THE ACOUSTIC PERFORMANCE OF BUILDING FACADES IN HOT CLIMATES

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy by

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SUMMARY

The aim of this investigation was to assess and suggest improvements in building facade performance in hot climates with respect to traffic noise. The facade investigated contained courtyard or closed balcony elements with three types of perforated screen; namely, a conventional perforated wall and two of unusual geometry.

The acoustic protection of a conventional perforated screen was measured in the field and by scale models. The results obtained by the two methods compared well in general and showed that this type of screen does not afford much acoustic protection.

The perforated screens of unusual geometry were also investigated by means of model work and computer simulation resulting from diffraction theory in which the barrier produces an amplitude gradient (thnadner) or a phase gradient (splitter). The acoustic protection of the free-standing devices was measured as a function of frequency and receiver position and results indicate that the protection obtained is similar to that of a solid thin barrier of equal height for a wide range of frequencies when the receiver is near the barrier. The thnadner and splitter screens were then examined, by means of one-tenth scale models, as a part of a courtyard and a closed balcony. Results showed that a considerable

reduction in traffic noise is achieved which is again of the same order as that of a courtyard with a solid wall.

The screening walls were also assessed with respect to other environmental factors and it was concluded that the devices can also be used, if correctly designed, for solar control, and provide sufficient daylighting and ventilation to the building.

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A	Attenuation, absorption area
a	Source barrier distance
B	Amplitude
b	Receiver barrier distance
c	Axial velocity of sound in material
C_o	Sound velocity in air
d	Width
F	Frequency
g	Auxiliary function of Fresnel integral
H	Barrier height
h	Effective barrier height
I	Intensity
K	Wave number
L	Thickness of barrier, sound level
M	Medium vehicles
N	Fresnel number
O	Original point
P	Sound pressure
Q	Traffic density
q	Mean speed
R	Resultant
r	Receiver position
s	Source position, area
T	Total time, reververation time
t	Time, reverberation time

V	Variable
v	Traffic speed
W	Acoustic power
X	Amplitude in x-direction
Y	Amplitude in y-direction
Z	Impedance
α	Absorption coefficient, variable
β	Variable
Δ	Bath differences
η	Refraction index
σ	Standard deviation
ξ ,θ	Diffraction angles
ϕ	Phase change factor
T	Transparency factor
λ	Wave-length

CHAPTER ONE

INTRODUCTION

Good architecture consists of aesthetically creative design and results in an economical and functional building performance and in the satisfaction of human requirements. Architecture, as defined by Le Corbusier *(1)* is the scientific, accurate and magnificent play of mass brought together in light. Buildings are not only important for enhancing human activity in or around them, but they are also part of human heritage. The study of architectural history and archeology often results in a clear statement of the culture and civilization of a time and the significant contributions such as those of the ancient Greeks, Romans and Moslems continue to stimulate modern architecture.

Unfortunately the lessons of the past and of vernacular architect are not always well learnt. The new town of Babil in Iraq has been built near the 5,000 year old Babylonian city of the same name. The external air temperature in Summer at this site exceeds 45°C. The internal temperature of a newly constructed council hall can be maintained at 20°C, but this involves the use of expensive and complicated heating, ventilation and air conditioning equipment. The shaded temperature inside the ancient city, for the same period, rarely exceeds 18°C and, at the same time, adequate ventilation, daylighting and visual relief are provided.

In hot dry climates such as at Kuwait and Saudi Arabia, the traditional enclosed courtyard is still used extensively and arguably offers better environmental conditions when compared with the modern air conditioned luxury homes of the rich.

1.1 THE NEED FOR PASSIVE CONTROL

Cowan states,

> "The use of massive air conditioning plant to correct an ill-conceived environment does not differ in principle from the use of a masonry facade to hide an unnecessarily ugly concrete structure."*(2)*.

In addition Olgyay states,

> "We do not expect to solve the problems of uncomfortable conditions by natural means only. The environmental elements aiding us have their limits. But it is expected that the architect should build the shelter in such a way as to bring out the best of the natural possibilities." *(3)*

A building should not only provide suitable space to accommodate the different activities of the occupants, but it should also create a comfortable environment within such space. The building envelope can be considered as a filter which ideally allows the desirable part of the external environment to influence the internal environment, while reducing or eliminating the undesired parts. The fabric, therefore, plays a major part in such environmental control and great care should be given to its design. In addition to the consideration of the impact of climate, there is the need to address the problems of fire control and pollution. The external walls and roof should allow the correct amount of light required for task illumination and the avoidance of glare. Solar penetration should be such as to provide permissible heat gain, heat loss should be minimised if external temperatures are low and the background noise level should be such as to provide a pleasant aural environment.

These requirements sometimes conflict and if there are many factors to be considered, the design becomes more critical and there is greater difficulty in obtaining an optimum solution. This is certainly the case in urban areas with hot climates where there are particular requirements of ventilation, solar protection and daylight penetration, but where there may be a conflicting requirement for traffic noise control.

1.2 THE AIM OF THE PRESENT INVESTIGATION

The acoustic environment is often neglected in architectural design and solutions to problems of noise control or sound enhancement are often remedial. The services of experienced acousticians and the remedies can sometimes be expensive and not particularly successful. Such difficulties are reduced or eliminated if acoustical consideration is included in the preliminary design. This requires that the architect has a fair knowledge in this field and can work constructively with a consultant.

The result of this research work, hopefully, will provide information in a form which will enable the architect to answer some of the architectural requirements when designing the building facade. The investigation was primarily concerned with building facade performance with respect to traffic noise in hot climates. It was thought that a slight modification in facade geometry might produce an appreciable increase in acoustic protection, without compromising other environmental factors.

1.3 LAYOUT OF THESIS

The thesis begins by describing the main sources of sound in urban areas in hot climates. It is seen, in Chapter Two, that the main problem is that of traffic noise control. A full description is also given of traffic noise spectra, propagation and prediction. In Chapter Three, previous work on the acoustic protection afforded by building facades is reviewed and it is seen that more work is required in this field.

Results of field measurements of building facade performance with respect to traffic noise are given in Chapter Four. The facade elements investigated were similar to those employed in hot climates but there was little opportunity to methodically vary the factors which influence acoustic performance.

In Chapter Five the theory of acoustic barrier performance is examined and previous experimental work critically assessed. A description is also given of perforated barriers of unusual geometry, the theory of which is examined by means of a computer. Results are encouraging and experimental model work was recommended.

Model techniques in acoustics are examined briefly in Chapter Six, with particular emphasis on requirements and limitations. Free-standing solid and perforated barriers were examined by means of model techniques, the results of which are given in Chapter Seven.

The above barriers were employed as a part of a building facade and their acoustic performance was examined by means of one tenth scale models (Chapters Eight and Nine). In Chapter Eight is given a description of the experimental procedure and parameters. In Chapter Nine, the results of the work are given and comparison is made between different building facades.

In Chapter Ten, the facade elements are examined with respect to other environmental factors such as those of solar control, daylighting and ventilation; again a comparison is made. In Chapter Eleven are given the conclusions and recommendations for further work.

REFERENCES

1. LE CORBUSIER "Creation is a Patient Search" New York: Praeger, 1960.

2. COWAN, H. J. "An historical outline of Architectural Science" Elsevier, 1966.

3. OLGYAY, V. and OLGYAY, A. "Solar Control and shading devices". Princeton University Press, 1957.

CHAPTER TWO

TRAFFIC NOISE

Noise generated from industrial installations, aircraft or road and rail traffic is a major problem in modern cities, in particular, in rapidly-expanding cities where there may have been insufficient control exercised at the planning stage. Problems caused by aircraft or industrial noise can be eliminated or reduced by siting airfields and industrial estates away from residential or other noise-sensitive areas. This solution is often the result of other considerations such as the need for large flat areas for large runways and the demands of access, storage and production spaces in large production industries. These, rather than the simple avoidance of noise, are usually the primary considerations.

Noise generated by road traffic, which is often an integral part of city activity, cannot be reduced in the same way. The rapid increase in the size of modern cities, in particular in underdeveloped countries, and the increase in the number of motor cars, in all countries, creates a major problem of noise pollution. The volume of traffic in England is doubling every ten years *(1)* and the rate of increase is likely to be greater in developing countries where traffic noise level will increase accordingly.

In less well controlled city developments, noise control will, for the time being, be remedial, rather than preventative. Noise resulting from road traffic dominates the external acoustic environment in these cities and a solution to such a problem cannot be achieved by separating roads from the residential areas but must be found for each road and residential building considered.

This chapter contains a review of previous work on traffic noise, and a description is given of the prediction techniques available in the assessment of potential problems. The factors which influence the level and frequency characteristics of traffic noise are examined and they are seen to include traffic flow, mean speed, traffic composition and road geometry.

A review of several theoretical models is also given, with a view to the construction of a suitable laboratory system to simulate real conditions. This is important because in this work, the measurement of building facade protection from traffic noise was to be by means of scale models, rather than by field measurement.

2.1 A REVIEW OF PREVIOUS WORK

Since 1940, attention has been drawn to the annoyance caused by excessive traffic noise in urban areas *(2)*. It has been found, for example, that since 1960, more than 40% of the U.K urban population lives near roads which produce noise levels considered undesirable *(3)*. It was suggested *(3)* that urban areas should be separated from main roads by means of cuttings, barriers or embankments. This proposal has quite obviously not been undertaken. Road traffic in the U.K since 1960 has increased by a factor of 2.5 and is doubling every 10 years *(4)*. Ninety percent of the population of urban areas is now exposed to traffic noise that exceeds 70dBA for most of their working hours and there is, therefore, an increased demand for protection of residential areas from road traffic.

Several works have been carried out to evaluate noise levels generated by road vehicles; in particular, noise levels have been related to the volume, speed and composition of traffic and measurements have been correlated with the subjective response of people living in close proximity to the road under investigation *(5,6)*. In a survey carried out by Griffiths and Longdom in 1968 *(7)* of 14 sites in the London area, residents were interviewed and traffic noise levels were recorded in dBA. It was found that the degree of dissatisfaction correlated well with both L_{90} and L_{10} during the period 6.00 a.m. to 12.00 midnight. L_{90} and L_{10} represent the sound levels in dBA exceeded 90% and 10% of the sampling period respectively.

A traffic noise index (TNI) was defined in terms of the noise climates ($L_{10} - L_{90}$) as

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \qquad (2.1)$$

The TNI index was an attempt to quantify the range of fluctuation and to the response of people to that range. At the time of the survey there were insufficient examples of housing adjacent to modern urban motorways and so the investigations were carried out in open spaces along roads carrying free-flowing traffic. The TNI was obtained for roads with traffic flow ranging from 4,000 to a maximum possible of 40,000 vehicles per day. This upper limit has since then increased by a factor of more than 1.5.

The National Swedish Institute *(8)* suggested in 1968 an index based on the equivalent continuous noise level (Leq)

$$\text{where Leq} = 10 \log \frac{\frac{1}{T_i} \int_0^{T_i} P^2 (t)\, dt}{P_o^2} \text{ dB} \qquad (2.2)$$

P(t) is the time-variant sound pressure,

Po is the reference sound pressure $= 2 \times 10^{-5}$ N/m

and Ti is the integrating time.

The social survey involved selecting 59 different areas covering a wide range of exposures to traffic noise and it was concluded that 20% of the residents would be seriously disturbed with an external level Leq of 55 dBA.

Robinson *(9)* in 1969, used the term 'Noise Pollution Level', L_{NP}, to accommodate the results of road traffic, aircraft and building noise disturbance. This term is given by

$$L_{NP} = \text{Leq} + 2.56\sigma \qquad (2.3)$$

where σ is the standard deviation.

This is the only noise rating method that includes time and amplitude fluctuations of the noise emissions from road traffic, aircraft and buildings. However, in practice, several sources of noise may operate at the same time and there have been relatively few studies in which this index has been compared with subjective reactions.

In the United States, L_{NP} criteria have been adopted and a set of guidelines concerning the external noise climate near houses has been proposed *(10)*. An LNP $<$ 62 dB NP is considered to be quite acceptable, 62 $<$ LNP $<$ 74 dB NP is normally acceptable, 74 $<$ LNP $<$ 88 dB NP is unacceptable and LNP $>$ 88 dB NP is clearly unacceptable.

Traffic noise levels measured in France *(11,12)* along with the results of a questionnaire given to people living within 10 - 150m of motorways, show that there was a significant correlation between annoyance and the L_{50} level. This survey indicates that levels exceeding 65 dBA for 50% of the time correspond to a rapid increase in the number of people disturbed.

Johnson and Sanders *(13)* carried out a survey of the noise emitted by free-flowing traffic on motorways and urban roads. Their study shows how noise level is affected by basic variables such as traffic density Q, mean speed v, traffic composition and distance d from the road-side, and the following equation was derived in which these parameters are related to sound level.

$$L_{50} = 51.5 - 10 \text{ Lag}_{10} \frac{Q}{d} + 3 \text{ d} \log \frac{v}{4} \text{ dbA} \qquad (2.4)$$

The effects of heavy vehicles and road gradient on the mean sound level were also included by means of correct-ions. The results of their field measurements, and of a theoretical analysis of the sound radiated from a linear array of moving sources, yielded a simple method of predicting noise levels from any projected roadway. The theoretical method will be examined in detail in section 2.6.

Social surveys and field measurements by Scholes and Sargent *(14)* indicate a correlation between L_{10} averaged over 18 hours and human dissatisfaction. The value of L_{10} used as their proposed index was defined as the arithmetical average over a weekday (6.00 a.m. to 12.00 p.m.) of the hourly values of the levels in dBA which is exceeded for 10% of the time. Their study has also resulted in a method of estimation of levels in a variety of circumstances and is now described more fully.

2.2 PREDICTION OF ROAD TRAFFIC NOISE LEVELS

The main factors governing noise levels at a given distance from a road have already been listed. Other factors include road surface, and gradient, the nature of the intervening ground, wind and reflection from building facades. Accurate prediction is difficult and, where possible, the noise exposure at the site should be measured directly, especially in densely built-up areas, in which there may be multiple reflection between parallel facades.

A noise disturbance index should be such that it can be simply related to the traffic flow parameters given above and, at the same time, give good correlation with the reaction of residents exposed to the traffic noise. A brief description is now given of the indices which have been proposed in the literature.

The traffic noise index (TNI) has already been defined, in section 2.1, and taken into account both impulsive and more continuous noise levels. The noise pollution level (L_{NP}), again previously defined, is similar in form to the traffic noise index and both are not of full practical use since the traffic flow parameters (which effect the magnitude and frequency spectrum) are lumped together and hence the possibility of isolating the effect of each factor is limited.

The mean energy level or continuous equivalent noise level (Leq) *(8)* has been proposed and recommended by the International Organisation for Standardization (ISOR 1996, 1971) and the relationship between Leq, L_{50} and L_1 levels is expressed as:

$$Leq = L_{50} + 0.43\,(L_1 - L_{50}) \qquad (2.5)$$

The calculation of Leq requires knowledge of how variation in control parameters affects the statistical distribution of the noise level. The prediction of Leq under a wide range of traffic conditions is still uncertain.

The prediction of noise levels for both free and non-free flowing conditions is now possible by use of an L_{10} index *(15)* which are given in terms of the measurement period (e.g. L_{10} (1hr), L_{10} (18hr)). The L_{10} (1hr) can be predicted, using the methods of Scholes et al *(14,15)* from,

$$L_{10}\ (1hr) = 10 \log_{10} q + 33 \text{Lag}_{10} (v + 40 + 500/v) + 10 \text{lag}_{10} (1 + 5P/v) - 27.6 \text{ dBA} \qquad (2.6)$$

where q is the mean hourly flow vehicles per hour,

p is the percentage of heavy vehicles, and

v is the speed of the traffic stream Km per hour.

L_{10} (18hr) over the period of 06.00 - 24.00 hours is predicted by the formula:

$$L_{10}\ (18hr) = 10 \log_{10} Q + 33 \text{lag}_{10} (v + 40 \quad 5000/v) + 10 \log_{10} (1 + 5P/v) - 40.7 \text{ dBA} \qquad (2.7)$$

Corrections for ground conditions, road surfaces and other factors have also been estimated and are found in BRE digest 185, 1976. Typical values of L_{10} (18hr) in normal traffic conditions are given by HMSO *(16)* as 80 dBA at a receiver point 18m from a busy motorway, 70 dBA for a main road through a residential area and 60 dBA on a residential area screened from a busy road by houses.

