INSTRUMENTATION AND ANALYSIS OF FULL-SCALE WIND PRESSURE MEASUREMENTS

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This paper describes wind pressure measurements at present being carried out by the Building Research Station on two tall buildings in central London. A resumé is given of the current research requirements in this field. A pressure transducer was developed for the programme which gives an electrical output suitable for use in conjunction with standard types of commercial recording equipment. The scope of the installation in the buildings is described. Multi-channel records are produced on ultra-violet sensitive photographic paper which are processed and digitised. Several computer programs have been written to analyse this data with a view to improving knowledge of the nature of wind loadings on buildings in an urban environment.

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1. INTRODUCTION

The problem of the loading on a building or structure caused by the natural wind is an extremely complex one. Until recently it had been considered adequate to assume that the wind applied a steady force to a building. In order to determine the actual pressures on various parts of the building, the basic pressure, derived from the design windspeed, was multiplied by coefficients obtained from model work in low-turbulence constant velocity wind tunnels. Eventually it was realised, by comparing pressures on a building with those on a model, that wind movements in this type of tunnel were not like those of the natural wind, and also that the forces on the building should be related to the gusts rather than the steady wind speed.

In the past few years, a considerable amount of wind tunnel testing has been carried out in turbulent regimes. This turbulence is obtained either by having a long working section with a simulated boundary layer on the approach to the model, or by installing turbulence generators of some kind. But it is not known whether the scale and intensity of turbulence that is introduced corresponds to the natural air movements in the centre of a large city. This is because there is only a very small amount of full-scale data available. Most wind records are obtained from open country sites; anemometers situated in such places as airports or on radio masts. However these sites are not where the majority of buildings are situated. Information is needed on the pressures to be expected on buildings and structures in urban areas. Unfortunately there have been few opportunities for comparing full-scale and model work. There are now, however, a number of full-scale studies under way in various countries, but these are mainly of a limited nature due to the large amount of time and money that is needed in this kind of work.

In 1960 the Building Research Station started a programme of full-scale wind pressure measurement on tall buildings in Central London. It was decided to restrict the investigations to tall buildings because of the large number that were beginning to be built in this country at that time, although clearly just as much information is needed on other types of buildings (such as those with low-pitched roofs). The present work is being carried out to give this information on the nature of wind loading in cities, and also to provide a comparison with wind tunnel studies.

There are many problems to be dealt with in the full-scale recording of wind pressures. The gusty nature of the wind means that there are very rapid pressure fluctuations, and therefore the pressure transducer must be sensitive to these changes. The size of the gusts in relation to the size of the building is also important; therefore numerous pressure transducers are needed over the whole building. Then if measurements are being taken on anything other than a circular building, the change in the mean wind direction and also in the gust direction can have a marked change on the pressure distribution around the building. There is also the problem of the exact value of the reference pressure against which measurements are being made.

Once these problems have been satisfactorily overcome, and the equipment has been installed in the building, the apparatus has to be in operation during strong winds. This is best achieved by having an automatic wind switch. If pressure measurements are being made, then they should be related to velocity measurements at the same time. This presents a problem: where to site an anemometer so as to obtain a true picture of the wind speed at any time, without any disturbing effects from the building itself, or any other buildings.

When the work started, it was planned to install equipment on two buildings; the first was an office block, Royex House, in the Barbican, and the second was the GPO Tower (Figures 1 and 2). As well as the pressure transducers and the associated cabling, a complicated venting system had to be installed as the structures were built. In order that the equipment should be developed and preliminary results obtained, two other office blocks, already completed were instrumented on a limited scale.

Royex House is a rectangular office block on the south side of London Wall. It is 66m (216 ft) high, 43m by 18m (142 ft by 58 ft) in plan and has relatively smooth faces; this avoids the complications of turbulence introduced by large mullions. The construction is in reinforced concrete with a curtain wall cladding, the wind load being taken by internal spines housing the lifts and stairways.

Forty-eight transducers were installed in the cladding on the 7th, 13th and 17th floors at heights of 26m, 46m and 60m (86 ft, 152 ft and 196 ft) above ground level (Figure 3). There are four on each face at each level in an asymmetric pattern, which it was hoped would provide greater information about the pressure distribution by combining pairs of records where the mean wind directions were equally inclined to the normal of the face. Unfortunately this has not proved possible, due to the lack of winds in the NW and SE quadrants. The transducers not only give the local loading on the cladding, but also they give an estimation of the overall structural loading on the building.

