as it was taken from the high altitude. The size of one picture element was obtained as 0.336m using the diameter of caisson (78m) as a scale. As a referential frame size for pattern matching in a correlation method was given as 25×25 picture element, each flow velocity vector can be regarded as the representative value in a flow area of about 8.4m×8.4m.

Two-dimensional flow velocity distribution

Figures. 4 (a) and (b) show the distribution of flow velocity in the region used in the

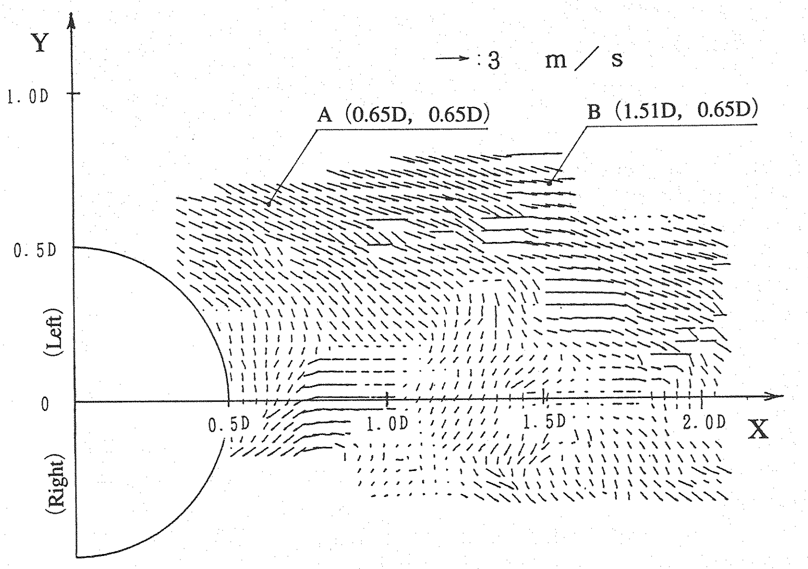


Fig. 4 (a) Two-dimensional plane distribution of flow velocity obtained from an image analysis (corresponding to Picture 2 (f))

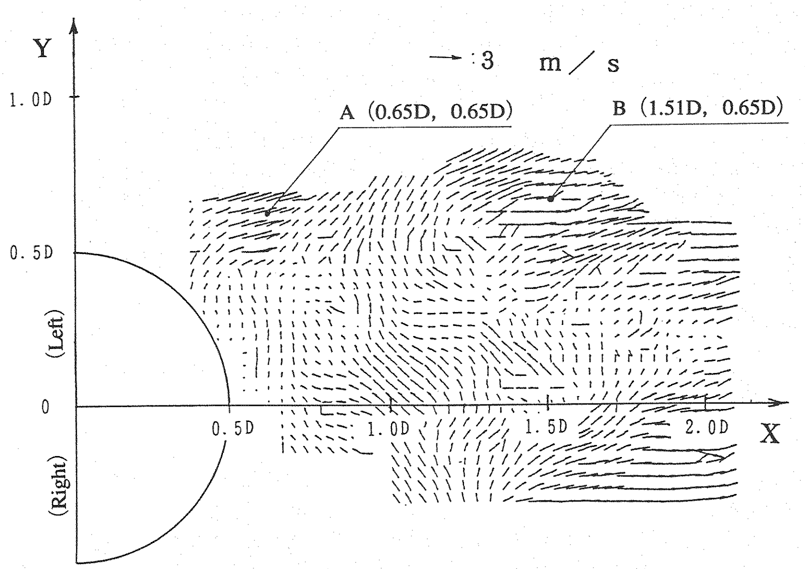


Fig. 4 (b) Two-dimensional plane distribution of flow velocity obtained from an image analysis (corresponding to Picture 2 (h))

image analysis, corresponding to Pictures 2 (f) and (h), respectively. These figures show the spatial movement in the right and left separate vortex zones. Around the boundary line of the shed vortex zones, the flow to the center of the caisson in Fig. 4 (a), and the flow to outward in Fig. 4 (b) were distinguished, and the flow direction reversed at 80-second intervals. The divergent vector around (X, Y)=(1.5D, 0) in Fig. 4 (b) was obtained as a result of the collision of upwelling flow (boil) with water surface, which was also confirmed in the picture taken by a video camera.

