DISASTER PREVENTION RESEARCH INSTITUTE
BULLETIN No. 30 DECEMBER, 1959

VARIATIONS OF WIND PRESSURE AGAINST STRUCTURES IN THE EVENT OF TYPHOONS

BY

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BULLETINS

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1. Introduction

To determine design forces for wind on structures, it is customary assumed that the wind is a uniform flow of air and the pressure is estimated by the drag of the structure under the suitable wind velocity. But the natural wind is not uniform in the velocity, so that its instantaneous value and distribution must be considered. Therefore, the varying wind pressure and the structural load must be first known in order to improve the wind-proof design of structures.

Many observations have been made and studied on the time-variations of wind velocities or pressures at one station, but their characteristics are so irregular that the essential part of this problem is not yet clear. Moreover, the simultaneous observation of wind at more than two stations, separated by a distance comparable to the scales of structures, is not known except the experiment by R.H. Sherlock[1]. Our method of experiment and procedure of analysis differs somewhat from those of Sherlock.

The wind near the ground is a turbulent flow, which is very complicated due to the influence of the surroundings. For its study, it is better to deal with the problem locally, in time and in space. The structures, such as buildings, steel-towers and bridges, have dimensions in the height and breadth, which are several meters or decameters, so we should consider the variation in wind velocity or pressure in the scales of these magnitude, but not in the large scales of wind observed for the weather report. Conversely, a very small variation of wind pressure should not been treated in this paper, as they have no influence on structures.

The fundamental natural periods of vibration of structures do mostly in range between 0.1 sec and 2.0 sec, so here the variations of wind pressure, which have these periods, come into question. Such variations of wind in time appear to have the above dimensions in space. Although there are few records available to show the periods of variations of wind shorter than 1 sec accurately, many structures have natural periods in this range, and the observations in these scales are very important for engineering.

Instruments, suitable for the wind observation from these view points, have not yet been developed. For this purpose, we have developed a new type wind-pressure-gage, and the records of wind observations carried out in 1956, 1957 and 1958 will be shown in the following section.

2. Instruments for observations

Instead of the wind velocity, we intended to measure the direct wind pressure on immovable planes, since the strength of structures is concerned with the wind pressure during a storm, and since structures are always immovable planes against the wind. The wind-pressure-gage, we have developed,

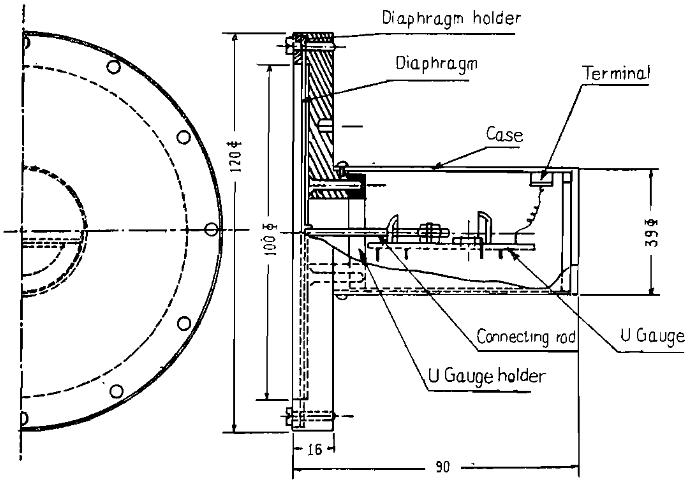


Fig. 1. Wind-pressure-gage.

is shown in Fig. 1. The pressure-plate is a disk, 10 cm in diameter, with unbonded wire-strain-gage. Records were obtained by an electro-magnetic oscillograph with galvanometers having natural frequencies of vibration of 15 cycles per sec.

The wind-pressure-gage was calibrated in a wind tunnel and its response was found to be linearly related to the wind pressure. The results are shown

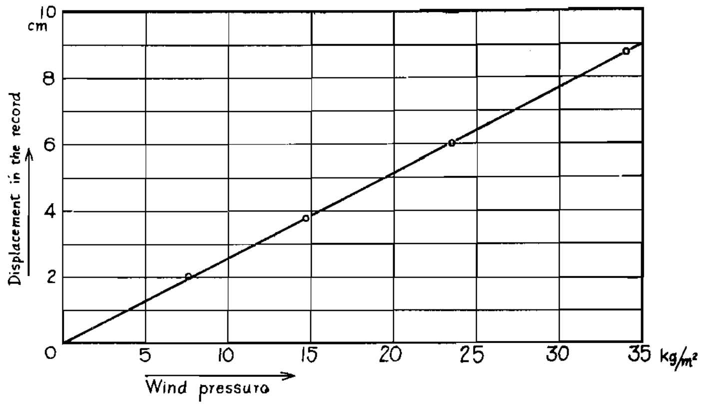


Fig. 2.