It was intended that a comparison could be made between winds from the west and those from the east, because the flow is relatively unobstructed to the west whilst to the north and east there are other buildings of a similar height.

The GPO Tower is 177m (580 ft) high, and basically circular in plan. There is an interruption in this simple shape between heights of 108m (355 ft) and 145m (477 ft) where the radio aerials are mounted. Although the pressure distribution is different from a rectangular block, the building is ideal for studying the variation of pressure with height over a city. Sixty-two transducers were installed at nine different levels; at 49m, 67m, 101m and 152m (160 ft, 220 ft, 330 ft and 500 ft) there are complete circles of twelve transducers spaced at 30° intervals around the tower, whilst at five other intermediate levels there are transducers in the south-west quadrant only (facing the prevailing wind). Some of the gauges are shown in Figure 4.

Before the Tower was constructed, a smaller lattice mast stood on the site, and for a short while these two stood adjacent to each other. By placing two anemometers on this mast, and one on top of the tower, it was possible to take simultaneous recordings of the wind velocity and direction at three different heights: 43m, 61m and 195m (140 ft, 200 ft and 640 ft). This is obviously very relevant to our pressure measurements, and has given a good idea of the variation of velocity with height over cities. The analysis of this work has been undertaken by the Meteorological Office[1].

2. INSTRUMENTATION

The Pressure Transducer

Among the requirements for the performance of the transducer or pressure gauge, two were of particular importance. Firstly, it was necessary to measure pressures of very short duration, down to about 0.1 second. This determined the frequency response. Secondly, it was desirable that the pressures recorded should be representative of those averaged over the area of cladding panels so that the loadings experienced by cladding components could be assessed. For this purpose the active area of the gauge needed to be as large as possible, compatible with easy installation. As no pressure transducer existed which satisfied these dual requirements, gauges were designed for this purpose (Figures 5 and 6).

The specification was as follows:

(i) The frequency response suitable for measurement up to 10 c/s.

(ii) The active area of the gauge as large as possible.

(iii) The gauge must record both positive and negative pressures and discriminate between them.

(iv) It must measure pressures in the range $\pm$ 1200 N/m^2 ($\pm$ 25 lb/ft^2).

(v) It must be able to measure to an accuracy of $\pm$ 12 N/m^2 ($\pm$ 0.25 lb/ft^2).

(vi) The gauge should be capable of withstanding overload without damage.

All these requirements were met in practice.

A diagram of the gauge will be found in Figure 7. A rigid pressure-plate (D) about 0.1m (4 in.) in diameter is mounted from the gauge body (B) on three symmetrically spaced cantilevers (C). A thin membrane (M) seals the annular gap between the pressure-plate and the body, thereby isolating the body-cavity from the external pressure. The nozzle (N) provided on the back of the gauge enables the interior to be vented to any chosen reference pressure. The pressure-plate thus bears a load proportional to the difference between the external pressure and that inside the body cavity. This load is transferred to the three cantilevers, which owing to the method of anchorage, are subject to reflex curvature.

Thus, on the surface of the cantilevers there are two positions of tension and two of compression. Foil resistance strain-gauges are attached at these four points on each cantilever and the whole gauge is wired to form a Wheatstone Bridge, in which each arm consists of three gauges from the corresponding position on each cantilever, in series. With this arrangement every strain-gauge is active which gives the maximum sensitivity, while at the same time averaging the deflection of the cantilevers. Electrical connection is made through a four-way plug on the back of the gauge (P) enabling the bridge to be energised through one pair of conductors and the response signal to be carried to the recording equipment through the other.