Measured values of L_{10} have been found to be over-sensitive, when compared to human response, to traffic accelerating and braking. In addition, people who are exposed to traffic noise during the night may have the quality rather than the quantity of their sleep altered. In both these situations the L_1 level gives greater correlation with subjective response than does L_{10} and it has been suggested as an alternative index *(17)*. An example can now be given (Table 2.1) of the use of the indices in the assessment of human annoyance.

Country	Sound Level	Percentage of People Disturbed
Austria	Leq = 45 - 50 dBA	30
Sweden	Leq = 50 - 55 dBA	15 - 23
France	Leq ≐ 60 - 65 dBA	Sharp Increase
England	L_{50} = 50 - 68 dBA	40

Table 2.1 The use of the indices in the assessment of human annoyance

The prediction of traffic noise in urban areas is not as simple as that described in the previous section for free flowing traffic. Other factors must now be included, such as the case when the traffic stream is interrupted by roundabouts, road junctions or traffic lights and is travelling through urban areas with multi-reflections from building facades. Noise also results from other streets and prediction is much more complicated.

2.3 NOISE LEVELS FROM NON-FREE FLOWING TRAFFIC

Noise levels at roundabouts of various geometries and road junctions were measured by Lewis *(18,19)* who was able to conclude the following:

1. The mean dBA level is always less than, or equal to, the mean free-flow level, for the case of decelerating vehicles and falls steadily as they approach the intersection.

2. The noise level rises above the free-flow level for the case of accelerating vehicles, but the increase is small and is within 2 dBA.

3. The distance where the above effect occurs is within 250m to 350m before and after the roundabout.

4. The geometry of the roundabout and the design of the approach roads do not affect the noise level appreciably.

Field measurements and computer modelling of road traffic at the approach of traffic lights have been conducted by Favre *(20)* and Jacobs et al.*(21)*. L_1 and Leq (dBA) were measured or predicted and results show that there is a 'traffic lights effect' within a zone of ±200m from the lights. A variation of 8 dBA to 10 dBA resulted at the roadside 25m from the lights. This variation gradually decreases with increased distance where traffic flow becomes regular. The traffic flow factors and traffic light cycle have no significant effect on the lengths (25m for the maximum and a total of 200m) of the zone influence.

In order to predict the L_{10} level in an urban area the empirical equation of Gilbert et al *(22)* may be used.

$$L_{10} = 43.3 + 11.02 \log_{10} (L + 9M + 13H) - 0.43Cw + 2.72/df \qquad (2.8)$$

where L, M, H are number of light, medium and heavy vehicles,

Cw is carriageway width in metres, and

df is the distance from the nearside kerb to nearside facades (m).

The reflection effects of near facades may also be included by an empirical formula which typically yields a correction of approximately 2.5 dBA *(22, 25)*.

Methods are thus available for the estimation of the noise levels from traffic in free-flow and non-free-flow conditions. The levels are usually given in dBA and it remains to describe more fully the frequency characteristics of traffic noise since it will be seen that the acoustic protection of facades can be highly frequency-dependent.

2.4 TRAFFIC NOISE IN HOT CLIMATES

In general, traffic noise is not recognized as a major problem in modern cities in hot climates. The problem, however, exists as a result of lack of planning and the acoustic requirements of building facades often conflict with those of ventilation, solar protection and day-lighting (See also the discussion by Fuchs *(24)* of traffic noise in Latin America). In addressing this problem, can existing criteria or recommendations formulated in more temperate climates be used?

In a rapidly expanding city, such as Amman in Jordan, roads and buildings are being constructed on slopes and low frequencies might dominate the traffic noise spectrum as a result of the use of low gears. The contribution of other roads might increase in significance as a consequence of the less efficient screening of buildings in excessively sloping areas.

Until appropriate criteria or recommendations can be evolved, the problem of traffic noise in hot climates will continue to increase and control will be remedial, rather than preventative.

2.5 TRAFFIC NOISE SPECTRA

Traffic consists of numbers of moving noise sources such as light vehicles, heavy vehicles and people. The resultant noise level is often highly variable and the noise spectrum is characterised by low frequency components which are more difficult to eliminate or reduce at the building facade. Low frequency sound is generated by vehicle (especially lorries and commercial vehicles) engines particularly at low speed, while noise in high frequencies results from light vehicles, brakes, acceleration, horns and whistles.

Typical spectral distributions are indicated in Figure 2.1 of noise from commercial and light vehicles *(25)*. In general, noise levels from light vehicles are greatest at 100 Hz to 200 Hz. Above 200 Hz the two spectra have the same shape but are of different magnitude.

In Figure 2.2 is shown typical traffic noise spectra (L_{10}) for a motorway with 3,000 vehicles per hour travelling at 112 km per hour and for a road in London at rush hour with a restricted speed of 48 km per hour*(25)*. The two curves are different in magnitude but similar in shape. In Figure 2.3 noise spectra are shown for heavy and light vehicles travelling at 100 km per hour and 50 km per hour *(26)*. A difference of approximately 10 dBA is seen between the two noise spectra as a result of vehicles' speed. This observation leads to the conclusion that variation in traffic flow parameters results in a variation in magnitude of traffic levels but not to the shape of the spectrum.

2.6. THEORETICAL PREDICTION

The discussion, so far, has been of the measurement of magnitude and frequency characteristics and the empirical prediction of noise generated in free-flow conditions and in urban areas. It is now necessary to examine, and select from, the mathematical models employed to simulate such noise.

Traffic which is freely flowing produces noise which has the following characteristics:

1. The proportion of time the noise lies between any two levels is normally distributed *(12, 27, 28)*

2. The distribution of the number of vehicles in a specified length of road can be assumed to be random *(29)*

3. An individual vehicle can be considered an omni-directional sound source to within ±2dB within a range of 100 Hz to 4 kHz.

4. Sound from traffic flowing freely on straight

level roads is non-directional about an axis in the direction of flow within ±2 dB *(30)*.

5. The characteristic spectrum of road traffic, as seen in Figure 2.2, is broad band *(31)* contains no pure tone although low frequencies predominate.

In an attempt to simulate the above characteristics, several theoretical models have been formulated which fall into four categories:

1. Models with equally spaced and identical sources

2. Models with equally spaced and non-identical sources

3. Randomly distributed and identical sources

4. Randomly distributed and non-identical sources.

Johnson and Sanders *(13)* made the first assumption in deriving the following formula to the L_{50} level:

$$L_{50} \propto 10 \operatorname{Log}_{10} \frac{\pi}{sd} \tan h \frac{2\pi d}{S} \qquad (2.9)$$

and

$$L_{max} \propto 10 \log_{10} \frac{\pi}{sd} \quad \text{Coth} \frac{\pi d}{sd} \qquad (2.10)$$

where d is the distance from the line source to the receiver, and

s is the distance between each two vehicles (Figure 2.4).

The intensity I is given by:

$$I \propto \frac{\pi}{sd} \left(\frac{\sinh \frac{2\pi d}{s}}{\cosh \left(\frac{2\pi d}{s}\right) - \cos \left(\frac{2\pi vt}{s}\right)} \right) \qquad (2.11)$$

where v is the speed of the vehicles, and

t is the time.

Figure 2.4 shows the levels obtained from equation 2.11 plotted against time. The maximum level occurs at t = 0, where the nearest sources are immediately opposite the observation point. The minimum occurs at $t = \frac{s}{2v}$, where the nearest sources are equidistant on either side. The mean level is shown at $t = \frac{s}{4v}$. The theoretically predicted values of L_{10} and L_{90} tend to be equal for traffic flows above 4000 vehicles per hour, while in real situations this is not the case where the measured difference is approximately 10 dBA *(32)*.

Blandamura and Spagnold *(32)* developed the previous model by simulating freely flowing traffic with non-identical point sources, at equal intervals, moving along a straight line. Account was taken of traffic composition, in particular the percentage of heavy vehicles. The calculated noise climate gave close agreement with field measurements.

Kurze *(33)* used a model in which the vehicles were randomly distributed, with uniform speed and composition.

The equivalent continuous noise level in free-flow conditions is given by

$$Leq = L_{ref} + 10 \text{ lag}_{10} \left[\frac{d_{ref}}{d} \cdot C \left(\xi_2 - \xi_1\right)\right] \text{ dB} \quad (3.12)$$

where C is the number of vehicles per unit length of the roadway,

L_{ref} is the SPL at a distance d_{ref} from single point source, and

$\xi_2 - \xi_2$ is the angle which encompasses the effective section of the source line at the observation point.

The standard deviation in noise level was given by $1.8\sqrt{M_n}$ dB where M_n is the mean number of vehicles over a length equal to the distance between the observer and the nearest point on the line source.

Blitz *(34)* developed Johnson and Sanders' method *(13)* for predicting L_{10} as a function of the position of the observer, the flow rate, and mean traffic speed. His theoretical model consisted of identical and equally-spaced point sources.

L_{10} was given by the formula:

$$L_{10} = 10 \log_{10} (\pi/sd) \frac{\sinh(2\pi/s)}{\cosh(2\pi d/s)-0.95} + L_o + 20 \log_{10} d \qquad (3.13)$$

where s and d can be seen in Figure 2.5, and

L_o is the mean reference level for individual vehicles.

Correction is then made to include the speed and percentage of heavy vehicles. This method is suitable in locations where variations in speed are not too great, such as on single carriageways, in an urban area, subject to low speed limits. Yamashita et al.*(35)* assumed the vehicles to be exponentially distribited with identical acoustic power. The model did not take into account the traffic composition, although uneven distribution of vehicles was considered.

Galloway et al.*(36)* employed a model based on a negative exponential distribution for space between successive vehicles, obtained from the following formula:

$$s = \frac{L_n \ (1 - RN)}{Q} \cdot v \qquad m \qquad (3.14)$$

where s is the spacing between successive vehicles,

RN is a uniform random number between 0 and 1,

Q is the flow of vehicles per unit time, and

v is the mean speed of the traffic.

A set of sources was assumed distributed randomly on both sides of the receiving point. The type of vehicles were chosen at random and their contributions to the noise level were calculated. Additional sets of point-sources were added on both sides until the last set did not contribute to the noise level by more than 0.5 dB. The total level resulted from the 'snap shots' recorded and the same steps were repeated several times. This result agreed closely with that obtained by Kurze *(33)* for the standard deviation, although there was no agreement in values of mean level.

SUMMARY

The main factors governing change in noise level are traffic flow and mean speed. The frequency spectrum is dominated by low frequencies, in particular below 250 Hz. The sound radiated from a traffic stream can be considered non-directional, within ±2dB about an axis in the direction of the traffic flow and the sound radiated from a single vehicle can be assumed omnidirectional, within ±2dB.

A set of point sources with random phase characteristics will give a reasonable simulation of a traffic stream. The point sources should be positioned as a line array and should radiate incoherently. This observation strongly influenced the choice of a scale model line source in the present work. Other requirements of a model sound source will be discussed in Chapter 6.

It is seen from the discussion so far that much work still needs to be done concerning traffic noise criteria, particularly in urban areas in hot climates.

REFERENCES

1. HOBBS, F. D. "Traffic Planning and Engineering" Pergamon Press, Oxford, 1979.

2. CHAPMAN, D. "A Survey of Noise in British Homes" National Building Studies, 1948, Technical Paper No. 2.

3. WILSON, S. "Noise" Final Report of the Committee on Problem of Noise, Cmnd 2056, London 1963 (H.M.S.O.)

4. PURKIS, H. J. "Transport Noise and Town Planning", 1964 B.R.S. Current Paper Design Series No. 25.

5. REICHOW, H. B. "Town Planning and Noise Abatement" 1963 Architects J. 137, No. 7, 357.

6. STEPHENSON, R. J. and BULKAN, G. H. "Noise from Elevated Trunk Roads" 1966 Town Planning Rev. 34, 146.

7. GRIFFITHS, I. D. and LONGDON, F. J. "Subjective Response to Road Traffic" J. Sound Vib. (1968) 8 pp. 16-32.

8. STATENS INSTITUT FOR BYGYNASFORSKING "Trafik buller i Bosland somraden" Statens Institut for Bygyasforsking, Report 36/68 Stockholm, 1968.

9. ROBINSON, D. W. "The Concept of Noise Pollution Level" Ministry of Technology, NPL Aero, Report. Ac 38, 1969.

10. CROOME, D. J. "Noise, Buildings and People" Pergamon Press, Oxford, 1977.

11. LAMURE, C. and ANZOU, S. Cah. Cent. Scient. Tech. Batim. (1966). 78, 1-18.

12. LAMURE, C. and BACELON, M. Cah. Cent. Scient. Techn. Batim. (1967) 88, 761-768.

13. JOHNSON, D. R. and SAUNDERS, E. G. "The Evaluation of Noise From Freely Flowing Road Traffic" J. Sound Vib. (1968) 7 (2), 287-309.

14. SCHOLES, W. E. and SARGENT, J. W. "Designing Against Noise From Road Traffic" App. Acoustics (4) (1971) 203-234.

15. BUILDING RESEARCH ESTABLISHMENT DIGEST "Prediction of Traffic Noise: Part 1". Digest 185, 1976.

16. NOISE ADVISORY COUNCIL PUBLICATIONS "A Guide to Noise Units" H.M.S.O., London, 1974.

17. ALEXANDRE, A., BARDE, J. P. et al, "Road Traffic Noise" Applied Science Pub. Ltd., 1975.

18. LEWIS, P. T, and James, A. "On the Noise Emitted by single vehicles at Roundabouts" J. Sound Vib. 1978 (58) pp. 293-299.

19. LEWIS, P. T. and JAMES, A. "Noise Levels in the Vicinity of Traffic Roundabouts" J. Sound Vib. 1980 (72) 1, pp.51-69.

20. FAVRE, B. "Noise at the Approach to Traffic Lights: Result of a Simulation Programme" J. Sound Vib. (1978) 58 (4), 563-578.

21. JACOBS, J. J. M., NIJS, L. and WILLIGENBURG, J. J. "A Computer Model to Predict Traffic Noise in Urban Situations Under Free-Flow and Traffic Light Conditions" J. Sound Vib. 1980 (72) 4, 523-537.

22. TRANSPORT AND ROAD RESEARCH LABORATORY "Noise from Urban Traffic under Interrupted flow conditions" Report 620, 1980.

23. DELANY, M. E., HARLAND, D. G., HOOD, R. and SCHOLES, W. E. "The Prediction of Noise Level L_{10} due to Road Traffic" J. Sound Vib. 1976 (48) 3 pp. 305-325.

24. FUCHS, G. L. "Subjective Evaluation of Transport Noise in Latin AmericaP J. Sound Vib. 1975 (43) 2, 387 - 394.

25. BUILDING RESEARCH LABORATORIES LTD. "Practical Building Acoustics" SRL Holbrook Hall, Little Walding Field, Sudbury, Suffolk, CO10 OTH, 1976.

26. LEWIS, P. T. "The Noise Generated by Single Vehicles in Freely Flowing Traffic" J. Sound Vib. 1973 (30) 2, 191-206.

27. OSTERGAARD, P. B. and DONLEY, R. "Background Noise Level in Suburban Communities" J. A. S. Am. (36) 1964 (3) pp.409-413.

28. FOXAN, J. and PEARSON, F. J. A Statistical Model of Traffic Noise" Applied Acoustics 1968 (1) pp. 175-188.

29. HAIGHT, F. A. "Mathematical Theories of Traffic Flow" Academic Press, New York, 1963.

30. RATH, S. J. "Ueber Methoden und Ergebnisse von Getanschmessungen an Motorfahrzeugen" EMPA, 1965.

31. MOHSEN, E. A. "Use of the Technique of Acoustic Scale Modelling For Traffic Noise Research". Dept. of Build. Science, Faculty of Architectural Studies, Univ. of Sheffield, BS20, 1975.

32. BLANDAMURA, F. and SPAGNOLO, R. "A Mathematical Model for Predicting the Noise from Freely Flowing Traffic" Acoustics (30) 1974, pp.235-240.

33. KURZE, U. J. "Noise From Complex Road Traffic" J. Sound Vib. (19) 1971 (2) pp.167-177.

34. BLITZ, J. "Prediction of L_{10} on Urban Main Roads" Acoustics, Vol. 29 (1973) pp. 210-218).

35. TAKAGI, K., HIRAMATSU, K., YAMAMOTO, T. and HASHIMOTO, K. "Investigation on Road Traffic Noise Based on an Exponentially Distributed Vehicle Model - Single Line Flow of Vehicles with the Same Acoustic Power" J. Sound Vib. (36) 1974 (3) pp.417-431.

36. GALLOWAY, J. W., CLARK, W. G. and KEVRIEK, J. "High Noise; Measurement, Simulation and Mixed Reaction" National Co-operative Highway Research Program, Report 78, Appendix C, 1969.