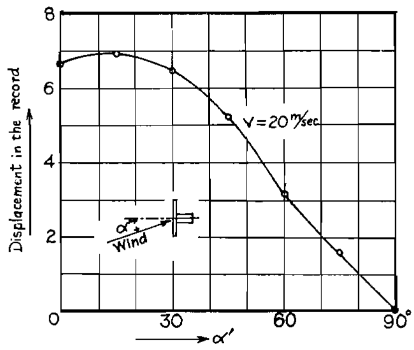


Fig. 3.

in Fig. 2. The response curve for various angle of inclination of the pressure-plate to the wind direction is shown in Fig. 3.

3. Storm observations

Fig. 4 shows a part of the records of wind pressure obtained during the typhoon on Sept. 27. 1956, at Magozaki, the Naruto Straits. The wind-pressure-gages were mounted on the railings of the lighthouse so as to measure the pressure in the average wind direction, that was the south-east, and the heights of pressure-gages were 9.5 m and 7.0 m above the ground. The locality, where the observations were made, was a headland, with cliffs

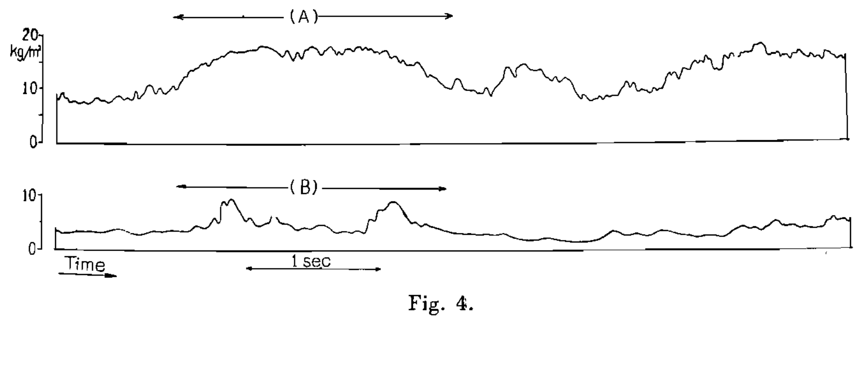


Fig. 4.

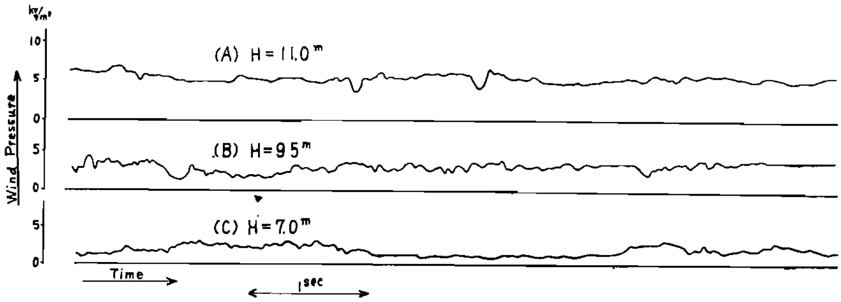


Fig. 5-1.

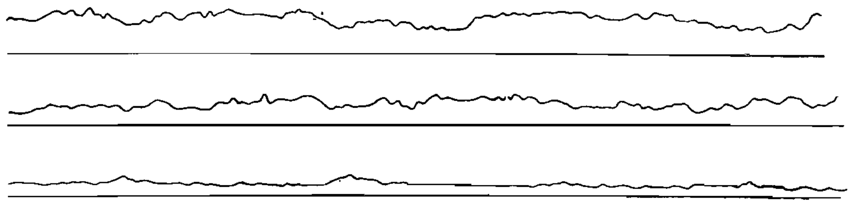


Fig. 5-2.