The only way of checking the zero position of the gauges is by recording during calm periods. The long term zero stability is therefore crucial to the satisfactory performance of the gauge. The two most important factors controlling stability are temperature compensation and freedom from internal stress in the gauge components. The arrangement of the strain-gauges ensures complete temperature compensation. The actual performance was checked in the range $-10^{o}C$ to $+40^{o}C$ no significant variation of zero being detected. The internal stress in the gauge components was minimised by selecting materials with a low stress content, by annealing, and by careful machining. A further improvement of zero stability was obtained by ageing the completed gauges on a specially designed rig. The interior of each gauge was connected to a common system in which the pressure was pulsed every few seconds by a piston. With these precautions long term zero stabilities equivalent to about $\pm$ 0.25 lb/ft^2 were achieved.

The nominal sensitivity of the gauge is 0.6μV/V/N/m^2 (30μV/V/lb/ft^2). That is if the gauge is energised with 1 volt and the pressure-plate loaded with 1 lb/ft^2 the output from the bridge will be 30μV. Gauges differ from each other in sensitivity owing to slight variations of cantilever thickness, so that each unit requires calibration. Initially calibration was carried out by varying the internal pressure, measuring this with a water manometer and recording the response of the gauge. For comparison a second calibration was done by loading the pressure plate with dead-weight, the body cavity in this case being open to the atmosphere. Subsequently dead weight calibration only was used because it was more convenient.

Site Installation

The gauge was designed to be mounted in suitable curtain walling components. The component chosen for this should be rigid since the gauge is sensitive to acceleration forces, and the mounting should leave the external surface as nearly smooth and free from projections as possible, in order to avoid interference with the external air flow. The mountings were designed so that the gauge could be inserted from the inside. Simultaneous pressure records were required at a large number of widely dispersed points on the surface of the building. Cables were installed connecting each gauge with the recording apparatus which was housed in a conveniently placed room inside the building. Each gauge also had to be vented to a common reference pressure, which necessitated the installation of long lengths of air-tight tubing.

The cable runs connecting each ~~gauge with~~ the recording room were in many cases very long, some at the GPO Tower being nearly 500 ft. Four core screened cable was used each core 14 x 0.0076 in. With cable lengths of this order care must be taken to balance the cable capacity.

The four conductors, viewed in section, lie in a square, the capacity between adjacent pairs being approximately the same but different from that between opposite pairs. If the vertices of the bridge are connected cyclicly round the square equal capacities are placed across each bridge arm. Provided this is done, the relatively small residual unbalance is easily accommodated by the trimmer provided on each carrier amplifier. In the recording room, cables were terminated in sockets mounted in trunking, and gauges used for recording were selected by plugging into the appropriate sockets.

Since the gauge measures the difference between the external pressure and that within the body cavity, the comparison of pressure on different parts of the building relies on venting all the gauges to a common reference pressure. The problem of finding an entirely suitable position for the reference is extremely difficult. Ideally the reference pressure should be the external static pressure, but it is impossible to obtain this with any certainty inside the building owing to the many routes connecting the air inside and outside (e.g. open windows and ventilators) and the complexity of air flow within the building. The problem still exists where there is air conditioning, when although the connection between inside and outside is better defined, there is generally a significant permanent pressure-head in the building.

Another problem arises from the interconnection of gauges at different heights when the temperature inside the building differs from that outside. If the vertical runs of the venting system are inside, the weight of the vertical column of air enclosed in the system will differ from that of the same column outside, implying that the reference pressure cannot be equivalent for all the gauges. The solution is to place the vertical runs of the venting system outside the building and preferably on the north side where they receive no direct solar heating.

At Barbican all gauges at the same level were vented to a common point. The venting tubes were led into a box which was not airtight placed in the ceiling space at the centre of the building, on the same level as the gauges.

At the GPO Tower a complete venting system was installed. Gauges at each level were connected to a pipe running round the building on the inside. The different levels were joined by a pipe running vertically almost the entire height of the building and shielded from solar heating by being placed on the north side. This vertical run was terminated at its lower end in the recording room, which appeared as satisfactory as possible for venting purposes being well isolated from external effects by the total absence of windows, ventilators and lift access.

Recording Equipment

Several methods of recording are practicable:

> Digital on magnetic or paper tape; Analogue on magnetic tape and Analogue on photographic paper. Each has advantages and disadvantages. The principal advantage of digital recording is that it can be used directly on a computer without the labour of conversion associated with analogue records. On the other hand much data is thrown away by digitising at the outset. Analogue records on magnetic tape offer the advantage of direct spectrum-analysis by electronic means. However, it was not known initially what characteristics the records would posses, so that it was considered that the advantages of being able to see and study the traces and of having an analogue record outweighed all others. It was therefore decided to produce analogue records on photographic paper.