37. TRANSPORT AND ROAD RESEARCH LABORATORY "Road Surface Texture and Noise" Leaflet LF 577, 1975.

38. SCHOLES, W. E., SALVIDGE, A. C. and SARGENT, J. W. Motorway Noise Propagation and Screening" J. Sound Vib. 1975 (38) pp.281-303.

CHAPTER THREE

REVIEW OF WORK ON ACOUSTIC PROTECTION OF BUILDING FACADES

This review is of the important work previously carried out on the acoustic performance of building facades. It will thus be possible to evaluate the present work of the author with respect to that described in the literature, and develop and improve existing measurement methods.

3.1 SCREENING IN FRONT OF AND SOME DISTANCE FROM THE BUILDING

Previous work on the acoustic protection of free-standing barriers consists of an assessment of the performance of full-scale barriers, scale model work in laboratory conditions or computer simulation (which will be examined in Section 5.2). The work can be further categorized into that of barriers well removed from buildings, such as when positioned alongside motorways, and barriers separated from, but in closer proximity to the building being protected.

In field work carried out by Scholes et al *(1, 2)* a full-scale barrier was placed along a section of six-lane motorway at Heston in London. It was constructed of an airtight double skin of hollow panels supported in metal framework and was of length 300 m. Each panel was nominally 20 mm thick and of height 2.4 m and surface mass was 7.7 kg/m^2 (Figure 3.1). The reduction in L_{10} value over 24 hours at a distance of 1m from nearby houses as a result of introducing the screen was measured as 8 dBA. At the same time, the subjective reaction of the residents was assessed by means of questionnaires and it was found that two thirds of the residents thought that useful noise reduction had resulted.

The performance of a highway noise barrier of pre-cast concrete, constructed in Toronto, Canada, in 1978 was measured by May et al *(3)*. The construction was of T-section girders at 3 m centres between which were placed plates of 20 mm thick concrete of height 4 m. On completion, it extended 18 km along a twelve-lane highway. Three surface treatments were considered, a reflective covering of 6.4 mm hardboard, eight types of absorptive covering and T-profile with 620 mm long cap made of 6.4 mm hardboard. An average insertion loss (difference in A-weighted Leq) was measured for each covering and values ranged between 5 and 10 dBA. This result agreed in general with those of scale model work by the same author *(4)*. The durability and weathering of sound absorbing materials used to cover the surface of the barrier facing the highway was also investigated. The absorption coefficient of some materials, such as wood fibres, chemically treated and bounded with Portland Cement and moulded under pressure, was shown not to decrease with weathering.

The conclusion to be drawn from this work is that a reduction in L_{10} (18 hr.) of approximately 8 dBA to 10 dBA might be obtained if a barrier of height 4 m is placed between and close to a motorway and a building. There may, however, be a restriction of view for the residents and, if placed near the building, there may be some loss of natural light. The main difference between previous work and that of the author is that the former deals only with free-standing barriers, whereas the latter is concerned with barriers as an integral part of the building facade.

3.2 FACADE WITH GLAZING

The results of laboratory measurements of windows with single or double glazing, of various glass and air gap thicknesses and of different constructions are well known and design guides and Tables are freely available *(6, 7)*.

Field measurements and laboratory results of the acoustic performance of glazed facades are described by Lewis *(8)*. In this investigation the effect of glazing thickness, workmanship, double glazing, construction and sealing was measured on site, using a real traffic noise as a source. From the result it can be seen that mean transmission loss over a frequency range of 100/3150 Hz of 4 mm single glazing (representing 50% of the external wall) at sound incident angles of 55° is approximately 19 dB. This value decreases to approximately 16 dB for sound incident at an angle of 73°. The mean value of double glazing (4 - 75 - 4 mm) was found to be 24 dB at sound incident angles of 37°.

From this result it is clear that an average transmission loss of 30 dB at higher floor levels where sound is incident at angles greater than 50°, will be difficult to achieve. This demonstrates that a room, at that height, exposed to traffic noise levels in excess of 80 dBA (a typical L_{10} value for a main road in an urban area during working hours) will suffer unsuitable aural conditions for almost all every day activities.

In the field measurement of Lewis a new method was introduced which was developed and accepted as an ISO recommendation (*(9)* and section 4.2). This method is adopted and used by the author in field measurements of the performance of building facade elements with respect to a real traffic noise.

3.3 FACADES WITH COURTYARDS

Courtyards, which can be described as walled areas without roofing, serve both visual and thermal purposes and enable doors and windows of rooms to open inwardly within the confines of the dwelling. In hot climates it operates as a thermal filter where vegetation, such as trees, reduce high temperature and excessive solar penetration. In fact, it has long been suggested that the best external space for thermal control was that of a courtyard house *(24)*. The 'inward-looking concept' was used by ancient Egyptian, Roman and Arab builders and is still used widely, being a common design response to thermal and other functional considerations.

The concept of courtyards as noise filters is a more recent inovation. Ettouny *(10)* investigated the acoustic performance of courtyards by means of half-scale models. A point sound source was positioned at a distance 0.5 m - 3 m from the ground. The depth of the courtyard was constant at 3 m and the height was 1.5 m. The attenuation was measured for normal incident sound at the one frequency of 4 kHz. Measured values and those predicted using the theory of Kurze and Anderson *(21)* are shown in Figure 3.2. The agreement is fair except when the receiver and/or the source are close to the courtyard outer wall. This may be due to the contribution of transmitted or flanking components in relatively thin walls and the results are of limited use for the following reasons:-

1. The acoustical protection of the control open area only was measured, rather than that of the rooms surrounding it.

2. A point source was used which does not adequately represent the directional characteristics of traffic noise.

3. Measurements were taken at 4 kHz only and for normally-incident sound.

4. The work was not extended to examine the effect of courtyard depth and road length and position. This was impossible due to the large size of the scale model, when compared with the anechoic space available.

Mohsen *(11)* and *(12)* developed the work, by means of 10:1 scale models, to investigate the protection afforded by courtyards for both the courtyard space and the surrounding rooms. This investigation also involved a computer simulation of a moving traffic stream. The result was a design chart *(11)* and formulae, which allow a prediction of attenuation, given as:

$$Att = 10 \log \frac{I_{sc}}{I_{un}} \quad dBA \tag{3.1}$$

where

$$\text{screen intensity } I_{sc} = \Sigma^{J} \quad I_{sej} \tag{3.2}$$

$$\text{unscreen intensity } I_{sc} = W^{j=1}/4\pi \quad \overline{SR}^{\,2} \tag{3.3}$$

$\overline{SR}$ is the shortest distance between source and receiver via the top of the barrier.

$$I_{scj} = \frac{w_j}{4\pi \ \overline{SR}^{\,2}} , \quad DFj, \tag{3.4}$$

$$DFj = 10^{(-Att_j/10)} \tag{3.5}$$

Atti is the value of barrier attenuation obtained from application of the equation of Kurze and Anderson *(26)*.

$$Att_j = 5 + 20 \ lag_{10} \frac{(2\pi \ Nj)^{\frac{1}{2}}}{Tanh \ (2\pi \ Nj)^{\frac{1}{2}}} \ dB, \quad \text{for } Nj > 0 \tag{3.6}$$

$$Attj = 5 + 20 \ lag_{10} \frac{(2\pi|N|)^{\frac{1}{2}}}{Tan \ (2\pi|Nj|)^{\frac{1}{2}}} \ dB \quad \text{for } 0 > Nj \tag{3.7}$$

$Nj = 2\Delta/\lambda j,$

Δ is the path difference between the direct, without the barrier, and the diffracted sound wave,

λj is the wave length corresponding to the centre frequency Fj of the jth frequency band of the spectrum.

w is the acoustic power of the source, and

wj is the acoustic power in the jth frequency and

I_{sc} and I_{un} are the intensities in a point with and without the courtyard respectively.

The model work and the computer simulation of Mohsen can be described as the first attempt to investigate methodically building facade performance and is of practical use in the prediction of the insulation afforded by a single element of a building facade such as a courtyard. Part of the results of Mohsen are shown in Figure 3.3.

The following points should be considered if the work of Mohsen is to be extended and applied more meaningfully:-

1. Ground reflection was neglected when the screened and unscreened intensities were computed (Eq.3.1). His justification that the line source was located close to the ground (75 mm) and the reflection component could be neglected is completely incorrect.

A ground reflected component equivalent to $W_i/4\pi\ \overline{SR}_1^2$, must be introduced when the unscreened intensity is computed. Three more components of similar intensity and different source-receiver distances should be included when the screened intensities are calculated. It will be seen that the improved model may yield results which differ from that of Mohsen by 10dB (Section 8.7 and references *(22, 23)*.

2. Interference between the direct and the ground reflected component was also neglected. The sound wave reflected at the ground surface interferes with the direct propagation of the wave to the receiver and causes a frequency-selective attenuation which depends on the height of the source and the receiver and on their separation. In this series of experiments source height was equal to one wave length of 5 kHz.

3. The receiver was a one half inch condenser microphone which could not be assumed omni-directional above 8 kHz since a polar deviation of 5 dB occurs at 12.5 kHx and more than 10 dB at 20 kHz *(14)*.

4. The point source used had an unusual frequency characteristic, in particular a large dip in output within the one third octave band centred on 3.15 kHz with a sharp rise in sound pressure level above 4 kHz of approximately 15 dB per octave (Figure 3.4). It thus failed to fulful the requirements of a model sound source in that a flat response is desirable in the frequency range under consideration (Section 6.3)

5. The measured performance of the courtyard has unexplained characteristics. An example is seen for a courtyard depth of 5 m and 3 m height where the L_{10} attenuation exceeds 15 dBA while the L_{90} attenuation is less than 5 dBA. The difference in L_{10} and L_{90} protection may be due to the simulated traffic noise spectrum. Thus L_{90} may be dominated by low frequencies while L_{10} might have higher frequency components. The courtyard, as a barrier, is more effective at high frequencies, and therefore the protection is more than that at low frequencies which dominate the L_{90} value.

3.4 FACADE WITH BALCONY

A balcony is an extension of an internal floor with access by means of a window or door to the internal volume. It provides protection from weather and direct solar radiation and provides a view. It is a familiar element in buildings, particularly in hot climates where the demand is for a link between the external and internal environment. A closed balcony is defined as a room without an external wall and an open balcony is that without three external walls.

Field measurements on gallery houses (consisting of 'street' balconies) were conducted by Gustafsson and Enarsson *(16)*. However, as in most field measurements, factors such as the balcony depth could not be varied and it is therefore not possible to extract suitable information from the work, other than a net reduction of sound levels, inside the rooms opening to the balcony, as a result of the gallery.

Gilbert *(15)* conducted field measurements of the insulation achieved by introducing a balcony between the source and a receiving room which was open to the balcony. The external sound source was a loudspeaker and the balcony was of 1 m depth constructed from wood of unstated detail. The balcony could be divided into small sections by vertical partitioning to form closed units. The internal surfaces could be covered with absorption material of fibreglass of unstated thickness. The effect of the sound incident angle vertically and horizontally was also examined. The conclusions which can be drawn are that the net insulation of a building facade will increase if a balcony screens a window or a door. The protection is, in general, small and frequency invariant at small incident angles, but increases with increased frequency for sound incident angles greater than 60°. Again, the effect of the balcony depth was not included and the field measurements did not fully represent real situations.

Field measurements were conducted by May *(18)* on high-rise balconies as a result of noise from freeways and compared with values obtained at ground floor. The reduction of noise level on the balcony as a result of introducing absorption materials, to the balcony surfaces, was also investigated. It was shown that the sound levels at the tenth floor were 10 dBA greater than at ground floor, and a further reduction of about 10 dBA was obtained by use of absorption. Again, these results are a minor contribution to this discussion since there is no information concerning the insulation afforded by the balcony to the internal space or to the balcony itself.

Mohsen *(17)* used one tenth scale models and computer simulation in an assessment of balcony performance. The model was constructed from 12.5 mm thick blockboard and consisted of a room (400 x 300 x 280mm^3) movable vertically in 300 mm increments, from first to fifth floor level. The room had a window opening on to a detachable balcony and the outside wall was also detachable in order to investigate the effect of variation of window shape. The model was housed in a semi-anechoic chamber with a reflecting floor surface of concrete (Figure 3.5). The measurement procedure consisted of sampling the noise level in the room with and without a balcony for a number of source positions. The reverberation time of the room was reduced to 0.05 seconds by means of absorption placed on the floor area, thus corresponding to a typical furnished living room. An average of noise level was obtained for a full scale of heights 1 and 2 m. The types of balcony, window shape and the source positions are shown in Figure 3.5 with the three orientations of the model. To predict the balcony performance with respect to traffic noise he established the variations in levels with time (associated with traffic noise) by sampling the resultant noise level at the receiver at regular intervals as the line of point sources moved along the road. The positions of sources relative to the receiver were fed into a computer which summed the resultant intensities assumed to be incoherent. In this way a cummulative level was calculated Fig.3.6. He employed the same equations (3.1 - 3.7) used for courtyard performance prediction and modified his design chart *(11)* to give an estimation of the performance of a balcony in conditions shown in Figure 3.5. It was concluded that a balcony at first floor level will provide an open room with an L_{10} insulation of 5.5 dBA (or an L_{90} insulation of 10 dBA).

SUMMARY

It is possible to point out, at this stage of the discussion, that there is still, in general, a shortage of reported investigations on building facade protection, theoretically, on field measurements and on model work. More work is required on different types of building facades, in particular, those that exist in hot climates.

REFERENCES

1. SCHOLES, M., SALVIDGE, A. C. and SARGENT, J. W. "Field Performance of a Noise Barrier" J. Sound Vibration 16 (4) 1971, pp.627-642.

2. SCHOLES, W. E., VULKAN, G. H., MACKLE, A. M. and HARLAND, D. G. "Performance of a Motorway Noise Barrier at Heston" App. Acoustics, Vol.(7), 1974, pp.1-13.

3. MAY, D. N. and OSMAN, M. M. "The Performance of Sound Absorbtive, Reflective and T-Profile Noise Barrier in Toronto" J. Sound Vibration (1980) 71 (1) pp.65-71.

4. MAY, D. N. and OSMAN, M. M. "Highway Noise Barriers: New Shapes" J. Sound Vibration (1980) 71 (1) pp.73-101.

5. BEHAR, A. and MAY, D. N. "Durability of Sound Absorbtion Materials for Highway Noise Barrier" J. Sound Vibration (1980) 71 (1) pp.33-54.

6. BERANEK, L. L. "Noise Reduction" McGraw Hill Book Co. New York, Toronto, London 1960 pp.300, 605-607.

7. KNUDSEN, V. O. and HARRIES, C. M. "Acoustical Designing in Architecture" John, Willey & Sons Inc. New York, London, Sydney, Sep. 1965 pp.442

8. LEWIS, P. T. "An Investigation of Variables Associated with Road Traffic Noise and its Penetration into Building" Ph.D. Thesis Univ. Newcastle-upon-Tyne, 1971 Chapter 5.

9. LEWIS, P. T. "A Method for Field Measurement of the Transmission Loss of Building Facades" J. Sound Vibration (1974) 33 (2) pp.127-141.

10. ETTOUNEY, S. M. and FRICKE, F. R. "Courtyard Acoustics" App. Acoustics (6) 1973, pp.119-132.

11. MOHSEN, E. A. "The Acoustics of Self Protecting Buildings: An Investigation of the Screening Effect of Building Forms with Respect to Noise from Road Traffic" Ph.D. Thesis, Dept. of Building Science Faculty of Architectural Studies, Univ. of Sheffield, 1976.

12. OLDHAM, D. J. and MOHSEN, E. A. "The Acoustical Performance of Self Protecting Buildings" J. Sound Vibration (1979) 65 (4) pp.557-581.

13. MOHSEN, E. A. "Use of the Technique of Acoustic Scale Modelling For Traffic Noise Research" Dept. of Building Science, Faculty of Architectural Studies, Univ. of Sheffield. Interior Report BS 20 Feb. 1975.

14. B. & K. "Condenser Microphones and Microphone's Preamplifier" December, 1976.

15. GILBERT, P. H. "Une etude sur la Protection des Habitations Contre les bruits Exterieurs Penetrant par les Facades" Cahiers du C.S.T.B. (Paris) No. 103 Cahier 901, 1969.

16. GUSTAFSSON, J. I. and EINARSSON, S. "Gallery Houses with Respect to Traffic NoiseP Proceedings of Inter-Noise 73, 1973 pp.271-275.

17. MOHSEN, E. A. and OLDHAM, D. J. "Traffic Noise Reduction due to the Screening Effect of Balconies on Building Facades" App. Acoustics (10) 1977 pp.243-257.