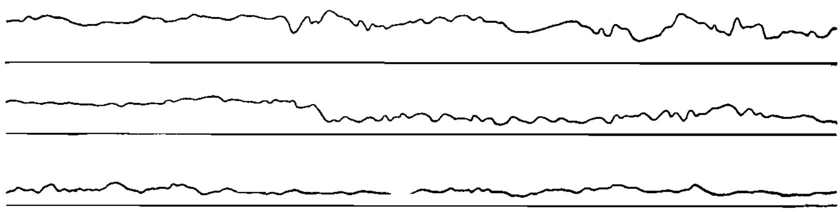


Fig. 5-3.

on both sides below the lighthouse, which was about 40 m above the sea-level. Fig. 5 shows the record obtained at the same place in the event of the typhoon of Sept. 27. 1957, but the heights of pressure-gages were 11.0 m, 9.5 m and 7.0 m above the ground, and the average wind direction was the north-west. The centers of the typhoons did not pass over the lighthouse, and therefore we could not get the records of the strongest wind.

Figs. 6, 7 and 8 are the parts of the records obtained at Shionomisaki, Wakayama Prefecture. The site, where the winds were observed, was near the sea coast and similar to the site on Naruto Straits. The record shown in Fig. 6 is obtained during the typhoon on Aug. 25. 1958, which passed over there. This is the record of the strongest wind we have observed, but the original record was indistinct by failure of the electric power, and the curves

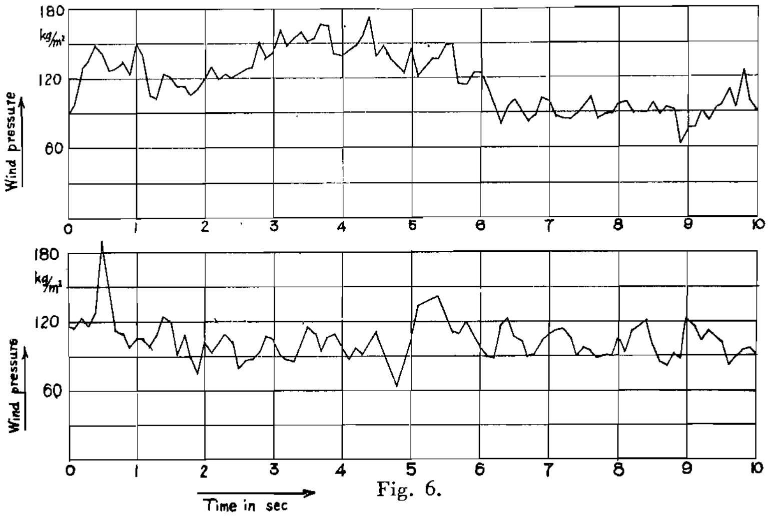


Fig. 6.

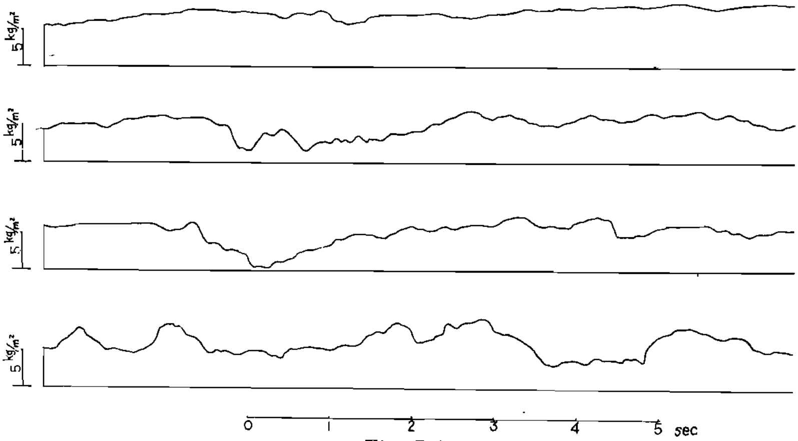


Fig. 7–1.