Recording equipment for 48 channels is shown in Figure 8. It comprises 2 multi-channel ultra-violet galvanometer recorders one at the top of each cabinet, and 48 amplifier modules mounted below the recorders. This is standard equipment manufactured by S.E. Laboratories, Feltham. The modules are arranged in groups of 12 attached to an oscillator unit which provides the carrier signal for energising the gauges. This signal is 5 volts at 3kc/s. The amplifier module receives back the gauge output for detection and amplification. Each amplifier output is connected to a separate galvanometer in the recorders. The number of channels which can be conveniently accommodated on the recording paper is governed by the need to avoid overlapping of the traces and to obtain large enough deflections for reading accuracy. 24 channels were spaced at 1 cm intervals on the 12 in. wide paper resulting in charts of the type shown in Figures 9 and 10.

It is clear that records will frequently be required when it is not possible to operate the equipment manually. A controller was therefore designed and built by the Station which allowed the recording apparatus to be switched on either at hourly intervals or when the wind exceeded any preset value. Combinations of the above are also possible. This unit is shown in Figure 8 below the amplifier modules. A standard Meteorological Office cup-generator anemometer was used as the wind speed sensor. Two timers are provided which enable recording periods from a few minutes to several hours to be preset. Sampling and wind actuated records may be set to differing lengths independently. The whole apparatus is switched off automatically when the photographic recording paper expires.

The lowest rack in each cabinet in Figure 8, contains a print unit (centre) which gives the exact starting time of each record. This is required for comparison with other Meteorological data. There is also a Slave unit (right) which works in conjunction with the controller, enabling more than one recorder to be operated simultaneously.

3. ANALYSIS

Once the records have been obtained on an ultra-violet recording paper, they have to be processed and converted to a digital form before any computation can be undertaken.

Processing of the record

In order to preserve the traces, the record is processed in a Bell and Howell oscillogram processor (Type 23-109B). The machine carries out a complete photographic process – as opposed to the simpler but less effective permanising method. The record is developed, fixed, rinsed and dried, a 60m film taking about 30 minutes. At the present time the processor has developed some 15,000m of film – the permanent records so produced can be looked at years later if necessary.

Analogue to digital conversion

In order to analyse the records they have to be converted to a digital form. This would prove impossible to carry out for all the records obtained, so records are selected covering a range of wind speeds and direction. This analogue to digital conversion is carried out on a Benson-Lehner Oscar trace assessor, which has been specially converted from the normal ten channels to deal with a time and twelve pressure channels. The data is output on a typewriter and a paper-tape punch.

Before reading can commence (i) a zero and (ii) a calibration has to be set in the machine for each channel. These two are obtained from other parts of the record (i) where there was no wind, and (ii) where each channel was calibrated using a dead weight loading.

Once the calibrations are set in, a pressure from each of the twelve channels, at a given time, can be output. This is achieved merely by locating two cursors over each data point of interest and pressing a read-out button. The cursors can be set to 0.003 in. When a time and twelve pressures (directly in N/m^2) have been output, one cursor is moved to the next time which is 1mm along the record. This usually corresponds to 1 second, although on a few open-scale records it corresponds to 0.1 second.

This process is repeated, normally for 1200 seconds (at 1 second intervals), giving a paper tape of nearly 300m. Originally this was on 5-hole tape, and was used in an NCR-Elliott 803 computer. This soon proved unsuitable, so a change was made to an NCR-Elliott 4120 computer – and with this it is better to use 8-hole tape. The Oscar output was therefore converted to 8-hole tape, as were the earlier 5-hole records.

In the four years that Oscar has been in operation, over one million pressure readings have been taken. Inevitably some erroneous readings are output, whether it be a machine or operator fault, so each tape has to be edited. This, however, is a very simple process on the 4120 computer, using the Edit 41 software.

Computation

In analysing full-scale wind pressures, a decision has to be reached as to how the problem is to be approached. Originally engineers and designers assumed the wind loads to be a static force applied to the face of a building. This was adequate when conventional building methods were employed, as a large safety factor was incorporated.