18. MAY, D. N. "Freeway Noise and High-rise Balconies" J. Acoustic Soc. Am. 65 (4) Mar, 1979 pp.699-704.

19. INTERNATIONAL STANDARDS ORGANIZATION (ISO) "Acoustics Measurement of Sound Insulation in Buildings and of Building Elements" Part V "Field Measurements of Airborne Sound Insulation of Facade Elements and Facades". 130, 140, 1978.

20. DELANY, M. E. HARLAND, D. G., HOOD, R. A. and SCHOLES, W. E. "The Prediction of Noise Levels L_{10} Due to Road Traffic" J. Sound Vibration 1976 (48) (3) pp.305-325.

21. KURZE, U. J. and ANDERSON, G. S. "Sound Attenuation by Barriers" App. Acoustics (4) (1971) pp.35-53.

22. JONASSON, H. G. "Sound Reduction by Barriers on the Ground" J. Sound Vibration (1972) 22 (1) pp.115-126.

23. BUTLER, G. F. "A Note on Improving the Attenuation Given by a Noise Barrier" J. Sound Vibration (1974) 32 (3), pp.367-369.

24. DUNHAM, D. "The Courtyard House as a Temperature Regulator" New Scientist, 8, 1960.

CHAPTER FOUR

FIELD MEASUREMENT OF BUILDING FACADE

The aim of this investigation was the field measurement of the acoustic protection of perforated screens in a high-rise building (or buildings) in and around Liverpool. The building or buildings selected would be similar to those used in hot climates and incorporate a perforated screen. The shape of perforation does not affect acoustic performance if the percentage perforation is constant. However, if the area of the perforation exceeds 10% of the total wall area, then the sound level reduction provided is negligible *(1)*. The measurements were carried out on one high-rise building only. This was due to the lack of suitable buildings in Liverpool.

4.1 MEASUREMENT METHOD

The measurements were carried out according to the international standard, 1SO/140 Pt. V *(2)*, which specifies the field and the laboratory methods for the measurements of sound attenuation at a facade under real acoustic conditions. The sound source was the traffic noise and the construction was assumed to be of average workmanship. The measured protection provided by a facade is expressed by the standardized level difference (D_{nT} tr) and is given by the formula:

$$D_{nT}, tr = Leq_1 - Leq_2 + 10 \log_{10} + \frac{T}{To} \qquad (4.1)$$

where Leq_1 is the equivalent sound pressure level 2 metres in front of the test specimen,

Leq_2 is the equivalent sound pressure level in the receiving room averaged over the room volume,

T is the measured reverberation time in the receiving room, and

To is a reference reverberation time given as 0.5 seconds.

The equivalent sound pressure level Leq is defined by the formula:-

$$Leq = 10 \log_{10} \frac{\frac{1}{T_i} \int_o^{T_i} P^2_{(t)} \, dt}{P_o^2} \, dB \qquad (4.2)$$

where P(t) is the time variable sound pressure;

Po is a reference sound pressure given as

2×10^{-5} N/m^2 and Ti is the integrating time.

It is possible to calculate Leq from eq.4.2 or by use of a Precision sound level meter (such as B&K type 2218).

To avoid possible fluctuations of the traffic noise level Leq_1 and Leq_2 are measured simultaneously on the two sides of the specimen by recording the sound on a twin-track magnetic tape.

The sound Reduction index, Rtr, can also be obtained from the equivalent sound pressure levels.

$$Rtr = Leq_1 - Leq_2 + 10 \; lag_{10} \frac{S}{A} \; dB \qquad (4.3)$$

where S is the area of the test specimen (m^2)

A is the equivalent absorption area in the receiving room, and may be evaluated from reverberation time measurements (1SO/R354)

where

$$A = \frac{0.163V}{T} \qquad (4.4)$$

V is the receiving room volume, m^3, and

T is the reverberation time in seconds.

The sound pressure level is measured using one third octave or octave band filters between 100 Hz and 3150 Hz.

The recommendations are as follows:

1. The volume of the room should be greater than 25 m^3.

2. The distance between the traffic noise source and the test specimen should be at least 6 metres.

3. The traffic noise source must be wide band and be uniformly incident over the whole specimen surf-ace.

4. The microphone should be placed 2 metres in front of the test specimen, thereby eliminating refl-ection effects.

5. The inside level must be the average of six micro-phone positions randomly distributed throughout the room and an averaging time of 5 seconds is required for each frequency band at each position. The average of the sound pressure level could also be recorded using a rotating microphone.

6. The internal microphone positions should be more than 500 mm from room boundaries and more than 1 metre from the test specimen.

7. The equivalent absorption area is determined from two reverberation time readings taken at each of three microphone positions *(2)*.

4.2 RATING METHOD

The method of rating the sound insulation of the facade elements described in this and subsequent chapters is that recommended in BS 5821:1980 *(3)*. In it, a description is given of a single figure rating (Rw) of the airborne sound insulation obtained by comparison of the spectrum of measured insulation with a family of reference curves which can be considered idealized insulation curves.

4.2.1 METHOD OF COMPARISON

1. The measured sound insulation is plotted on a graph similar to that shown in Figure 4.1.

2. A reference curve is selected such that the total unfavourable deviation does not exceed the permitted limit of 32 dB within the frequency range of 100 Hz to 3150 Hz.

3. The value of the reference curve on the ordinate of 500 Hz is the insulation index, Rw, Figure 4.2.

The advantages of this rating method are that it is possible to state a frequency-dependent insulation as a single figure which is easy to quote and allows comparison of structures which might have different frequency characteristics. It is assumed, however, that the insulation curve of any construction does not differ greatly in shape from the idealised reference curves.

4.3 DESCRIPTION OF SITE AND BUILDING

Figure 4.3 shows the site plan of the building under consideration. Included are the streets which contributed to the external noise level. The most important noise source was a dual carriageway used by approximately 3,000 vehicles per hour (counted between 1600 and 1700 hrs.). The nearest point on the road to the building was at a distance of 140 metres.

A second contribution resulted from another dual carriageway taking approximately 4,000 vehicles per hour (between 1600 and 1700 hrs.). The nearest point was at a distance of 350 metres. On both roads the speed limit was 40 miles per hour with a 1% gradient and with 20% heavy vehicles.

A third contribution resulted from narrow blocked roads surrounding the building with single cars passing during the measurement period.

The building was a block of flats of height 50 metres, containing 15 floors. The internal measurement positions were on the 8th, 11th and 13th floor levels. Below the 8th floor level the building facade lay below the line of sight to the dual carriageway and traffic noise was partially screened by small surrounding buildings. Above the 13th floor level the floor plan changed and no equivalent measurement position existed (Fig. 4.4).

The internal volume, where measurement took place, consisted of a common access area screened from the outside by perforated units (300mm x 200m x 200m each) of concrete. This part of the facade was of 35% perforation. The plan of the access area and detail of a perforated unit is shown in Figure 4.5. The inside surface of the enclosure was of 3 mm glass with wood frames containing one openable door (0.80 x 2.0 m). This screen separates the access area from a common hall in which are lift door, stairs and four apartment entrances. On one of the remaining walls was placed the waste disposal shute. The remaining walls and the ceiling in the access area were of hard, smooth painted surfaces, while the floor was of smooth concrete.

4.4 MEASUREMENT PROCEDURE

In Figure 4.6 is shown the measurement equipment. The external sound field was sampled by means of a one inch microphone (B&K type, 4165) on which was placed a wind screen. The microphone was positioned 2 metres from, and central to the building facade. It was connected by means of a calibrated cable to a sound level meter (B&K type 2209) and then to one channel of a tape recorder (UHER type 9200).

Inside the building a similar microphone also covered with a wind screen, was attached to a rotating boom, thus allowing a good spatial sample. This microphone was connected by means of an extension cable (B&K type AO 0033) of length 3 metres to a second sound level metre which, in turn, was connected to the second channel of the tape recorder.

Measurements were first taken on the 11th floor. Two calibration signals were recorded simultaneously, using two piston phones (B&K type 4220). The recording level in each channel was suitably adjusted so as to give a full scale reading on the indicator at the same time as a full scale deflection was displayed on each sound level meter. Recordings took place between 16.45 and 17.15 and thus including the rush hour. Recording duration was typically 10 minutes, and measurements were repeated for each floor level.

4.4.1 ANALYSIS

The two channels of the recorder were separately connected by means of an input adaptor (B&K type DD 2414) to an input stage (B&K type AC 0007) and then to a Precision Sound Level Meter (B&K type 2218). The meter was connected to a one-third octave band filter (B&K type 1616) and gave direct reading of Leq for the duration of 30 seconds for a sampling rate of 0.3 per second.

4.4.2 MEASUREMENT OF REVERBERATION TIME

Three sources were used in order to produce an impulsive noise of sufficient energy and frequency range. They were a slamming door, a pistol shot and bursting balloons. The resultant decays were recorded on both channels and the microphones and sources were moved to give 12 separate measurement positions inside the room volume.

4.5 RESULTS AND DISCUSSION

4.5.1 REVERBERATION TIME

Figure 4.6 shows the room reverberation time and standard deviation calculated from twelve decays corresponding to twelve microphone sound-source positions. As expected the reverberation times were large but highly variable at low frequency (100 Hz to 250 Hz) This is undoubtedly due to low mode densities where one or a few modes predominate. The spatial variations in reverberation time as indicated by the standard deviation decrease with increased frequency and in the frequency range 250 Hz to 3150 Hz give a value ± 0.1 seconds.

The reverberation time varied between a value of 2.2 seconds below 125 Hz and 0.81 seconds at 3150 Hz which is to be expected for an area with hard and smooth surfaces. In standardizing the measured level differences, this measured reverberation time is compared to a standard reverberation time of 0.5 seconds which is assumed typical for a dwelling.

4.5.2 SOUND REDUCTION INDEX (Rtr)

In Figures 4.7 and 4.8 are shown the measured protection in terms of (Leq_1 - Leq_2) and the calculated sound reduction index Rtr as defined in equation 4.3 obtained for the 8th, 11th and 13th floor levels. There was always a direct sound component between the traffic and the receiver and the sound incident angle did not vary more than 5^o for the floor levels considered.

Rtr is varied between a minimum of 5 dB at 630 Hz to approximately 10 dB at 125 Hz for the three floors considered. It is seen that there appears to be a decrease in level difference with increased height (of approximately 1 dB between 8th and 11th floors and between 11th and 13th floors). However, this variation lies within experimental error and cannot be considered a true effect. It would be expected that the direct component would decrease with increased height but, at the same time, the reflected component would increase. The calculated resultant level difference would, to a first approximation, be unchanged.

As it can be seen, most of the calculated protection results from the correction terms in equations 4.1 and 4.3 values of which lie between 2 dB and 6dB. With reference to Figures 4.7 and 4.8, there is a clear dip in the measurement curves at 630 Hz. This may be due to standing waves set up between floor and ceiling and between the side walls separated by approximately 2 metres.

In Figures 4.9 and 4.10 are shown the sound reduction index (Rtr) and the standardized level difference (D_{nT} tr) for 8th and 13th floor levels. It can be seen that there is no significant difference between the two results, thus indicating that in this case the correction terms 10 log $\frac{S}{A}$ and 10 log $\frac{T}{To}$ are equivalent.

In terms of the sound insulation index rating (BS 5821: 1980), this building facade gives a protection of 5 dB, 6 dB and 7 dB for the 13th, 11th and 8th floors, respectively.

4.6 SUMMARY

The perforated screen afforded a better protection than expected. However, the normalized or standardized protection depends to a great extent on the third term of equations 4.1 and 4.3 and thus on the accuracy of reverberation time measurement.

There are, in this field measurement, many important factors, the effect of which could not be assessed. Examples are the sound incident angle, the type of perforated facade elements and the associated structure. It was also difficult to isolate and assess each acoustic meachanism (such as transmission, absorption and diffraction), contributing to the resultant protection. Isolating traffic noise from that generated within the building was another difficulty in an inhabited area. There were also problems associated with field measurement in which the equipment, although accurate, was delicate and transportable rather than portable.

For the above reasons, it was decided that further measurement should take place in laboratory conditions. It was also decided that scale model techniques would be used.

REFERENCES

1. LAWRENCE, ANITA, "Architectural Acoustics" Elsevier Pub. Co. Ltd., England 1970. pp. (79).

2. International Organization of Standardization "Measurement of sound insulation in buildings and of building elements" Part V "Field Measurement of airborne sound insulation of facade elements and facade" 1SO 140/V - 1978 (E).

3. British Standards Institution "Methods for Rating sound insulation in buildings and of building elements" BS 5821: 1980.

CHAPTER FIVE

BARRIERS

In this chapter, the diffraction theory of sound waves and its application in describing the acoustic performance of barriers is briefly discussed. Previous work on the subject is reviewed and a comparison made between theoretical and experimental results in previous work.

The development of the diffraction theory is also examined with particular reference to the acoustic performance of thnadners and splitters, which will be defined. A computer simulation allows a full description of the sound field within the shadow zone and a parametric survey is carried out on both thnadner and splitter performance.

5.1 DIFFRACTION OF SOUND

When sound waves are obstructed by any object, a shadow zone is erected which is small compared with the expected geometrical zone due to the diffraction of sound waves around the edges of the object. The ratio of the sound wave length to barrier dimensions is always greater than that for light waves and thus the shadow zone is much less extensive.

The first study of diffraction phenomena was made by the Frenchman Fresnel (1788-1827) who considered diffraction of a plane wave of light by a straight edge. The methods however, apply equally well in a description of the diffraction sound waves. In Figure 5.1, AB represents a section through a plane wave-front advancing toward a plane CD, the contribution ΔY to the receiver r of a source element ΔS placed at position at distance S from O and $(a + \Delta)$ from r is given according to Huyghen's principle, by

$$\Delta Y = B\Delta s . \text{Sin } 2\pi[t/T - (a + \Delta)/\lambda] \quad (5.1)$$

where B is the amplitude which is assumed proprotional to ΔS and the phase is retarded by $(a + \Delta)\lambda$

where λ is the wave length,

the resultant disturbance at r due to all elements on the wave-front is given by:

$$Y = B \int \sin \; 2\pi[(t/T) - (a + \Delta)/\lambda] \, ds \quad (5.2)$$

It is possible to re-write equation (5.2) to give

$$Y = B \int \sin 2\pi[(t/T - a/\lambda) - (\Delta/\lambda)]\, ds \qquad (5.3)$$

or $$B\sin[2\pi(t/T - a/\lambda)] \int\cos(2\pi\Delta/\lambda)\, ds$$

$$-B\cos[2\pi(t/T - a/\lambda)] \int\sin(2\pi\Delta/\lambda)\, ds \qquad (5.4)$$

If it is assumed that

$$R\cos\theta = B \int\cos(2\pi\Delta/\lambda)\, ds$$

and $$R\sin\theta = B \int\sin(2\pi\Delta/\lambda)\, ds \qquad (5.5)$$

Then $$Y = R\sin[2\pi(t/T - a/\lambda) - \theta] \qquad (5.6)$$

Intensity is equal to the square of amplitude.

Thus:

$$I = R^2 = B^2 \left[\left[\int\cos\frac{(2\pi\Delta)}{\lambda}\, ds\right]^2 + \left[\int\sin\frac{(2\pi\Delta)}{\lambda}\, ds\right]^2\right] \qquad (5.7$$

Put $\Delta = S^2/2a$

Then

$$I = R^2 = B^2\left[\left[\int\cos\frac{(\pi S^2)}{a\lambda}\, ds\right]^2 + \left[\int\sin\frac{(\pi S^2)}{a\lambda}\, ds\right]^2\right] \qquad (5.8)$$

or

$$I = R^2 = D^2 \left[\left[\int \cos \frac{(\pi V^2)}{2} dV \right]^2 + \left[\int \sin \frac{(\pi V^2)}{2} dv \right]^2 \right] \quad (5.9)$$

where $V = S \sqrt{\frac{2}{a \lambda}} = S \sqrt{\frac{2F}{Ca}}$

and $D = B \sqrt{(a\lambda/2)}$

The expressions in brackets in equation (5.9) are the well known Fresnel integrals. On integrating them between the correct limits of V, the resultant of the secondary disturbance arriving at r and arising from that portion of the wave-front lying between the limits of S is obtained.

If

$$\begin{matrix} X \\ Y \end{matrix} = \int \begin{matrix} \cos \\ \sin \end{matrix} \left(\frac{\pi V^2}{2}\right) dV \quad (5.10)$$

and taking X and Y as co-ordinates of a point for different values of V, the resultant curve (Figure 5.2), known as Cornu's Spiral (from French physicist, A. Cornu) passes through and is symmetrical about the origin and approaches to the points.