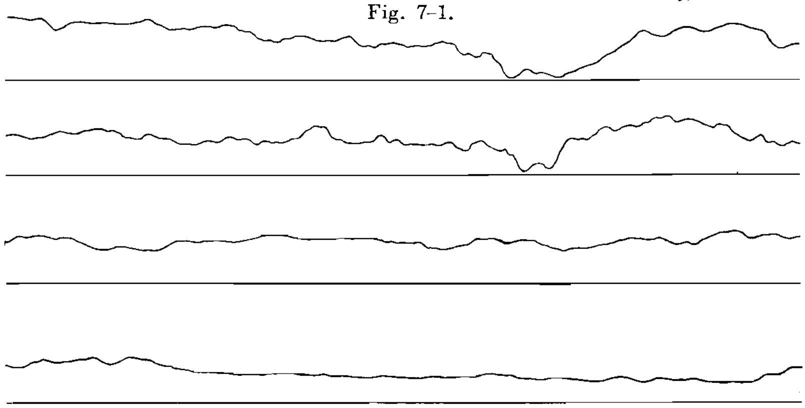
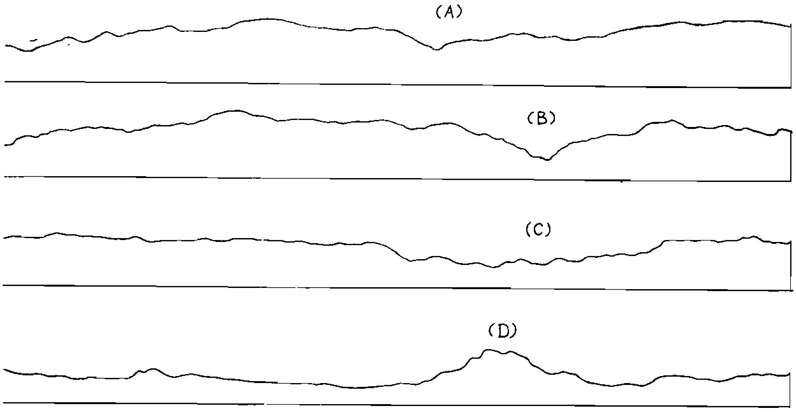


Fig. 7–2.



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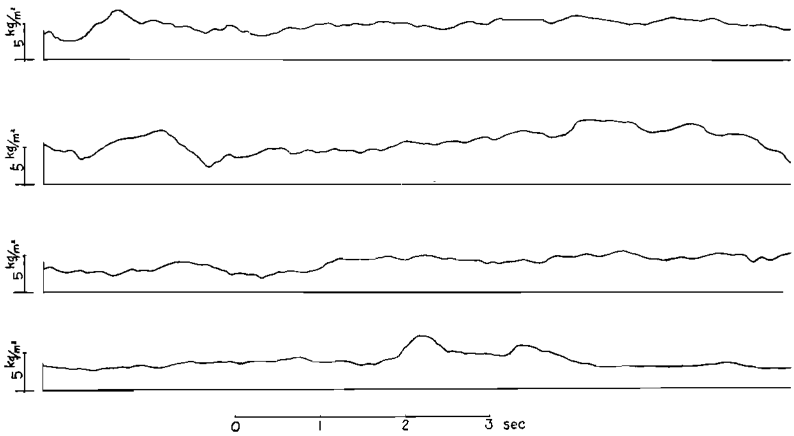

Fig. 8-1.

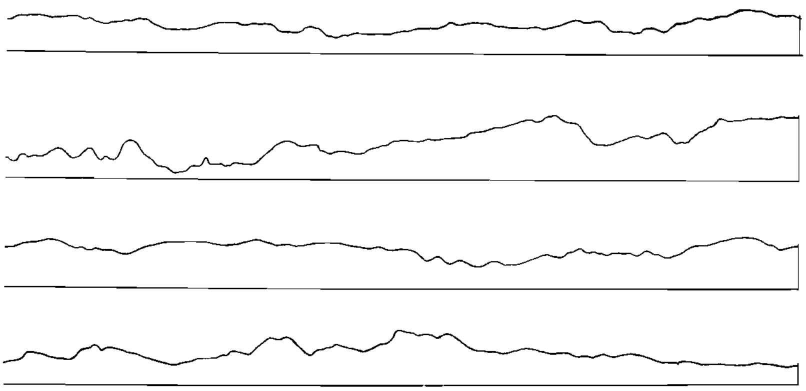

Fig. 8-2.

shown in Fig. 6 are redrawn after measuring the displacements of the original curves of the 0.1 sec intervals. The distance between the pressure-gages, by which the two curves shown in the figure were obtained, was 3 m and the gages were mounted on a wall, of which height was 2 m above the ground. On Sept. 18. 1958, the four pressure-gages were mounted on a fence, with the height of 1 m. Fig. 7 is a part of the records when the gages were 3 m apart from each other, and Fig. 8 is the case of the gages 5 m apart.