However, modern, taller, lighter buildings have demonstrated the need for more precise knowledge on the nature of wind loads; in particular the dynamic loads arising from the short-term gustiness of the wind. The aerodynamicist has therefore approached this problem from a more theoretical point of view.

With the data tapes produced as they are, with twelve simultaneous channels, program writing has always been a problem; although it is very convenient to deal with all of one face at a time, it does need a large computer store. However a system is now used which reads in 60 seconds of data, processes it, then ignores the first 10 seconds and reads a further 10 seconds, in order to repeat the processing for a new period of 60 seconds.

One program, using this method, deals with pressures of individual gauges. Mean pressures (ranging from 1 second to 60 seconds) are computed for each gauge, at various intervals. All the pressures are output on the lineprinter, whilst at the same time they are inspected and if necessary placed in an array for maximum and minimum pressures. These maximum pressures can be plotted – a routine has been written to do this directly on the digital plotter – and related to the maximum gust speed. Also the lineprinter output can be inspected around the period of maximum pressure to obtain further information on the nature of the gusts.

Another program combines pressures from each gauge at a floor level, and by allocating a certain area to each gauge the total load can be calculated on the floor, and also on the whole face. These can be added to the loads from the opposite face in order to get the load on the whole building. This analysis is only performed on records where the wind direction is square-on to the building, whereas the pressure analysis is carried out for all directions.

It is from this work that the importance of short duration gusts has been seen – not only for local loads on cladding panels, but also on the overall structural loading of the building. With this in mind both programs have been modified to take account of the open-scale records with pressure readings at 0.1 second interval.

In considering spectral analyses, it is more difficult to take in small parts of the data. The entire record has to be entered into the computer – in this case twelve different channels – in order that the mean value can be deducted from each pressure reading. The rms value can also be determined for each channel. The main part of this dynamic approach is the estimation of the power spectral density for each channel, and of the cross-correlation spectral densities for pairs of channels. For this latter case, as twelve channels on one face are input at one time, eighteen horizontal and twelve vertical cross-correlations can be computed.

Power spectral density estimates are computed using methods described in Blackman and Tukey(2) and also in Bendat and Piersol(3). This involves calculating the auto-correlation function, and transforming by a cosine series to obtain the power spectral density function. Also, for the cross-correlation, the lagged cross products for any pair of channels have to be calculated, and these are transformed by cosine and sine series to give the cross-correlation spectra. The program will accept any length of record at any interval of reading – even at 0.1 second, although limitations are imposed by the size of the computer.

Conclusions

One of the main problems with this work is the amount of data that is involved. However, once the conversion from an analogue to a digital record has been made, and the resulting tapes have been edited, they are readily available for computation with any number of programs.
Two or three programs have been run so far, but before the project is complete further analysis will be made with this data. At the time of writing, some of the results obtained from Royex House have been published – see references(4) and (5).

References

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Fig. 1 Royex House, Barbican