Z (0.5, 0.5) and Z (-0.5, -0.5) for

V = + ∞ and - ∞ respectively.

The amplitude due to any given portion of the wave front is thus obtained by finding the length of the chord of the appropriate segment of the spiral. The square of this length gives the corresponding intensity.

Diffraction of a Cylindrical Wave by a Straight Edge

In a manner similar to that employed for a plane wave front, a cylindrical wave front can be divided into half period zones (Figure 5.3).

V in this case is given by

$$V = S\sqrt{\frac{2(a+b)}{ab}}$$

or $$V = S\sqrt{\frac{2F(a+b)}{abc}}$$

where b is the radius of the cylindrical wave front (or the distance between the source and the edge). The rest of the nomenclature is shown in Figure 5.3.

If an edge is erected between the source s and the receiver r such as to block the lower part of the wave front (point o in Figure 5.3, then the contribution from the upper part of the wave front is the chord of the spiral, the arc of which has length OZ. The square of this amplitude proportional to the intensity at r. If the edge is elevated until at point B on the wave front, the amplitude at r from the remain part of the wave front is the chord of the spiral, the arc of which has the length BZ.

The application of this barrier theory will now be examined in the next section.

5.2 A REVIEW OF PREVIOUS WORK ON ACOUSTIC BARRIERS

A theoretical description was given by Redfearn *[1]* of the attenuation of sound from a point source at infinity by a semi infinite screen expressed as a function of effective height h (ie. the height of the barrier above the sight line) to the wave length and the diffraction angle. The design chart figure 5.4 developed was simple and practical since only two parameters, h/λ and the diffraction angle are involved.

The relation between barrier height H, wave length and source distance a and receiver distance b to the resultant attenuation was first given by Parcell *[2]* as a function of log n

$$\text{where} \quad n = \frac{2}{\lambda} \left[a\left(\sqrt{1 + H^2/a^2} - 1\right) + b\left(\sqrt{1 + H^2/b^2} - 1\right) \right.$$

$$\simeq \frac{H^2}{\lambda a} \quad \text{if } b \gg a \gg H \qquad (5.11)$$

The predicted attenuation is obtained from a design chart (Figure 5.5 which is surprisingly similar to an empirically derived chart resulting from the model work of Maekawa *[3]*.

Rettinger *[4]* gives the attenuation of a semi infinite barrier in terms of a Fresnel Integral for the variable V defined earlier.

This is given in the form:

$$Att = 3 - \log_{10}[(0.5 - x\ (V_2))^2 + (0.5 - Y(V))^2] \qquad (5.12)$$

where X (V) and Y (V) can be calculated using eq. (5.10)

The curve which results from equation (5.12) is given in Figure 5.6 along with theoretical values according to Fehr *[5]*. Rettinger results are some 6 dB higher than those of Fehr and this may be due to the fact that ground reflection is neglected in the latter work.

Stanley *[6]* developed the work of Rettinger and simplified equation (5.12) such that:

$$Att = 6 + 6\sqrt{N} \qquad (5.13)$$

Where N = V/2 and V is the Fresnel number defined in equation(5.9)where barrier height, h, is used instead of distance s along the circumference of the wave front. The curve of this equation is also given in Figure 5.6 and gives a straight line which joins the point corresponding to the edge of geometrical shadow, which has a value 6 dB, with a point corresponding to the practical upper limit and gives similar values (within 4 dB) to that of Fehr when $0 \leq N \leq 20$.

Experimental work has been carried by Maekawa *[3]* using scale models (the scale factor is not given) where the point source emitted a pulsed tone and the diffracted signal was isolated in time such that all other components could be neglected. A simple design chart resulted where barrier attenuation is given as a function of $Log_{10}N$, where $N = \frac{2\Delta}{\lambda}$ and Δ is the path difference between the direct and reflected sound Figure 5.7. The scale of the abssisca N was adjusted for values of $N > 1$ such that the curve becomes a straight line.

Kurze and Anderson *[7,8]* predicted the attenuation of a semi-infinite barrier where:

$$Att = 10 \log_{10} 4\pi^2\frac{\Delta}{\lambda} - 20\log_{10}\frac{d}{a + b} + 10 \log_{10} (1 + \frac{d}{a + b}$$

$$- 20 \log_{10} \quad 1 + \frac{\sin \phi/2}{\sin (\theta + \phi/2} \quad dB \qquad (5.14)$$

Where a, b, d, ϕ and θ are shown in Figure 5.7.

The first term in the above equation is similar to that of Maekawa's results for values of $N > 1$ and can be written as:

$$Att = 10 \log_{10} 20 N \qquad (5.15)$$

The second term describes the excess attenuation due to the increased spherical divergence of sound wave and the third term yields a 3 dB correction which can correct the average value of the fourth term. Agreement between the formula of Kurze and the experimental results of Ma kawa, is good for $N > 1$. Kurze adjusted his equation (9.15) to fit Mackawa's result in the range $N \gtrsim 0$ in the following manner:-

$$Att = 5 + 20 \text{Log}_{10} \left[\frac{(2\pi N)^{\frac{1}{2}}}{\text{Tanh}(2\pi N)^{\frac{1}{2}}}\right] \quad dB$$

and for $o > N > -0.2$

$$att = 5 + 20 \log_{10} [\frac{(2\pi |N|)^{\frac{1}{2}}}{Tan (2\pi |N|)^{\frac{1}{2}}}] \qquad (5.16)$$

Pierce *[9]* calculated the attenuation of a spherical wave by a semi-infinite knife edge barrier by use of the formula.

$$att = 3 - \log_{10} [f^2 (\sqrt{N}) - g^2 (\sqrt{N})] \text{ dB} \qquad (5.17)$$

where f and g are auxiliary functions of Fresnel integrals given by

$F^2 (N) = \frac{1}{\pi N}$, $g^2 (\sqrt{N}) = 0$ for $(\sqrt{N}) \geq 2$

an $\Delta << A + B$

Equation (5.17) then simplifies to

$$Att = 3 + 10 \log 10 N$$
$$= 13 + 10 \log N. \qquad (5.16)$$

A comparison of the results of Kurze and those, so far discussed is also given in Figure 5.7. With the exception of the result of Rettenger, agreement is within 2 dB where $N \lesssim 10$.

The performance of an acoustical barrier against traffic noise, considered a line source, was measured by Koyasu and Yamashita *[10]* by means of scale models. The barrier was constructed of plywood of thickness 20 mm and formed a knife edge. The model was placed on absorption material (50 mm glasswood board) and the line source was a mechanically driven device. The noise reduction of the barrier was measured at frequencies of 1, 2, 4, 8 and 16 KHz and an empirical chart resulted in which sound attenuation and Fresnel number are related. Results were compared with those from the model work of Maekawa in which a point source was used. The discrepancy varies between 3 dB and 5 dB but when compared with the theoretical curve of Kurze *[8]* in which an incoherent line source is assumed (Figure 5.8 the maximum deviation is 2 dB.

Porada *[11]* also employed scale models (of factor 1:100 and 1:20) in an investigation of the attenuation by single and double barriers against a line source. The barrier was of 1 mm sheet steel placed on a reflective floor in an anechoic chamber. The line source was an air jet emanating from an opening and measurements were carried out at 3.15 KHz and 16 KHz only.

The following empirical formula resulted

$$Att = (10 + 6 \log_{10} N) \text{ dB} \qquad (5.19)$$

where $N = 2\Delta/\lambda$ and λ is the wave length.

The resulting curve is given in figure 5.9 along with that calculated by Kurze and Anderson (equation 5.15)

The experimental values are 1.5 dB less than those of the theory for 90% of the measurement points. This agreement can be considered satisfactory. In general the good correlations obtained between theory and scale measurements suggest that scale model techniques may employ with real confidence.

A design chart was introduced by Scholes et al *[12, 13]*, as a result of a comparison made between nearly all previous work on barrier performance, in order to predict the reduction of traffic noise by screens in a wide range of conditions. The barriers were initially assumed infinite in length and on flat ground (Figure 5.10 Corrections for angle of view, ground surface conditions, combination of noise levels (when the barrier is exposed to noise from more than one road) and traffic flow and composition were given. The resultant charts are given in Figure 5.11 for the predicting of L_{10} by symmetrical partial screen as well as by infinite barriers.

The measured performance of full scale barriers against traffic noise is also given by May *[14]* and Scholes et al *[15]* and their work has been examined in section (3.1). The results correlate well with prediction and with scale model measurement.

The acoustic protection of barriers which are an integral part of a building facade has been investigated by Ettoung *[16]* and Mohsen *[17]*, both in the form of a screen wall of a courtyard house and also by Mohsen *[18]*, as part of a balcony. The work involved the use of models and computer simulation and again, in general, there is good agreement. This investigation was examined in more detail in sections 3.3 and 3.4.

5.3 FACTORS RELATED TO THE ACOUSTIC PERFORMANCE OF BARRIERS

In section 5.2 a full discussion has been given of the effect of barrier height, sound wave length and source receiver geometry on acoustic performance and it now remains to consider some secondary factors such as barrier length, thickness and ground conditions.

5.3.1 BARRIER LENGTH

In much of the previous theoretical and model work in this field the assumption has been made that the barrier is infinite in length. In practice, a reasonable approximation to this simplified assumption is possible for the case of a point source but barrier length is more critical for the case of a line source. In this case, it must be of sufficient length in order to screen the whole traffic stream from the receiver and thus attain maximum benefit.

Scholes et al. *(12)* gave the noise reduction at a barrier, as a function of the angle subtended at the reception point by the edges (Fig. 5.11). It was concluded that the half angle (A) must be at least 45° before appreciable attenuation can be expected.

Mohsen *(19)*, as a result of his model work on the effect of barrier length on performance, indicates that a semi-infinite barrier can be replaced by a right angle barrier and the theory remains valid in the prediction of the noise reduction if the receiver is completely screened. This configuration is fairly common such as, in domestic situations, a good example being a balcony.

5.3.2 GROUND ABSORPTION

For a given distance, the received sound level in the absence of the barrier is determined by the direct sound and that reflected from the ground. On inserting a barrier, the level at a receiving point can be determined by a measurement of four sound paths (Fig. 5.12). When both the source and receiver are located above a reflective surface, the unscreened level will be 6dB greater than the free field level and the screened level will be 12 dB greater. The effectiveness of the barrier is, therefore, reduced by 6dB when placed on a totally reflective surface.

Fehr *(5)* theoretically describes this effect and the resultant curve is 6dB less than that predicted using the simple theory of Kirrochhoff (Fig. 5.6). Ettouny *(16)*, by means of scale models, also indicates the importance of ground conditions, and again shows this 6dB increase in performance when the ground is highly absorbent. In similar experiments Mohsen *(19)* gives an increase in performance of 5dB and the result is obviously dependent on source and receiver height above ground level where a decrease in height will result in an increase in attenuation.

5.3.3 BARRIER THICKNESS

Barrier protection increases with increased distance between the two diffracting edges. Maekawa *(3)* suggested that the attenuation afforded by a thick barrier is equivalent to that of a thin barrier with a height determined by the intercept of the two tangents to the edges from the receiver and the source. This suggestion has been criticized by Kurze *(7)* who argues that when both the source and receiver are close to the barrier the assumption will yield incorrect results. In his analysis the attenuation resulting from double diffraction is equivalent to the sum of attenuations of two single diffractions, one resulting from the path from source S to receiver R along the top of the barrier at a distance rR from the edge, and the other resulting from the path from source S in the plane of the barrier top and at a distance rS from the edge to receiver R (Fig. 5.13). The attenuation is given by the equation:

$$\text{Att dd} = \text{Att (N1)} + \text{Att (N2)} - 5 + 20\text{Log}_{10} \frac{L}{d} \text{ dB} \quad (5.20)$$

where Att (N1) and Att (N2) are the attenuation corresponding to Fresnel numbers N1 and N2, respectively and L and d are shown in Figure 5.13. It was also suggested that for two parallel barriers separated by a distance less than a wave length, the attenuation is 5dB greater than that of a solid barrier with the same width. The sound level is increased by 3dB and thus the third term in equation (5.20) becomes -8.

In the model work of Parada *(11)* an investigation of the performance of double barriers against traffic noise resulted in the following empirical formula:

$$\Delta L \quad = \quad \Delta L_1 \ (N1) \ + \ L_2 \ (N2) \ dB \qquad (5.21)$$

where ΔL is the total noise reduction and ΔL_1(N1) and ΔL_2(N2) are the noise reduction by the first and second barrier separately. Maekawa et al.*(20)* have also used scale models to determine the increased attenuation due to increased thickness and the resultant measurements correlated well with theory where the effect of thickness for a band of noise is given by:

$$E \quad = \quad R \ Log_{10}(Kb) \ dB \qquad (5.22)$$

where K is the wave number,

b is the thickness of the barrier, and

R is inclination of lines found in Figure 5.14.

3. ABSORPTION MATERIAL ON BARRIER SURFACES

The sound level at a diffracting edge will vary according to surface condition. Of particular interest are the cases where the surface is hard (totally reflective with no phase change), soft (totally reflective with phase change) or absorptive. For a totally absorptive barrier there is no image source.

Butler *(21)* predicted the attenuation for three boundary conditions as a function of diffraction for a particular geometrical configuration shown in Figure 5.15. The result indicated that a significant improvement in performance can be obtained by using absorbent treatment. An even greater improvement can be obtained by use of a soft surface. There are, however, problems in physically realizing such a surface before these results can be of practical value. The analysis also indicated that surface absorption is more effective at angles of diffraction greater than 50°, where a 5dB improvement was obtained, while at lower angles (towards the limit of the geometrical shadow) it was found to be approximately 0.5dB.

Maekawa et al *(21)* in a recent paper present a method of calculating the effect of absorption on barrier attenuation. The effect is expressed as a function of the reflection coefficient, R and angle of diffraction and the curves are based on theory in which phase (imagining part of admittance) is neglected (Figure 5.16). The curve which represents total absorption (R = 0) compared well with those given by Butler. A model constructed of wood and glass wool gave measured results which compared well with theory. However, the diffraction angle rarely exceeds 90° and hence a small effect only is obtained. This observation is confirmed by field measurements of Jannsson *(23)* and May et al *(14)* in which an average improvement of 2dB only was achieved.

5.4 DIFFRACTION OF SOUND WAVES BY MEANS OF PERFORATED BARRIERS, THNADNERS AND SPLITTERS

The diffraction of sound by a solid knife edge has been described in section 5.1 in terms of Fresnel integrals and Cornu spirals. The development and application of this theory to the case of a solid, unperforated and semi-infinite barrier has also been examined. In this section the theory is further developed in order to predict the performance of various perforated screens. The description is similar to that of Wirt *(24)* who first suggested the use of designed perforated screens as a noise device.

It was previously stated (section 5.1) that if a barrier is constructed between a source and a receiver which blocks the lower part of the wave front, the modulus of the resultant vector will be reduced from ZZ to OZ (Figure 5.17). If the solid wall was such as to block the first half period zone of the wave front (point B), then the resultant becomes the vector BZ and the attenuation will then be:

$$A = 20 \log_{10} \frac{OZ}{BZ} \text{ dB} \qquad (5.23)$$

The difference between BZ and CZ (the vector resulting from screening the first and the second half period zone) is small and the increased attenuation resulting from this increase in wall height will also be small. It should be thus possible to reduce the resultant vector by selective elimination of certain vector contributions which make up part of the cornu spiral.

If it was possible to reduce every sub-zone vector, in the first half period (1, 2, 3 . . . 9) (Figure 5.17) such that each was equal in magnitude to that of the ninth sub-zone vector, then the spiral becomes a circle as shown in Figure 5.17 with a resultant vector R equal to the radius centred at Z. Any resultant vector, the origin of which lies on this circle and ends at Z, represents an attenuation equal to that of a solid wall blocking the first nine sub-zones. Fuither, if the first nine sub-zones are further reduced and form a semi-circle (Figure 5.18) between Z and B, then the resultant vector for the first half period is now equal to zero. Therefore, in theory, this differential attenuation provided by a suitably designed perforated screen will result in a perfect shadow at a certain frequency and at a certain receiver point in space.

In general, the attenuation provided by such a hypothetical screen is characterized by the mechanisms of amplitude gradient and phase gradient.

1. <u>Amplitude Gradient</u>

Let it be assumed that a wall is transparent in such a way that the first sub-zone is attenuated more than the second sub-zone (direction remaining constant) and the second sub-zone is attenuated more than the third, and so on. This device will be referred to as a Thnadner*(33). The varying transparency can be represented by modifying the Fresnel Integrals such that:

$$X = \int_{-\infty}^{\infty} T \cos \left(\frac{\pi v^2}{2}\right) dv \qquad (5.24)$$

and:

$$Y = \int_{-\infty}^{\infty} T \sin \left(\frac{\pi v^2}{2}\right) dv \qquad (5.25)$$

where T = O, for an 'opaque' portion, and

T = 1, for a transparent portion.