4. Considerations on the records

(1) Wind pressure distributions

Fig. 9 shows instantaneous wind pressure distributions in the vertical direction, obtained from the record shown in Fig. 5. As the pressure distributions

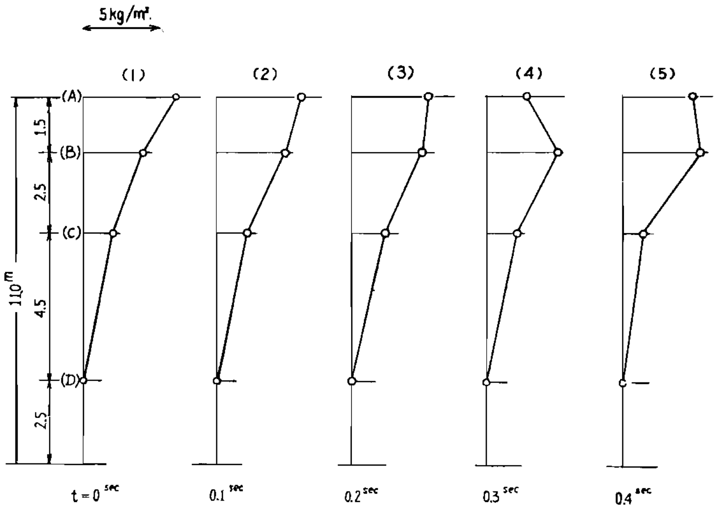

Fig. 9. Wind pressure distributions.

between the points A and B, or B and C are not known, they are combined by the straight lines in order to see the distributions easily. Fig. 10 is wind pressure distributions in the horizontal direction, drawn from the record shown in Fig. 8. From these figures, we can see that maximum wind pressure does not occur at more than two points at the same instant, hence if we consider the dimensions of structures we should not take the maximum value of the pressure all over the area in the wind direction for the wind-proof disign. R. H. Sherlock[1], W. J. Humphreys[2], G. S. P. Heywood[3] and others pointed out the importance of these characters of wind for structures, and the author believes that the pressure difference between two points near the ground is unexpectedly large in many cases, especially for strong wind. In the observations to make clear this problem, distances between the pressure-gages should be shorter than several meters, because we can hardly see the correlation between the curves of wind pressure at the station afar more than about 10 meters.

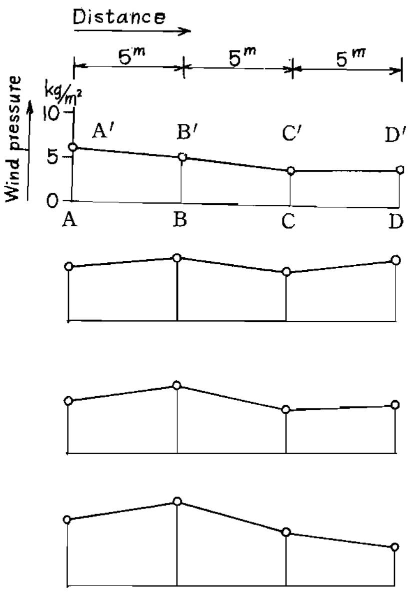

Fig. 10. Wind pressure distributions.

We may include from the above that the wind pressure for design should be more reduced as the area considered becomes larger. How much we can reduce the maximum values for a certain area will be discussed in the following section.

(2) Relation between the surface extensions and gust factors

The gust factor is generally defined as the value that the maximum wind velocity is divided by the average velocity within a certain time interval. Expediently, here the wind pressure is taken to consider the gust factor, because the wind pressures in storms were observed.