Fig. 2 GPO Tower, London

Fig. 3 Pressure transducer in the cladding of Royex House

Fig. 4 Pressure transducers in the windows of the GPO Tower

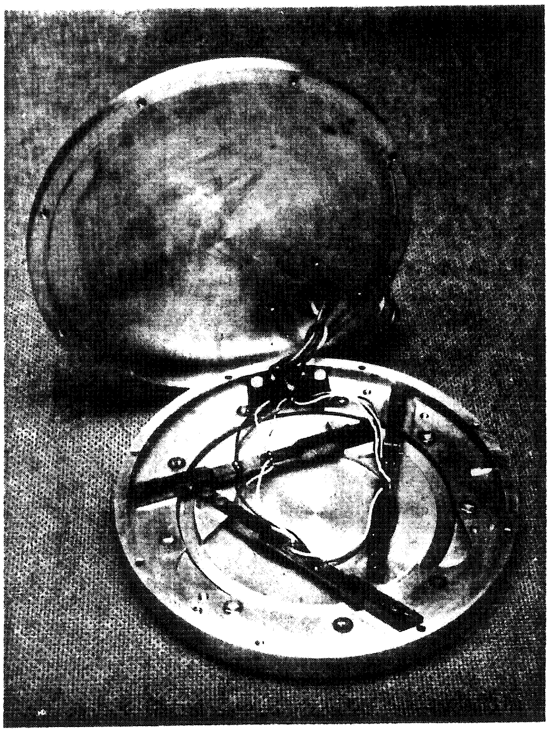

Fig. 5 Pressure transducer

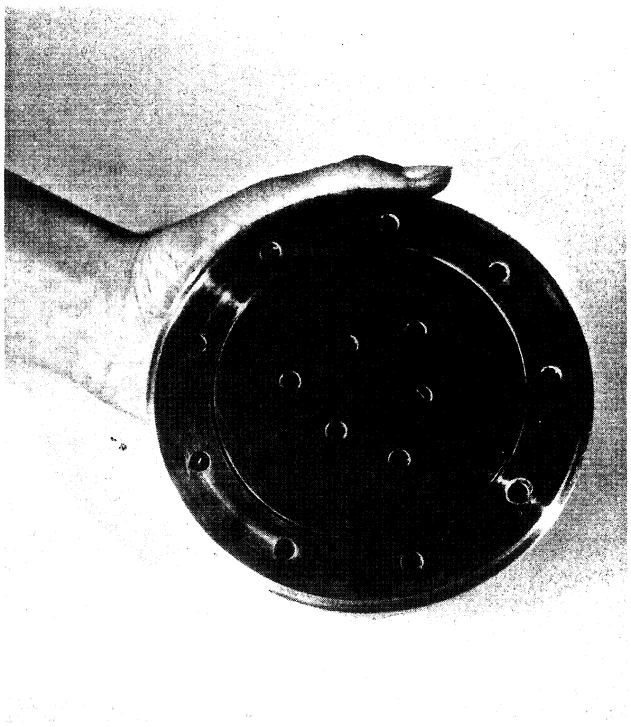

Fig. 6 Pressure transducer