Time series characteristics of flow velocity at the fixed points

Figure. 5 shows the time series of flow velocity at three points obtained from the image analysis. The method of moving averages was taken in order to eliminate the components with high frequency, so it was clearly described how the components with low frequency were distinguished as they moved away from the caisson. Figure. 6 shows MEM spectrum which was obtained in order to examine the characteristics of frequency. Each spectrum had multiple peak values. At the point A (0.65D, 0.65D) near the caisson, the peak frequency was about 0.012Hz (the period = about 80 seconds), which backed the discussion in '*Surface flow structure at the rear of the 3P caisson*'. At the point B (1.51D, 0.65D) a little apart from the caisson, the peak frequency was about 0.007Hz (S_t=0.17, the period= about 140 seconds), shifting to the lower frequency side. This period is close to the period of 160 seconds estimated using Pictures 2 and Fig. 4.

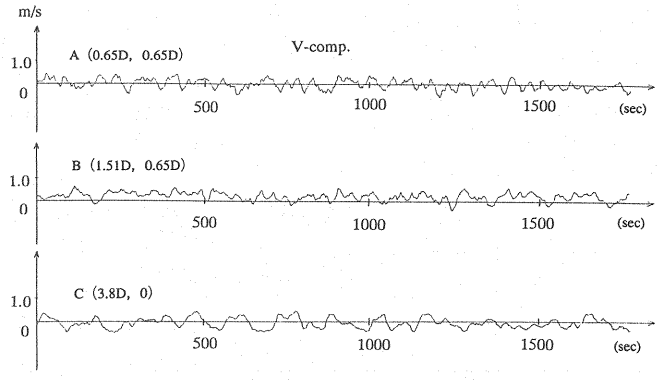


Fig. 5. Time series of flow velocity component V in the direction of Y at the fixed points (A, B, C) obtained from an image analysis

At the point C (3.8D, 0) further from the caisson, the peak became more and more distinguished, while the second and third peaks diminished. It can be said that the shed vortices were converged and small scale vortices diminished as they were flowing downward, and thus large scale vortices became distinct. However, since the points B and C were in a short distance, the peak frequency did not shift to the lower frequency side.

DISCUSSION ON THE PERIOD OF LARGE SCALE VORTEX OCCURRENCE AND THE STROUHAL NUMBER

Based on the data such as the water surface configuration around the caisson, flow velocity spectrum and the period of the shed vortex occurrence from the 3P caisson (30 sec), which were obtained from the field observation in October 1989 when the incident flow velocity was 3.3m/sec in the westward, Ishino et al.[6] indicated that the period of large scale vortex occurrence at the rear of the 3P caisson was four times as large as that of shed vortex occurrence which was 30 seconds. From the result of this observation, the Strouhal number was obtained as S_t=0.21, which almost agreed to the measured value S_t=0.19 to 0.26 with $R_e=10^7$.

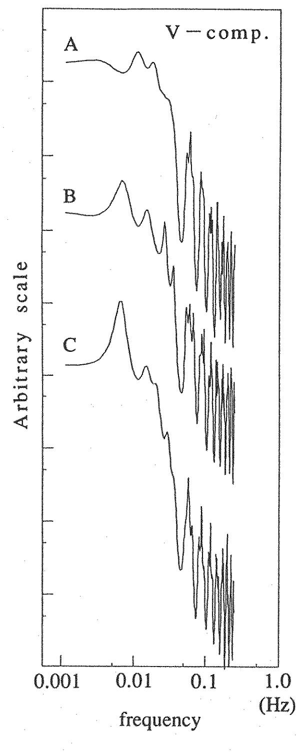


Fig. 6. MEM spectrum of flow velocity at the fixed points (A, B, C) obtained from an image analysis

According to the results from the field observation in May 1994 when the incident flow velocity was 3.2m/sec in the eastward, the period of shed vortex occurrence from the left side of the caisson was 20 seconds, and the period of large scale vortex occurrence, equivalent to

Karman vortex, was 160 seconds which was eight times as large as that of shed vortex occurrence.