In Fig. 10 the gust factor on the point A is defined as the ratio of the maximum instantaneous wind pressure, expressed by the line AA′ in the figure, to the average pressure on the point in a time interval. Taking the surface extension into account, the gust factor on the length AB is the ratio of the maximum area ABB′A′ in the figure to the average area of ABB′A′. The gust factors on the length ABC or ABCD can be also be obtained in a similar manner, considering the area ABCC′B′A′ or ABCDD′C′B′A′ in the figure. From the above records, the gust factors in several cases were computed and they are shown by the curves in Fig. 11. The values of gust factors on a point or on the distance 0 m, are different in each case due to the time interval considered and other conditions, but they become all smaller as the lengthes considered become longer. If we take the curve ③ in the figure, about 20% of the gust factor will be reduced for the distance 10 m.

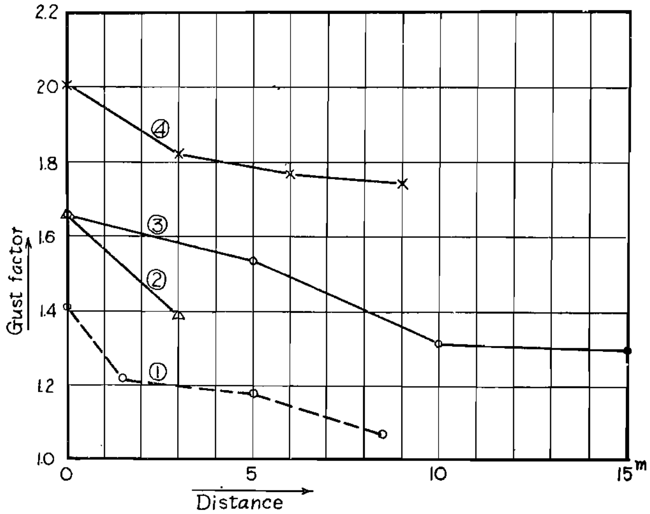

Fig. 11.

(3) Consideration on the vortex in strong wind

The curves of the records, shown above, are very irregular but the pressure variations are perhaps due to so-called gusts or lumps of air. Even if at present we cannot see why they arise, some of the pressure variations appear to be due to a kind of vortices, so the pressure variation due to Rankine's combined vortex is considered as the most simple one.

(i) *Wind pressure variations due to Rankine's combined vortex*

As well known, the velocities v of particles in and out of Rankine's combined vortex, are

$$\begin{cases} r \leqq a & v = \dfrac{\kappa r}{2\pi a^2} \\ r \geqq a & v = \dfrac{\kappa}{2\pi r} \end{cases}$$

where a is the radius and κ is the circulation of the vortex. From above equations, we can get the pressure p_0 due to the velocities of the vortex as

$$\begin{cases} r \leqq a & p_0 = \dfrac{\rho}{2}\left(\dfrac{\kappa r}{2\pi a^2}\right)^2 \\ r \geqq a & p_0 = \dfrac{\rho}{2}\left(\dfrac{\kappa}{2\pi r}\right)^2 \end{cases}$$

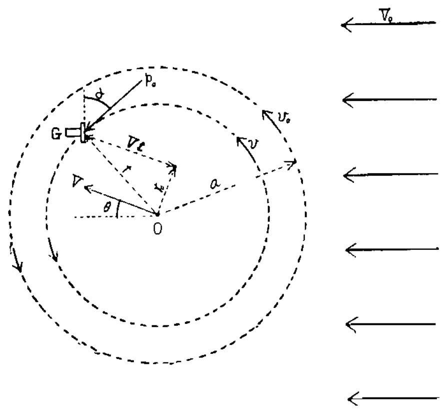

Fig. 12.

where ρ is the density of air. As shown in Fig. 12, if we assume that the pressure variations due to the angle of attack α can be approximately expressed by $\sin\alpha$ refering to Fig. 3, and the plate of the wind-pressure-gage is perpendicular to the general flow of air, and if we let $t=0$ at the instant when the center of the vortex comes nearest to the gage, the pressure variation that applies to the gage is as follows.

$$\begin{cases} r \leqq a & p = \dfrac{\rho}{2}\left(\dfrac{\kappa}{2\pi a}\right)^2 \left\{\left(\dfrac{r_0}{a}\right)^2 + \left(\dfrac{Vt}{a}\right)^2\right\} \sin\alpha \\ r \geqq a & p = \dfrac{\rho}{2}\left(\dfrac{\kappa}{2\pi a}\right)^2 \left\{\dfrac{1}{\left(\dfrac{r_0}{a}\right)^2 + \left(\dfrac{Vt}{a}\right)^2}\right\} \sin\alpha \end{cases}$$