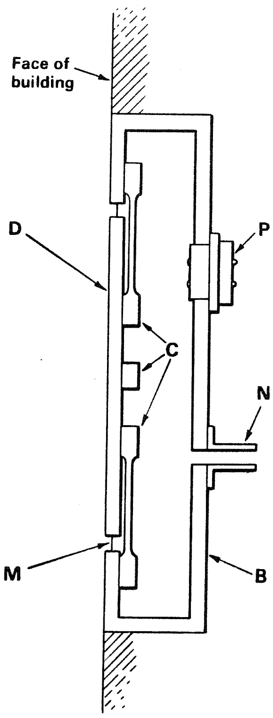

Fig. 7 Diagram of the transducer

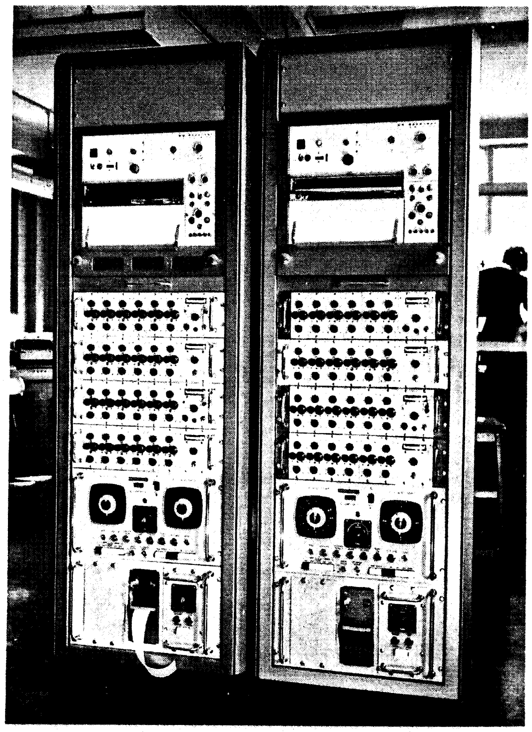

Fig. 8 Recording equipment

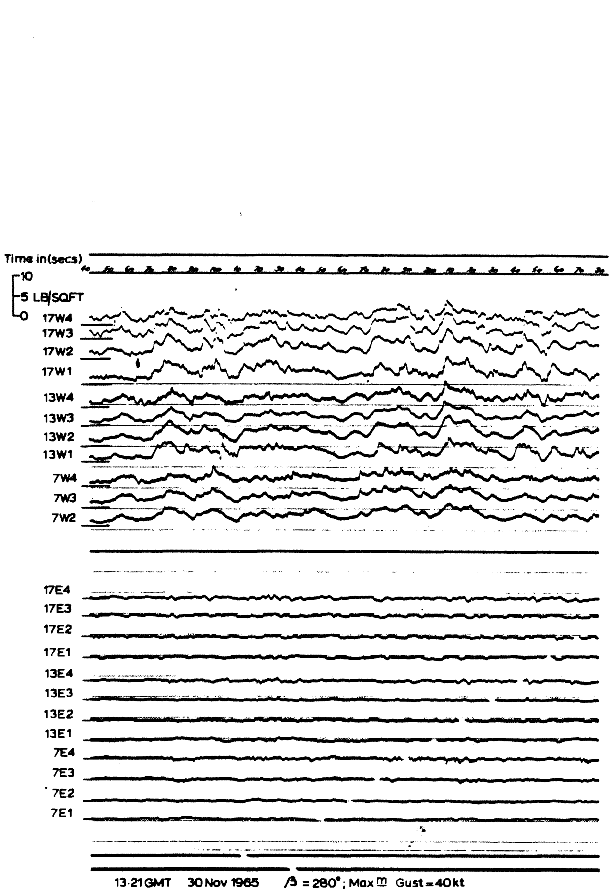

Fig. 9 Sample record, Royex House

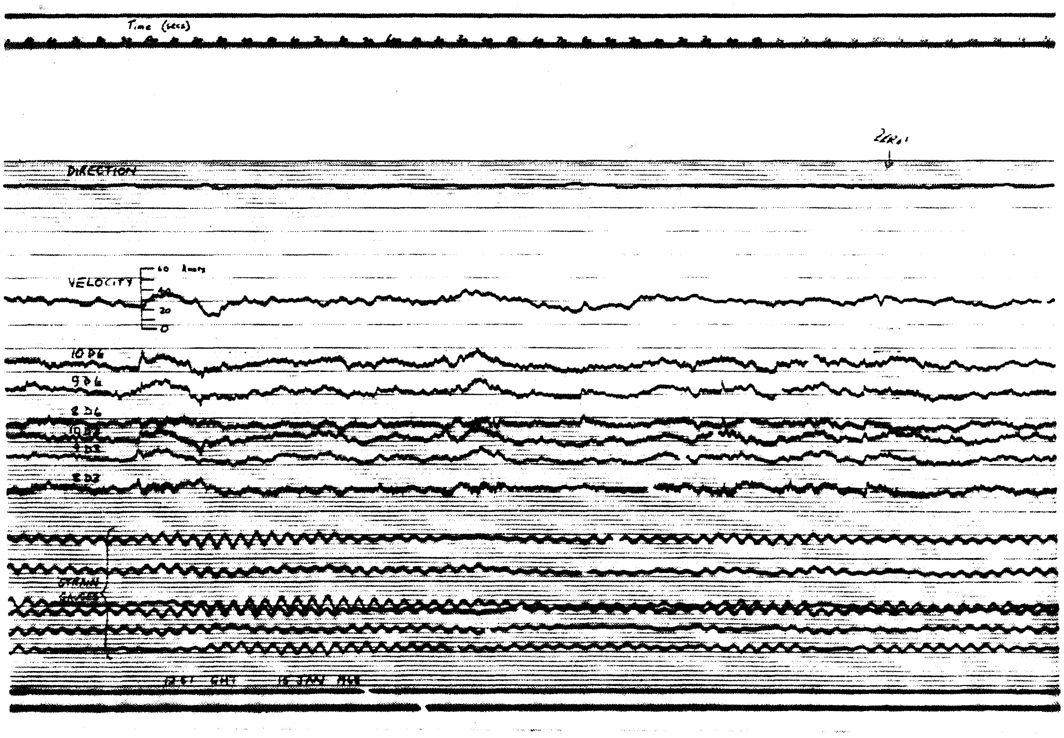

Fig. 10 Sample record, GPO Tower