Equations (5.24) and (5.25) can represent any degree of opacity.

---

* And Thnad is for Thnadners and oh,
are they sad, oh!
The big one, you see,
has the smaller one's shadow.
The shadow the small thnadner has
should be this.
I don't understand it, but
that's how it is.
A terrible mix-up in shadows! - Cee-whizz!

(An appropriate literary to describe this barrier (33).)

For the case of a solid barrier of height H2 (v2), the Fresnel Integrals are as follows:

$$X_1 = \int_0^\infty \cos\left(\frac{\pi v^2}{2}\right) dv \qquad (5.26)$$

$$Y_1 = \int_0^\infty \sin\left(\frac{\pi v^2}{2}\right) dv \qquad (5.27)$$

$$X_2 = \int_0^v \cos\left(\frac{\pi v^2}{2}\right) dv \qquad (5.28)$$

$$Y_2 = \int_0^v \sin\left(\frac{\pi v^2}{2}\right) dv \qquad (5.29)$$

The absolute value of the resultant vector R for a solid wall of height H2 (v2) is

$$|R| = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \qquad (5.30)$$

For a barrier which is partially transparent in the manner described above, the Fresnel Integrals are given as follows:

$$X_3 = \int_{v_1}^{v^2} T(v) \cos\left(\frac{\pi v^2}{2}\right) dv \qquad (5.31)$$

and

$$Y_3 = \int_{v_1}^{v^2} T(v) \sin\left(\frac{\pi v^2}{2}\right) dv \qquad (5.32)$$

where X_1 Y_1 and X_2 are the same as in equations 5.26 to 5.29, respectively. The absolute value of the resultant vector (T) for a thnadner of height H_2 (v_2) is therefore:

$$|T| = \sqrt{(X_1 - X_2 + X_3)^2 + (Y_1 - Y_2 + Y_3)^2}$$

The attenuation afforded by the thnadner compared with that of a solid barrier of the same height is given by:

$$A = 20 \log_{10} \frac{|T|}{|R|} \text{ dB} \quad (5.34)$$

2. Phase Change Gradient

The cornu spiral, as it appears in Figure 5.2, results from the assumption that the axial velocity of sound in material (C) is equal to that in air (Co). The ratio Co/C, which is the refraction index (η) of the material, may differ from unity. If C/Co > 1, then the component vectors of the cornu spiral will change in direction, but not in magnitude, and the origin of point B, for example, in Figure 5.19 will be moved towards Z, thereby providing a deep shadow. For the case C/Co < 1, the resultant vector will be expanded and the spiral will rotate counter clockwise.

The Fresnel integrals (Eqs. 5.31 and 5.32) can now be modified to describe phase change by including a factor ϕ (v).

$$X_3 = \int_{v_1}^{v^2} \cos \frac{\pi}{2} (v^2 + \phi^2 (v)) \, dv \quad (5.35)$$

and

$$Y_3 = \int_{v_1}^{v^2} \sin \frac{\pi}{2} (v^2 + \phi^2 (v)) \, dv \quad (5.36)$$

The barrier describing this mechanism will be referred to as a splitter.

The absolute value of the resultant vector and thus the attenuation is calculated from equation 5.33, where X_1, Y_1 and X_2, Y_2 are as in equations 5.26, 5.27, 5.25 and 5.29 respectively.

For a wall possessing both amplitude gradient and phase change gradients equations 35 and 36 become:-

$$X_3 = \int_{v_1}^{v^2} T\ (v)\ \cos\ [\tfrac{\pi}{2}\ (v^2 + \phi^2\ (v))]\ dv \qquad (5.37)$$

and

$$Y_3 = \int_{v_1}^{v^2} T\ (v)\ \sin\ [\tfrac{\pi}{2}\ (v^2 + \phi^2\ (v))]\ dv \qquad (5.35)$$

The attenuation for this case is calculated in the normal way.

It remains now to investigate numerically the effect of amplitude gradient and phase change gradient in a prediction of the acoustic performance of thnadner and splitter barriers.

5.5 THE COMPUTER SIMULATION

The theories set out in section 5.4 allowed a parametric survey using an ICL 1906S main frame computer at Liverpool

University. The language used was Algol 68 and the survey was divided into two program according to the barrier mechanism being investigated.

5.5.1 THE AMPLITUDE GRADIENTS

In this part of the computer program the phase factor ϕ in equation 5.37 is set to zero and the transmission factor T is assumed to be a linear function of height above the horizontal plane through the boundary between the solid base and the semi-transparent region and is given in terms of the transparency below the sight line (α) and above the sight line β. Thus:

$$T = \alpha + \beta \frac{h - h_1}{h_2 - h_1} \qquad (5.39)$$

where h, h_1 and h_2 are the height of the perforated part, the height of the solid part and the total height of the barrier above the sight line respectively.

The expression can be of the form:

$$T(v) = \alpha + \beta \frac{v - v_1}{v_2 - v_1} \qquad (5.40)$$

where v, v_1 and v_2 are the relative v of the height

$$v = h\sqrt{\frac{2(a + b)}{\lambda ab}}$$

and the other notations are shown in Figure 5.20.

α and β are defined by the following ranges:

$$0 \lesssim \alpha \lesssim 1, \quad -1 \lesssim \beta \lesssim 1$$

hence

$$0 \lesssim \alpha + \beta \lesssim 1, \text{ and } -0 \lesssim T \lesssim 1$$

5.5.1.1 EFFECT OF SOLID PART HEIGHT

In the first part of the study it was assumed that $\alpha = 0$ and $\beta = 1$ (i.e. the centre line passes through the solid part). The solid part height h_1 was increased in increments of 5m. The distance between the barrier and the source is constant at 10.0m and the results are normalized by comparison with the performance of a solid barrier of equal height (Figure 5.21). It can be seen that for the source, barrier, receiver geometry considered the protection afforded by a thnadner is greater than that of the solid barrier at frequencies less than 400 Hz and for a receiver position 1 m distant. The performance is equal to that of a solid barrier, within ± 2dB, at receiver distances greater than 4 m for all frequencies. It is also seen that the height of the solid base does not affect the acoustic performance of the thnadner. At a receiver distance of 1.0m and for h_1 equal to 5 m the protection is greater when compared to the case when h is 15m within the frequency range 200 Hz to 500 Hz. This might be due to differential attenuation which provides deeper shadows at certain frequencies and positions.

5.5.1.2 EFFECT OF THE RECEIVER HEIGHT

Figure 5.22 indicates relative protection at six receiver heights over a frequency range 100 Hz to 1 kHz. As would be expected, thnadner performance decreases with increased receiver height. At 100 Hz the relative protection decreses from OdB for h = 0m to -12dB for h_i = 20m.

At frequencies below 400 Hz and for receiver heights of 8m and 16m above the solid part, the performance decreases to -6dB to -2dB, respectively, compared to the case of no barrier above the centre line. The protection increases where h_1 is equal to 0m and 4m above the solid part for receiver distances less than 1 m from the barrier. It is thus clear that in this case the sound energy is re-distributed from the lower to the upper part of what would normally be the shadow zone. This result is also confirmed in Figures 5.23 and 5.29 for the case of thnadner barriers of 25% and 12.5% perforation, respectively.

5.5.1.3 THE EFFECT OF PERFORATION

Figures 5.25, 5.26 and 5.27 represent the relative protection at frequencies 200 Hz, 400 Hz and 1 kHz, respectively, for a constant source, barrier, receiver geometry where percentage perforation is varied from 12.5 to 50. The relative protection is +3dB to +8dB at receiver distances less than 5 metres but there is no difference for the case of 25% and 12.5% perforation at frequencies greater than 1 kHz. Surprisingly, for 25% perforation, and at frequencies less than 1 kHz, the protection is greater than that for the case of 12.5% and 50% perforations.

5.5.2 PHASE CHANGE GRADIENT

By setting the amplitude component $\tau(v)$, in equations 5.34, 5.35 and 5.36, equal to unity, the effect of phase can now be isolated and investigated. The phase lag is calculated for a variable thickness L by means of the formula *(35)*.

$$\text{Phase lag} = \frac{2\pi L}{\lambda} + \frac{2\pi}{\lambda}(\Delta - L)$$

$$= \frac{2\pi\Delta}{\lambda} + \frac{2\pi L}{\lambda}(\eta - 1) \qquad (5.41)$$

where η is the refraction index $(= \frac{Co}{c})$

It may also be written:

$$\text{Phase lag} = \frac{\pi}{2} v^2 + \frac{\pi}{2} \phi^2 \qquad (5.42)$$

$$\text{where } \phi = \frac{4(\eta^2 - 1)L}{\lambda}$$

If the thickness of the transmission region is assumed to be L_1 at position h_1 (v_1) and the thickness of the splitters is a linear function of h then,

$$L = L \left(1 + \beta \frac{h - h_1}{h_2 - h_1}\right) \qquad (5.43)$$

or

$$L(v) = L_1 \left(1 - \beta \frac{v - v_1}{v_2 - v_1}\right) \qquad (5.44)$$

if $\phi^2 = \frac{4(\eta - 1)}{\lambda}$

$$\text{then } \phi^2(v) = \phi_1^2 \left(1 + \beta \frac{v - v_1}{v_2 - v_1}\right) \qquad (5.45)$$

Values of $\phi^2(v)$ were used in equations 5.34 - 5.37 to calculate the attenuation afforded by splitters relative to that of a solid barrier of the same height.

For commercial sound absorption materials, the refraction index (η) is rarely large and, except for very dense materials and at low frequencies, usually ranges from unity at high frequencies to 3 at low frequencies *(25)*.

5.5.2.1 EFFECT OF REFRACTION INDEX (η)

Figures 5.28 and 5.29 show the effect of η for frequencies between 100 Hz to 1 kHz where other factors are kept constant for the two extremes of receiver distance. The performance increases with decrease in η at frequencies less than 700 Hz and for receiver distances less than 1m. However, there is no significant difference for different values of η at frequencies greater than 300 Hz and at a receiver distance of 31m.

5.5.2.1.2 EFFECT OF SPLITTER HEIGHT

In Figures 5.30 and 5.31 are shown the relative performance of splitters of height h, 5m, 10m, 15m and 20m above the sight line and for receiver distances of 1m and 31m, respectively. As would be expected, an increase in splitter height gives an increase in protection. However, at high frequencies this effect becomes small and height invariant. The attenuation at all frequencies is significantly greater than that of a solid barrier.

5.5.2.3 EFFECT OF THE RECEIVER HEIGHT

In Figure 5.32 is shown the relative protection of a splitter barrier at different receiver heights h_1 above the plane through the line separating the perforated and solid parts; all other factors being constant. For $h_1 = 20m$ and $h_2 = 0.0$ (i.e. the sight line passing the top of the splitters) the relative performance is worse than having no wall above the sight line and decreases to -22dB at a frequency 400 Hz. For $h_1 = 8m$, $h_2 = 12m$, the protection also becomes worse at frequencies less than 200 Hz. This result reinforces that of the amplitude gradient program which showed that these barriers are re-directing the sound energy from lower to upper regions behind the barrier.

SUMMARY

The concept of using solid barriers to reduce the excessive external noise, in particular traffic noise, is now an acceptable method. Both theoretical and experimental work correlate well and the attenuation of a solid barrier against traffic noise can be predicted with confidence.

The modification of classical diffraction theory has resulted in devices (thnadner and splitter) which theoretically give an acoustic protection sometimes greater than that of a solid barrier. Their effectiveness is more pronounced for receiver distance less than 5 metres and at frequencies less than 500 Hz. The mechanism here is one of redirection of sound energy from the lower to the upper part of the shadow zone.

Absorption material placed between splitters can cause a phase change, the magnitude of which decreases with increased barrier height and decreases splitter width. The optimum distance between the splitters and the thnadners is governed by the wave length of sound and thus the range of frequencies under consideration. If the devices are to attenuate sound below 1 kHz, then the maximum distance between the splitters and the thnadners should not exceed 300mm.

It now remains to test the validity of this theory, by means of scale model measurements.

REFERENCES

1. REDFEARN, S. W. "Some Acoustical Source-Observer Problems" Phil. Mag. 7 (30), 1940.

2. PARCELL, J. B. C. "Control of Airborne Sound by Barrier" Noise Control, July, 1957, 20 - 26, 56 and 58.

3. MAEKAWA, Z. "Noise Reduction by Screens" App. Acoustics 1 (1968) pp. 157 - 173). Thesis Univ. of Sheffield, Appendix Vl) 1968.

4. RETTINGER, M. "Noise level Reduction of Barriers" Noise Control, Sept. 1957.

5. FEHR, R. O. "The Reduction of Industrial Noise" Proc. of the 2nd Annual National Noise Abatement Symposium, Chicago, 1951.

6. STANLEY, E. "Development of a Simple Relation for dB Reduction of a sound screen wall" (A contribution to H. W. Pratt, Ph.D. Thesis, Univ. of Sheffield, 1968.

7. KURZE, U. J. and ANDERSON, U. J. "Sound Attenuation by Barriers" Applied Acoustics (4) 1971 pp. 35-53.

8. KURZE, U. J. "Noise Reduction by Barriers" J. Acoustic. Soc. Am. Vol. 55 (3), 1974 pp. 504-518.

9. PIERCE, A. D. "Diffraction of Sound Around Corners and Over Wide Barriers", J. Acoustic. Soc. Am. 1974. 56 (2) pp. 332-337.

10. KOYASU, M. and YAMASHITA, M. "Scale Model Experiments on Noise Reduction by Acoustic Barrier of a Straight Line Source". Applied Acoustics (6) (1973), pp. 233-242.

11. PORADA, W. "Model Measurements Noise Screening of Line Sources by Single and Double Barrier" Applied Acoustics, (8) (1975) pp. 271-280.

12. SCHOLES, W. E. and SARGENT, J. W. "Designing Against Noise From Road Traffic" Applied Acoustics (4) (1971) pp. 203-234.

13. BUILDING RESEARCH STATION, Garston, Watford WD2 7JR. "Prediction of Traffic Noise" Building Research Establishment Digest 185, January, 1976.

14. MAY, D. N. and OSMAN, M. M. "The Performance of Sound Absorptive, Reflective and T-Profile Noise Barrier in Toronto" J. Sound Vib. (1980) 71 (1) (65-71).

15. SCHOLES, M. SALVIDGE, A. R. and SARGENT, J. W. "Field Performance of Noise Barrier" J. Sound Vib. 16 (4), 1971 627-642.

16. ETTOUNY, S. M. and FRICH, F. R. "Courtyard Acoustics" Applied Acoustics (6) (1973) pp. 119-132.

17. MOHSEN, E. A. and OLDHAM, D. J. "The Acoustical Performance of Courtyard Houses with respect to Noise from Road Traffic" Internal Report BS41. Dept. of Building Science, Faculty of Architecural Studies, University of Sheffield, Feb. 1975.

18. MOHSEN, E. A. and Oldham, D. J. "Traffic Noise Reduction due to the Screening Effect of Balconies on Building Facades" Applied Acoustics (10) 1977 pp. 243-257.

19. MOHSEN, E. "A Scale Model Investigation of the Performance of Noise Barriers" Dept. of Building Science, Faculty of Architectural Studies, Univ. of Sheffield, Internal Report, BS 21, Feb, 1975.

20. FUJIWARA, K., ANDO, Y. and MACKAWA, Z. "Noise Control by Barriers - Part 1: Noise Reduction by a Thick Barrier" Applied Acoustics (10) (1977) pp. 147-159.

21. BUTLER, G. F. "A Note on Improving the Attenuation Given by a Noise Barrier" J. Sound Vib. (1974) 32 (3) 367-369.

22. FUJIWAR, K. ANDO, Y. and MAEKAWA, Z. "Noise Control by Barrier - Part 2: Noise Reduction by an Absorptive Barrier" Applied Acoustics (10) (1977) pp. 167-179.

23. JONASSON, H. G. "Sound Reduction by Barriers on the Ground" J. Sound Vib. Vol. 22, (1) 1972 pp. 113-126.

24. WIRT, L. S. "Sound Control by Thnadners" Acoustica Vol. 42 (1979), 73-88.

25. SCOTT, R. A. "The propagation of Sound between Walls of Porous Materials" 1946 Proc. Phys. Soc. 358-368.

26. MATTER, A. B. M. "The Acoustics of Tropical Window" M.A. Thesis, Dept. of Building Science, Univ. of Sheffield, August 1971.