Where $\overline{OG} = r_0$ $(t=0)$ and V is the velocity of the translation of the vortex. The values of p were calculated from the above equations and shown in Fig. 13, 14 and 15 in the cases $\theta = 0°$, $90°$ and $45°$, where θ is the angle between the directions of the general flow and the translation of the vortex. The curves

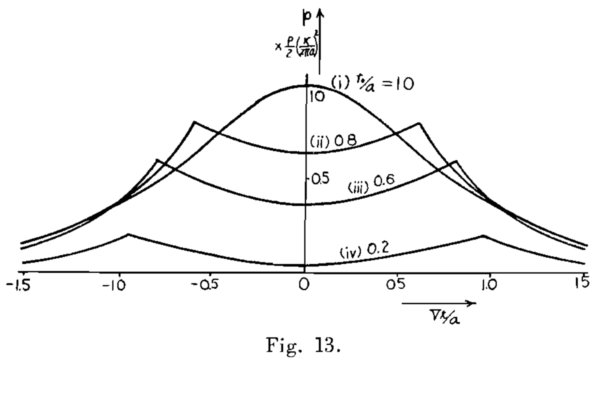

Fig. 13.

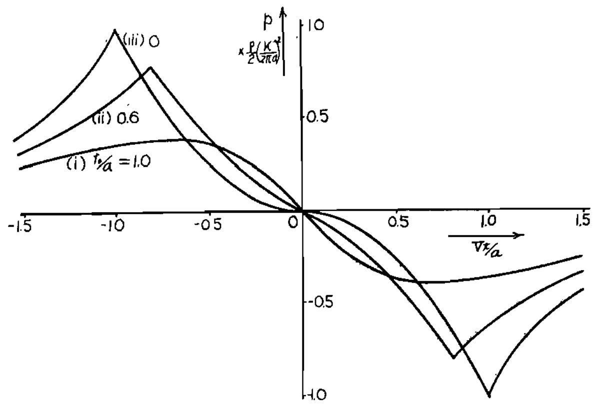

Fig. 14.

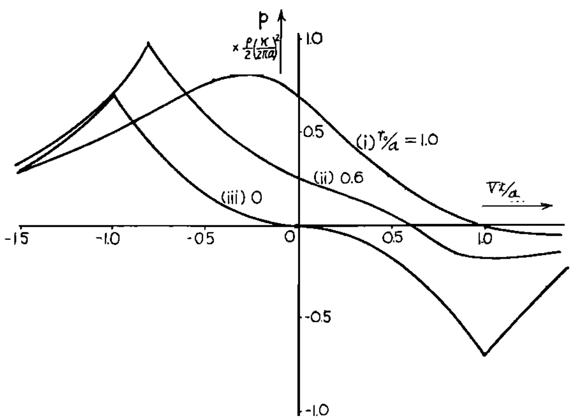

Fig. 15.

shown in Fig. 13, are the time variation of pressure when $\theta=0°$, or the direction of the general flow coincides with the direction of translation of the vortex for the cases of $r_0/a=1.0$, 0.8, 0.6 and 0.2. The curves in Fig. 14 shows the pressure in the cases of $\theta=90°$ and $r_0/a=1.0$, 0.6 and 0, and the curves in Fig. 15 show the pressure when $\theta=45°$.

(ii) *Pressure variations due to the vortex and the records*

If the variations of wind pressure are due to Rankine's vortex, the pressure computed above should coincide with the curves in the records obtained by the observations. The curve (A) in Fig. 4 is similar to the curve (i) in Fig. 3, disregarding many small unevennesses and the curve (B) resembles to she curve (iii) or (iv). From these facts, we can deduce that the variations of wind pressure on (A) and (B) are due to a vortex similar to Rankine's vortex. In the following, the strength and diameter of the vortex will be considered by the record.