From the result of this field observation, the Strouhal number was obtained as S_t=0.15. The following are the differences between the above two field observations:

- The season differed; one was carried out in May, while the other was in October.
- The flow direction was opposite; one was westward, while the other was eastward.
- In October 1989, there was no structure around the caisson which might cause large roughness, while in May 1994, scaffolding struts were constructed around the caisson 5m below the water surface, which caused the roughness and turbulence on the water surface.

As Kimura[5] pointed out, when R_e is large, R_{eT} can be estimated as in the following equation using coefficient of eddy viscosity ($\nu_T=10^7 cm^2/sec$; Nakatsuji et al.[10] numericaly calculated at the Akashi Kaikyo Strait) instead of kinematic viscosity (ν), since the incident flow was turbulent.

$$R_{eT} = \frac{u \cdot D}{\nu_T} = \frac{3.2 \times 10^2 \times 78 \times 10^2}{10^7} = 250$$

Here, R_{eT} changes largely in accordance with the changes in ν_T. Also, the Strouhal number changes significantly when R_e (R_{eT}) is in an order of 10^2 (for example Roshko[2]). We assume that this is why S_t values obtained from the observational data in October 1989 and in May 1994 differed.

CONCLUSION

Through the field observation from the top of the main tower on the 3P caisson of the Akashi Kaikyo Ohashi bridge, large scale vortex occurrences equivalent to Karman vortex in the rear of the 2P and the 3P caissons were examined. The following results were obtained, where Pier Reynolds number using kinematic viscosity was $R_e=2.5\times10^8$, and Pier Reynolds number for turbulent flow using eddy viscosity ($\nu_T=10^7 cm^2/sec$[10]) instead of kinematic viscosity (ν) was R_{eT}=250.

(1) Within the region of 1.75D from the center of the 3P caisson, the energy of vortices shed from the caisson at 20-second intervals became imbalanced between the right and left zones, and in the region further than 1.75D downstream formed large scale clockwise and counterclockwise vortices equivalent to Karman vortices at 160-second intervals, which was eight times as large as that of shed vortices, 20 seconds.

(2) Pictures taken by a video camera were analyzed by an image analysis technique applying a correlation method, and the following results were obtained:

- In two-dimensional distribution of moment flow velocity obtained using each flow velocity vector as the representative value of a flow area of about 8.4m × 8.4m, the movement of the boundary line of the shed vortex zones and upwelling flow (boil) can be reproduced well as in a recorded video image.
- MEM spectrum was obtained using values of velocity vector with 1,000 pictures which were obtained at sampling frequency 1Hz. It was observed that as the distance from the caisson increased, the spectrum peak with lower frequency corresponding to a large scale vortex became distinguished, while the spectrum peak with higher frequency corresponding to a separate vortex diminished.
- In the field observation in October 1989, on the westward current, the incident flow velocity was 3.3m/sec and the period of shed vortex occurrence from the caisson was about 30 seconds, while in the field observation in May 1994, on the eastward current, the incident flow velocity was 3.2m/sec and the period was about 20 seconds. In both cases, changes in water

surface and flow velocity were even-numbered times as large as the period of shed vortex occurrence. It is assumed that the difference in the period of shed vortex occurrence was caused by the differences in season, flow direction (east or west), and changes in eddy viscosity due to the presence of scaffolding struts around the caisson.

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