27. YERGES, L. F. "Sound, Noise and Vibration Control" Van Nostrand Reinhold Co. New York, Cinicinnati, Toronto, London and Melbourn, 1969.

28. FRENCH, A. P. "Vibrations and Waves" Thomas Nelson & Sons Ltd., London, 1971.

29. LAWRENCE, A. "Architectural Acoustics" Elselvier Publishing Co. Ltd., 1970, Sydney.

30. KLEIN, M. V. "OPTICS", John Wiley & Sons INC, New York, London, Sydney, Toronto, 1970.

31. JENKINS, F. A. and WHITE, H. E. "Fundamentals of Optics" McGraw-Hill Pub. Co. Ltd., New York, London, Toronto, 1951.

32. HARRIS, C. M. "Handbook of Noise Control" Sec. Edition. McGraw-Hill Co., London, 1979.

33. SEUSS, Dr., "On Beyond Zebra" Random House, New York, 1955.

CHAPTER SIX

SCALE MODEL TECHNIQUES IN ACOUSTICS

Acoustic modelling is a technique which potentionally permits the evaluation of acoustic properties of materials and enclosures in advance of construction and has the advantage of being economical and time-saving. It has been used, with success, to predict the acoustic performance of auditoria and has been employed in noise control research, such as in the study of traffic noise propagation in urban areas.

It was the inability to vary (or find sufficient variety) in facade types in the field measurements described in Chapter Three which led the author to continue the research program using scale model techniques. All factors contributing to building facade performance could thus be isolated and examined individually.

It was first necessary to critically examine these techniques before applying them in the present work, including basic principles and conditions of application.

A review of acoustic modelling in rooms and in urban areas will be given with particular emphasis on previous attempts to provide transducers or transducer arrays which adequately simulate traffic noise.

The acoustic performance of an anechoic chamber employed to simulate free field conditions was experimentally measured as an additional factor in the choice of scale.

6.1 BASIC PRINCIPLES

Any structure or volume may be represented by a model of reduced scale, the scale factor being simply the ratio of the physical dimensions of the model to those of the prototype.

If a model is to be measured in air and has a scale factor of $1/n$ where $n \geq 1$ then the following conditions must be fulfilled *(1)*.

1. The wave length of sound must be reduced by a factor n, and this involves an increase in frequency of a factor n.

2. The time of flight between surface reflections must be reduced by the same factor.

3. Air absorption at the model (higher) frequency must have a value equal to that of the full scale (lower) frequency.

4. If the acoustic impedance (and thus absorption coefficient) of the model surfaces in the model frequency range are made equal to that of full scale surfaces at the full scale frequency, the reverberation time must be reduced by factor n.

Therefore, two conditions must be fulfilled if the model system is to faithfully reproduce the relevant acoustic properties of the full size structure. First, the absorption (impedance), reflection and transmission must be similar in both structures and secondly, the laws that relate the various factors in the full scale model must apply without alteration to the model. Examples are the incident angle of a sound wave at a surface, the mass low in the transmission of sound through a structure, and the ratio between wave length and model dimension.

Similarity Conditions

There are many possible types of similarity in modelling: geometric similarity, in which the distances in full scale structure and scale model have a constant ratio, kinematics similarity where velocities in both structures have a constant ratio and dynamic similarity, in which forces in both structures have a constant ratio. Other typoes involve thermal and electrical properties.

A scale model is considered physically similar to a full scale structure if it fulfils all above conditions. This situation, however, is not often possible, nor often necessary. In acoustics, for example, thermal or electrical factors can be completely neglected and a geometrical similarity is often sufficient if reflection or diffraction of sound waves only is to be considered. In room acoustics and in noise control the requirement is for similarity with respect to geometry and the acoustical properties of the material.

6.2 REVIEW OF PREVIOUS WORK

Scale model techniques have been used extensively in room acoustics for over sixty years as an aid to auditorium design and continue to be successfully applied *(2)*. The earliest experiments involved the use of simple optical devices *(3)* and ripple tank methods *(4)*, and were primarily employed in a study of diffraction, reflection and transmission phenomena.

More recently, the development of reliable and accurate electro-acoustic transducers and associated instrumentation has resulted in improvements in the technique; in particular in the assessment of the effect on the steady state and transcient sound fields within rooms of surface modelling and absorption, audience absorption, room geometry and source/receiver position. The improvement in design of loudspeakers, microphones, head amplifiers and magnetic tape machines has allowed accurate measurements up to frequencies of 100KHz *(5)*. These measurements, such as those of the reflection, transmission and absorption characteristics of materials *(6)* make it possible to use large scale factors. In general, a small model which yields accurate results is quicker and more economical than larger models. In auditorium design results obtained by these methods compared favourably with full scale measurements. An example can be found in the work by Harwood and Bund *(2)*, in which a 1:10 scale factor was employed and where the maximum error of the reverberation time was 20%. This method is now an acceptable tool for the assessment of room acoustics at design stage *(2, 7, 8)*.

The acoustical performance of building facades and the predictions of the aural environment (in particular, that due to traffic) of urban areas has also been investigated by use of these techniques. Here the scale factors are much greater and can be of the order of 1:25 or 1:100 *(9, 10, 11, 12)*.

A scale factor 1:30 was used by Delany et al.*(13, 14)* in an investigation of traffic noise propagation within large urban areas which included houses and roads. The model was constructed of 3mm hardboard to simulate building facades and grassed areas were simulated by the use of soft board of thickness 11 mm, covered by coarse-wear nylon cloth. Results obtained were compared with those from field measurements and, despite the apparent crudity of the modelling and the simplifying assumptions with respect to the scale noise source, satisfactory correlation was obtained. The discrepancy between the scale model data ranged from 1.7 - 2 dBA compared with real measurement.

Weathering conditions have also been simulated and in work by Jones et al.*(15)* a scale factor of 1:8 was used in an investigation of traffic noise propagation. Building materials were simulated by the use of sanded polystyrene bonded to thin tissue paper. The model traffic noise source was an ultra-sonic device producing sufficient power within a frequency range of 1KHz - 160KHz. Air movement was represented by use of a stream of dry nitrogen. Again, measurements on the scale model were compared with field measurements and the maximum difference was found to be less than 2 dBA. This was despite the fact that the source did not display the same spectrum and directional characteristics as real traffic noise. In addition, the reflection and absorption coefficients of the materials at the scale frequencies could not be assumed the same as those of the building material at full scale frequencies.

Scale model techniques have been widely used in investigations of noise reduction by barriers. Measurements on scale models such as found in the work of Maekawa *(16, 17)*, have correlated well with those obtained on full scale barriers and with prediction obtained from classical diffraction theory. A full review of previous, theoretical, model and full scale work has been given in section 5.2. It is recognised from the review that none of the previous model work completely fulfils the physical similarity requirements. However, the results were satisfactory when the diffracted field was correctly modelled.

The protection provided by courtyards (defined as a walled area without roof) against traffic noise was also examined by Ettouny *(18)* and Mohsen *(19)* using scale factors of 1:2 and 1:10, respectively. A 1:10 scale factor was also used in an investigation of the protection afforded by a balcony *(20, 21)* and the work in this field has been critically examined in sections 3.3 and 3.4. Again, the sound sources used cannot be assumed to have similar characteristics to real traffic noise. It is sufficient to say at this point that in order to correctly describe the acoustic performance of a facade element, then the diffracted and reverberent components of the sound field must be correctly simulated.

6.3 MODELLING OF SOUND SOURCES

Sound sources in models can be classified according to the method of sound generation, duration of signal and directional characteristics.

Under the first heading, sound source types are listed as follows:

1. Electro discharge sources (sparks), where the acoustical power output is dependent on the current flowing through the spark gap. This type of source has been used by Walters *(22)* in a study of 24th scale models of auditoria.

2. Electro acoustic sources (tweeters), an example of which was employed by Day *(8)* in a 10th scale model in a study of the acoustic field in landscape offices. A small pressure drive unit was employed by Gibbs *(23)* in which the horn

was removed and replaced by a flat plate through which a half-inch turned pipe was passed. The narrow pipe ensured that source was omni-directional below a frequency of 32KHz. Ettouny *(18)* employed a similar device to simulate the sound field produced by a single car.

3. Aerodynamic sources similar to those employed by Yamashita et al.*(30)*. The source which utilises vortex separation produced as an air jet, strikes sharp blades. The air flow was stabilized by inserting a conical piece in the open end of a tube which improved the omni-directionality of the source and increased output at low frequencies.

4. A mechanically-generated source employed by Koysu et al.*(24)* consisted of a 'c' section of stainless steel channel divided into compartments, each of which contained the same number of small balls. When the channel was mechanically oscillated the ball impacts resulted in a broad band noise, having random phase characteristics. The device was employed in an investigation of noise reduction by barriers against a line source.

When discussing duration, a sound source can produce a pulsed signal of short duration (often less than a millisecond), or a steady state signal which can be sinusoidal or complex. The former has been used with success in auditorium design *(9, 25)* and, more recently, in airborne and structure sound transmission measurement, *(26)* The latter has also been employed in investigations into barrier protection.

The directional characteristics are dictated by the sound source geometry which can be simply classified into: point, line and planar. A stationary machine, such as a car, or compressor, can often be modelled by a point source while a continuous stream of road traffic must be simulated by a line source.

6.4 REQUIREMENTS OF A MODEL SOUND SOURCE

A model source must meet the following requirements depending on the real source and the acoustic field being simulated:

1. Acoustical output power must be sufficient to achieve adequate signal to noise at all measurement positions and frequencies.

2. The output should be constant with respect to time.

3. The frequency response must be reasonably flat

within the frequency range of measurement.

4. The directional characteristics must be similar to those of the real source.

5. The source must be relatively small, compared with the model, so as not to perturb the sound field within and around the model.

6. In the case of traffic noise simulation the source may be required to be sufficiently long so as to be considered infinite.

Much work has been produced on traffic noise simulation but there remains a clear need for a model source which correctly simulates traffic noise according to the requirements stated above. Most of the previous work employed omnidirectional point sources *(10, 11, 12, 13, 14)*, which by definition are not generating the cylindrical waves required, and thus the incident wave will not strike the building facade at the correct angle or angles.

The mechanical noise source employed by Koysen et al. *(24)* referred to earlier, can be considered a true line source, but produced spectrum which unpredictably alter with the channel and ball-size.

A simple line source was successfully employed by Porada *(27)* and consisted of a metal pipe of rectangular cross-section of 20 mm x 20 mm and of length 2 metres. One end of the pipe was connected to an air compressor and the other was rigidly closed. Twenty-two holes of 5 mm diameter were drilled in one side of the pipe with centres varying between 75 mm to 125 mm to compensate for the decrease in air pressure along the pipe. The frequency spectrum of noise radiated from this source, measured at 1.0 m distance, is shown in Figure 6.1 and it can be seen that the output is reasonably constant, within 7 dB, in the frequency range of 1KHz - 40KHz. The power output is seen to be inadequate, however, and the signal at distant measurement positions would be insufficient.

An omni-directional air jet source was developed by Mohsen *(20, 21)* which generated a broad band output. Traffic noise was simulated by adding the signals recorded at a receiving point when the point source was moved along the model road. The resultant spectrum was adjusted, by means of a spectrum shaper device, to correspond to an A-weighted traffic spectrum. The equalizing device consisted of a number of third octave filters, connected in parallel, the gain of each being adjusted by means of potentiometers. The spectrum of this source was examined in section 3.3. The method is, in general, time-consuming and five or more measurements are required for one result at one frequency.

6.5 THE LINE SOURCE USED

It was thus decided initially that an aerodynamic line source similar to that of Porada *(27)* should be developed and improved. The first line source consists of a metal pipe of cross-section 20 mm x 20 mm and length 2 metres. Instead of varying the spacing between the holes to compensate, the air supply was connected at both ends and the holes were equally spaced. The pipe was connected to a cylinder of compressed air which could be placed in the anechoic chamber without introducing additional noise. This line source, unfortunately, proved impractical since the cylinder could not provide sufficient compressed air for more than 2 minutes.

It was, therefore, decided to develop an electro-acoustic device and the second line source consisted of an array of small piezo-electric tweeters (model KSN Toterala 6005A) used without horns; the diameter of the tweeter cores being 35 mm. Twelve identical units were connected to a straight, thin metal rod of length 3 metres at intervals of 250 mm. The length was limited by space available in the anechoic chamber. Each tweeter was supplied by separate white noise through a separate amplifier. The white noise was generated by means of a psuedo-random binary noise generator consisting of an 18 stage CMOS shift register clocked at approximately 60 KHz. The sources were thus phase-independent, although of equal magnitude.

The frequency range of the tweeter was given by the manufacturers as 2 KHz to 40 KHz *(28)*. In Figure 6.2 is shown the frequency spectrum of the noise radiated from the line source measured at 1.0 m distance by means of a condenser microphone and narrow band filter (Hetrodyne Analyzer, B&K type 2010) with a selective band width of 100 Hz. It is clear from the figure that this source radiates sufficient power in the frequency range of 2 KHz to 25 KHz and the level is constant within a range of 10 dB between a maximum at 20 KHz and a minimum at 2KHz. The spectrum can be seen to contain no pure tones. The figure also shows the spectra at points parallel to the centre line at a constant distance of 1.0 m. In Figure 6.3 is shown the directional characteristics at frequencies 2 KHz to 25 KHz looking along the line source.

This line source can be considered constant within ± 2dB with respect to angle of radiation within an angular range of ± 45^{o}. The line source selected by the author fulfils successfully all the requirements previously stated.

The investigation of the performance of free-standing barriers and of building facades was to be examined in anechoic conditions, thereby isolating unwanted components. It was, therefore, necessary to ensure the chamber offered true free field conditions within the frequency range under consideration.

6.6 THE ANECHOIC CHAMBER

The anechoic chamber of any acoustical laboratory is used to simulate free field conditions where there is no reflection components. The design is such that all, or nearly all, sound incident at its surfaces is absorbed. Sound pressure level should then reduce at the rate of 6 dB per doubling of distance from a point source. The performance of an anechoic chamber is thus dictated by the absorption coefficient with respect to frequency of the internal surfaces.

It was the purpose of this part of the investigation to assess the performance of the anechoic chamber at Liverpool University, by measuring the deviation from the inverse-square law at different frequencies. This would then allow an estimate of the lowest frequency at which the chamber can be considered anechoic.

In Figure (6.4) is shown the plan and cross-section of the anechoic chamber at Liverpool University. The plan dimensions are 6.7 m x 5.5 m and the height is 4.5 m. The length of the absorbent wedges used was 900 mm. The chamber is constructed as a separate room of brickwork of thickness 250 mm with a reinforced concrete ceiling of 150 mm.

The Inverse-square Law

If a point source, which is assumed omni-directional is vibrating in a free field, the intensity I, at any point will be inversely proportional to the square of the distance r, and proportional to the source power w. Thus:

$$I = \frac{w}{4\pi r^2} \text{ watts/m}^2$$

since rms pressure $p = \sqrt{Iz}$, where z is the characteristic impedance of air and is equal to 410 rayls (SI units).

The relationship between sound pressure level, SPL, and the sound power level of a point source is given by:

$$SPL = w - 20 \text{ lag}_{10} r - 10.9 \qquad (6.1)$$

By doubling the distance, r, the sound pressure level will be decreased by 6 dB.

Ideally, the SPL inside the chamber (if true free field simulation) would be expected to perform in the above manner. However, the chamber walls are not likely to display perfect absorption and there may, thus, be a discrepancy between measured SPL and that predicted. In addition, the deviation can be the result of the presence of standing waves, absorption by the enclosed air and reflection at hard surfaces, such as wire-mesh or supporting frame.

For the purpose of measuring SPL with respect to distance inside the chamber, two sound sources were used; a cone loudspeaker of diameter 100 mm within a box of dimensions 125 mm x 250 mm x 200 mm. This source could be considered omni-directional below 1500 Hz. At higher frequencies the sound source used was a condenser microphone (B&K 3444) of diameter 38 mm *(31)*.

A 25 mm condenser microphone (B&K 4131) was used as a receiver and was assumed to be omni-directional below 2.5 KHz *(29)*, within the frequency range of 2.5 KHz to 8 KHz a condenser microphone (B&K 4165) of diameter 13 mm was used.

Two methods of assessment were considered. In the first, both source and receiver were moved separately. In the second case the source was stationary at one part in the chamber and the receiver moved along a line from the source at increments of 250 mm. The deviation from the inverse square law inside the chamber is given graphically at frequencies 100 Hz to 8KHz, Figures 6.5 and 6.6 .