If the curve (A) corresponds to the curve (i) in Fig. 13 and (B) does to the curve when $r_0/a = 0.5$, the radius of the vortex is

$$a = \frac{2.5}{0.5} = 5.0\,\mathrm{m},$$

because of that the distance between the stations where the pressures (A) and (B) were observed, is 2.5 m. The maximum wind pressure due to the vortex is about $12\,\mathrm{kg/m^2}$ from the curve (A), so the maximum circumferential velocity of the vortex is

$$v_0 = \sqrt{\frac{2\times 12}{0.125}} \doteqdot 14\,\mathrm{m/sec}.$$

Since the time necessary to the vortex pass through the station observed is about 1.6 sec, the velocity of translation is

$$V = \frac{2\times 5.0}{1{,}6} \doteqdot 6\,\mathrm{m/sec}.$$

The average wind velocity at the station when the above record was obtained cannot be set accurately, but the 5 mimute average velocity obtained by using a Robinson type anemometer at the station 2 m higher than the upper station (A), is 20 m/sec. Generally, the average velocities obtained from the records by the wind-pressure-gages, are smaller than the velocities by Robinson type anemometers, but the average velocity when the record obtained, was obviously greater than 10 m/sec, and this is greater than the velocity of translation of the vortex, 6 m/sec. The average velocity of wind is not always equal to the velocity of the translation of the vortex.

On the part (D) in Fig. 7, we can see the distinct upward pressure and on the (B) the downward pressure, notwithstanding there is only a little downward pressure change on the (C). These are perhaps due to a vortex with a nearly vertical axis, passing through the observation points. Some of pressure variation might be due to the vortices as in above examples, but they are not so distinct to be explained by the vortices, according to the complexibility of curves in the records.

There will be many pressure variations due to the vortices, having not only the structures of Rankine's type but also others. Though the records obtained during the previous three years were not sufficient to clarify the structures of vortices in storms, they have shown us some examples and the conclusions that the more detailed observation must be planned.

(iii) *Effects of the variations of wind pressures by the vortex against structures*

When there is a pressure change in natural wind by a vortex, the pressure distribution on the front of a structure, is similar to the curve in Fig. 14, added to the pressure of general flow. Especially when the center of the vortex is near the front of a structure, it tends to twist or bend the structure, though the vortex may no longer keep the original shape. If the center of the vortex is at the middle point of the front of the structure, the total pressure is unchanged from that of the general flow, because the wind directions of the vortex are opposite in the both sides of the center. In other cases, the average pressure becomes smaller as the area considered becomes larger, because the area attacked by the maximum pressure is extremely small. For instance, when the radius of the vortex is 5 m, considering the maximum peak of the curve (iii) in Fig. 14, the average pressure should be reduced about 10% of the maximum pressure of the vortex as concerns the length of 1 m, and it should be reduced more than 20% as the length 3 m. Since in natural wind there is a maximum peak of pressure which is not so distinct as the peak of the curve (iii), the average pressure for design should not be reduced so much as shown above, but it is obvious that the maximum pressure for design can be reduced, considering the dimensions of structures.

There are two maximum values of the curves in Fig. 13 and it is important to consider the dynamic effect of wind against structures. In natural wind, the continued two equal vortices have been scarcely observed, except for the special cases by wakes, but the continued two variations of wind pressures which have equal periods, may often attack structures, although they do not uniformly spread over them.

5. Conclusion

Hithertofore the statistical method were often used to the problems on wind pressures or velocities, for instance, the frequency distribution of periods of velocities were studied to analyse the records, but this is not believed so important, as the maximum value of wind pessures and its dimension are necessary for design. The numerous very short periods of the pressure variations are found from the records but they are not strong. We should find out the possible maximum variation of wind pressures and its distribution in a plane.

For this purpose, we have pointed out some characters of the storm effective to structures, which are the gust factors under considering the dimensions of structures and the simple vortex in the wind. The wind pressure variations appear to be due to not only the simple vortex but also other complicated movements of air. What kind of movements are there, is our future study.

Acknowledgement

The writer is indebted to Profs. Ryo Tanabashi and Yoshitsura Yokoo, Kyoto University, for encouragement to execute the observations and Prof. Tadao Namekawa, Kyoto University, for his helpful instructions. Gratitude is also expressed to the Kansai Electric Power Company for their cooperation and services, and to Messrs. Sumio Kawamura, Hiroshi Nakaji and Changgoo Heu for the assistance in the observations.

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Bulletin No. 30 Published December, 1959

昭和 34 年 12 月 20 日 印刷
昭和 34 年 12 月 25 日 発行
編輯兼発行者 京都大学防災研究所
印刷者 山代多三郎
京都市上京区寺之内通小川西入
印刷所 山代印刷株式会社