From these figures it can be seen that the chamber cannot be assumed to provide free field conditions at frequencies below 250 Hz. Above this frequency, the chamber performed well, despite the deviation of approximately 2 dB at frequencies above 8 KHz and distance greater than 3 metres. This is attributed to the increased effect of air absorption. A deviation of 2 dB from the inverse-square law can be expected at frequencies below 250 Hz.

REFERENCES

1. BBC Research Unit "Acoustic scaling: An evaluation of the proving experiment Report No. 1972/3.

2. HARWOOD, H. D. and BURD, A. N. "Acoustic Scaling of Studios and Concert Halls" Acoustica, Vol. 28 (1973), 330-340.

3. DAVIS, A. H. and FLEMING, N. "Sound Pulse Photography as Applied to the Study of Architectural Acoustics" J. Sci. Instrum. 3(1926), 393.

4. DAVIS, A. H. "The Analogy Between Ripples and Acoustic Wave Phenomena" Proc. Phys. Soc. (London) 38 (1925/26) 234-239.

5. BBC Research Unit "Acoustic Scaling: Instrumentation" Report No. 1972/4

6. BBC Research Unit "Acoustic Scaling: A one-eighth Scale Model Reverberation-room" Report No. 1971/3.

7. HEGROLD, L. W. "A 1:8 Scale Model Auditor" App. Acoustics, (4), 1971, 237-256.

8. DAY, B. and WHITE, R. J. "A Study of the Acoustic Field in Landscape Offices with the aid of a Tenth-scale Model" App. Acoustics, (2), 1969. pp. 161-183.

9. VENEKLASEN, P. S. "Model Techniques in Architectural Acoustics" J. A. S. A. (47) (2) pt. 1, 1970.

10. KORN, T. S. "Measurement of Street Noise on Models" Noise Control, Nov/Dec 1960, 5-6.

11. DANAVON, R. R. "Model Study of the Propagation of Sound from c/stal Aircraft into urban Environment" Abstract" 86th Meeting of J. A. S. A. v. 55 No. 2, 1974 p. 485.

12. BULLEN, R. and FRICK, F. J. "Sound Propagation of a Street Intersection in an Urban Environment" J. S. V. (1977) 54 (1), 123-129.

13. DELANY, M. E. RENNIE, A. J. and Cullins, K. M. "Scale-Model Technique for Investigation of Traffic Noise Propagation" J. S. V. (1978) 56(3) 323-340.

14. DELANY, M. E. RENNIE, A. J. and COLLINS, K. M. "Scale Model Investigation of Traffic Noise Propagation" NPL Acoustics Report AC 58, Sept. 1972.

15. JONES, H. W., STREDULINSKY, D. C. and VERMEOLEN, P. J. "An Experimental and Theoretical Study of the Modelling of Road Traffic Noise and its Transmission in the Urban Environment", App. Acoustics, 13 (1980), 251-265.

16. MAEKAWA, Z. "Noise Reduction by Screens" App. Acoustics 1(1968) 157-173.

17. FUJIWARA, K. ANDO, Y. and MAEKAWA, Z. "Noise Control by Barriers - Part 1· Noise Reduction by a Thick Barrier" App. Acoustics (10) (1977) 147-159.

18. ETTOUNEY, S. M. and FRICK, F. R. "Courtyard Acoustics" App. Acoustics (6) (1973) 119-132.

19. OLDHAM, D. J. and KOHSEN, E. A. "The Acoustical Performance of Courtyard House with Respect to Noise from Road Traffic" Univ. of Sheffield, Dept. of Building Science, Internal Reports BS 41, 1978.

20. MOHSEN, E. A. and OLDHAM, D. J. "Traffic Noise Reduction Due to the Screening Effect of Balconies on a Building Facade" App. Acoustics (10) 1977, 243-257.

21. OLDHAM, D. J. and MOHSEN, E. A. "The Acoustical Performance of Self Protecting Building" J. Sound Vib. (1979) (65) (4), 557-581.

22. WALTERS, B. C. "Instrumentation for Acoustic Modelling" J. A. S. A. Vol (47) (2) Pt. 1 1970.

23. GIBBS, B. M. "Distribution of Sound Energy Within a Room" M. A. Thesis, Univ. of Sheffield, 1970.

24. KOYASU, M. and YAMASHITA, M. "Scale Model Experiments on Noise Reduction by Acoustic Barrier of A Straight Line Source". App. Acoustics (6) 1973 233-242.

25. PINFOLD, H. C. "Traffic Noise in Miniature" New Science, 14 Dec., 1967.

26. DAVIS, J. C. and GIBBS, B. M. "The Oblique Incidence Measurement of Transmission Loss by an Impulse Method", J. S. V. (1981) 74(3) 381-393.

27. PORADA, W. "Model Measurements on Noise Screening of Line Sources by Single and Double Barriers" App. Acoustics (8) (1975) 271-280.

28. Wilmslow Audio Ltd. "Instruction and Application" Swan Works, Bank Square, Wilmslow, Cheshire.

29. BROEL and KJAER "Condenser Microphones and Microphone's Amplifier" B&K Applications Dec. 1976 Denmark.

PAGE NUMBERING AS ORIGINAL

30. KOYASU, M. and YAMASHITA, M. "Traffic Noise Propagation in Transverse Direction to the Main Road in the City area" Proc. of 8th I.C.A London, 1974.

31. B. & K. TECHNICAL REVIEW Microphones used as sound sources. B. & K. Applications 1970, Denmark.

CHAPTER SEVEN

SCALE MODEL MEASUREMENTS OF FREE STANDING BARRIERS

The theoretical analysis and computer implementation, described in sections 5.4 and 5.5, show that thnadners and splitters can (at certain frequencies and receiver positions) produce a deeper shadow than that of a solid thin wall of the same height. The validity of this prediction was now examined by means of scale model measurements.

A review of the previous measurements on model thnadners and splitters is given and a description is also given of the experimental set up and procedure employed in this investigation. In a discussion of the results obtained, recommendations are given for the employment of these barriers in real situations, in particular as part of the building facade.

7.1 REVIEW OF THE PREVIOUS WORK

Little work has been published on the performance of thnadners and splitters, all of which resulted from the use of fairly crude scale models. It was Wirt *(1)* who first developed the theory of thnadners and splitters, and who first measured their performance, using models of notional one size scale factor. The models were constructed of alluminium sheeting of unstated thickness, and the point sound source was a tweeter supplied with a pink noise signal and was positioned on a normal central to the model. The results obtained indicate that thnadner and splitter barriers can give a protection ranging between + 8dBA and -3dBA, compared with that of a solid barrier of equal height. The results were promising but more work was required for the following reasons:

1. The performances of the thnadners and splitters were given for a restricted range of frequencies and receiver heights.

2. A point source was used, whereas a line source would appear to be more suitable. Here the performance of these barriers would be more critical.

3. The effect on the barrier performance of the size of the perforation and solid base was not included and it is difficult to assess the relative contribution of the amplitude gradient through the solid part.

4. Important details in the description of the models were not given and thus the requirements for valid model work, given in section 6.1, may not have been fulfilled. The relation between the wave length, barrier height and perforation size, so important in scaling a diffraction field, is not given.

5. Predicted and measured values were not properly compared and, therefore, no conclusive statement could be made on the validity of either theory or experiment.

A recent paper by Osman et al.*(2)* includes results of measurements on similar models. Again, the effectiveness of shaped noise barriers is confirmed, particularly at frequencies below 500 Hz and at receiver positions less than 5 metres from the barrier. However, the model technique is crude and cannot be considered a parametric study and the solid part of the thnadner barrier was greater than half of the height of the reference solid barrier.

In addition, the thickness of the splitter base was approximately 5 times the thickness of the reference barrier and, therefore, the measured performance cannot be considered truly comparative.

7.2 THE SCALE MODELS

It was concluded from the computer simulation that the important factors governing performance of thnadner and splitter barriers are the relation between sound wave length, size of perforation, source, receiver and barrier geometry. It was also considered important to measure acoustic performance with respect to a line source for a wide range of frequencies.

7.2.1 THE BARRIER

In figure 7.1 are shown five types of barrier investigated, all of which were made of perspex of thickness 8 mm. The sixth barrier was a solid reference barrier of the same thickness, with a knife-edge cut at 30°. All were of a height of 200 mm supported on a wooden base (100 x 50 mm) and the scale factor is given as 1:10. The base of the thnadner element varied in width between 30 mm for model 1 and 100 mm for model 4. All shapes were saw-toothed in section with 50% perforation, with the exception of model 3 on a base of width 30 mm, which was of a flat-top type of 25% perforation.

The splitters, which are triangular in section, were constructed from perspex of dimension 200 x 100 x 8 mm and were covered by a layer of absorbing plastic foam of thickness 5mm, on both main surfaces. The distance between each splitter was set at 20 mm, giving 50% perforation.

These barriers were fixed by means of a groove of depth 20 mm into a wooden base and all precautions were taken to eliminate or reduce unwanted paths. The barrier arrays, of length 4 metres, extended a distance of 500 mm inside the acoustic wedges of the anechoic chamber and, as could be assumed, semi-infinite. The floor of the chamber was covered with plywood of thickness 25 mm over which was placed an absorbing layer of plastic foam of thickness 50 mm. The normal incident absorption coefficient of the foam had been measured using a standing wave apparatus and was found to be greater than 0.8 at frequencies above 1KHz, (Figure 7.2).

7.2.2 THE RECEIVER

Sound source levels were monitored by means of a half-inch condenser microphone (B&K 4165) placed at a distance 300 mm from the centre of the line source. It was connected to an audio frequency spectrometer (B&K type 2112) and was used to detect drift in the source output. Typically, the level was constant within ± 0.5 dB during a measurement run, which was often of eight hours duration.

Sound field measurements were recorded by means of a quarter-inch condenser microphone (B&K type 4136), which could be considered omni-directional below a frequency of 20 KHz *(3)*. The microphone could be moved by means of a graduated boom, consisting of a light-weight structure of thin metal rods of diameter 4 mm separated by thin rings of diameter 35 mm at intervals of 100 mm. The microphone support moved smoothly by means of a graduated pulley system and was mounted 300 mm from the track such as to avoid reflection from the supporting structure.

The signal from the microphone and cathode follower was amplified and filtered by means of a Hetrodyne analyser (B&K type 2010), with a selective band-width of 100 Hz. The layout of the experiment, including the equipment is shown in Figure 7.3.

7.2.3 THE LINE SOURCE

The line source used has been described in section 6.5 and was positioned 1 metre from the model barrier at a height of 35 mm above the absorptive ground, thereby reducing the effects of reflection and interference.

7.2.4 THE EXPERIEMENTAL PROCEDURE

Sound pressure levels were recorded at several receiver positions on a 100 mm grid in the absence of any barrier between the source and the receiver. The solid barrier was then inserted and the levels were recorded at the same receiver positions. The difference between the two levels is then the protection, or attenuation, afforded by the solid barrier for that receiver position. The solid barrier was then replaced by the model thnadners and splitters and, again, levels were recorded for the same source, barrier and receiver positions. Results were compared with those for the solid wall and with computer prediction.

The frequency range of measurement was 2KHz to 20KHz, representing a full scale frequency range of 200Hz to 2KHz. The receiver height was set at 35 mm, where no direct path existed between source and receiver, 50 mm, 150 mm and 250 mm where there was no barrier above the sight line. The receiver was also moved horizontally at each height in increments of 100 mm along a normal to the barrier from a distance of 50 mm to 2 mm.

7.2.5 RESULTS AND DISCUSSION

The Reference Barrier

In Figure (7.4) is shown the measured attenuation afforded by a solid reference barrier plotted as a function of Fresnel number, $N(\doteq 2\Delta/\lambda)$, where Δ is the difference between the direct and diffracted path length and λ is the wave length). Also shown is a theoretical curve according to Kurze and Anderson *(4)* for a coherent line source, an empirical curve derived from the model work of Maekawa *(5)* using a point source and an empirical curve produced by Yamashita et al.*(6)* using model measurements and a line source.

The agreement between the results of the present investigation and those of Kurze is within 1 dB for the case $N < 0.4$ and $N > 5$, while the agreement is within 3 dB, within the range $0.4 < N < 5$.

The curve of Maekowa is approximately 3 dB higher when $N < 0.5$ and increases to approximately 5 dB when $N > 0.5$. This discrepancy is the result of using a point source in the case of Maekawa's work and a line source in the present work. This observation is reinforced when comparing the work of Yamashita (line source *(6)*) with that of the present work. The results agree well for the full range of measurements. For the range $N < 0.6$ the mean measure protection is 1 dB higher and for the range $N > 0.6$ the mean values of both sets of results can be said to coincide. The relation between the mean values of Yamashita and those of the present work is shown in Figure 7.5. The correlation coefficient was calculated to be 0.944 and the confidence limit of 95% is within ± 1 dB.

The correlation between the results for a solid barrier obtained by the author and those of previous theoretical and experimental work is acceptable and sufficient to provide a degree of confidence in the subsequent investigation of the other barriers.

The Thnadners Models

In Figure 7.6 is shown the results for the four types of thnadner investigated, compared with those of the solid (reference) barrier of equal height for a receiver position (a) 50 mm from the barrier. The source distance was fixed at 1.0 m. It can be seen that for this case the relative protection, in general, decreases slowly with increased frequency. This may be due to the increase in relative size of perforation compared with wave length. This would appear to agree with theory in which a differential reduction in amplitude of the incident wave is required before any diffraction and thus attenuation can be achieved. When the size of the perforation becomes of the order of one wave length, the differential transmission will not result in the required distructive diffraction, although the solid parts only will give a small area shadow zone immediately behind. The results show also that the measured protection of any thnadner lies within ± 4 dB of that of a solid barrier. In addition, within this band the performance of a constant percentage perforation thnadner is not greatly affected by variation in geometry as long as a differential amplitude attenuation occurs.

The relative protection obtained by thnadner 1 is greater than that obtained by the other models. A maximum of 8 dB occurs at 5 KHz with values of 5 dB occuring at several frequencies. This supports the theory which predicts that perfect shadow occurs at certain positions and certain frequencies.

Figure 7.7 shows the relative protection of the thnadners for the case of a receiver distance of 2.0 m where all other conditions are the same as the previous case. The relative protection is seen to increase with increased frequency until 5 KHz, above which it can be assumed constant, lying within + 3 dB of the value for a solid barrier. The relative protection is again greater than 0 dB at almost all frequencies, and thnadner 1, in general, gives a higher performance than those of the other types.

In Figure 7.8 is shown the variation with receiver distance in predicted and measured protection of thnadner 1 for a receiver height (h) of 35 mm and for a frequency range 2 KHz to 10 KHz. At most frequencies the greatest protection occurs at receiver distances less than 500 mm (or 5 m full scale). Also seen is that predicted and measured values agree within 1 dB at 2 KHz and within + 3 dB at 4 KHz and 10 KHz. The increased protection is greater than predicted for all frequencies and all receiver positions.

The relation between predicted and measured values is also seen in Figure 7.9 as a function of receiver height and distance from the barrier. It can be seen that at a receiver height of 35 mm, where there is no direct path between source and receiver, the agreement is within 2 dB, with the performance of the thnadner being greater than that of the solid at all distances but one. When the receiver height is greater than 50 mm a direct path now exists and the relative performance decreases to a value between -2 dB to -6 dB. The agreement between predicting and measurement is less good but still lies within 6 dB.

Similar results are shown in Figures 7.10 and 7.11 for frequencies 4KHz and 6KHz, respectively. Measured values are 2 dB to 4 dB greater than predicted at 4KHz and 1 dB to 6 dB greater at 6KHz for a receiver height equal to 35 mm. The values are 6 dB lower at 9KHz and 6KHz for a receiver height of 250 mm. The results shown in Figures 7.9 - 7.11 indicate that these barriers provide a deeper shadow, compared with a solid barrier, where the direct path to the receiver is blocked. However, there is a concomitant enhanced illumination wherever a direct path exists. This leads to the important conclusion that thnadners re-direct, rather than absorb or reflect sound energy from one region to another, in what is known as the shadow zone.

The Splitter

The splitter configuration investigated is shown in Figure 7.1 The refraction index (η) of the applied absorption coating was assumed to be 1.05 when predicting relative protection. In general, at high frequencies, the predicted result was little changed by variation in refraction index; however, a phase change must always occur at the absorption layer in order that the splitter barrier is effective.

In Figure 7.12 is shown the relative theoretical and measured protection afforded by the splitter for the case of a receiver position 50 mm from the barrier and at a height of 35 mm. The line source was fixed at a distance of 1.0 m and was also at a height of 35 mm. Agreement is within ± 2 dB and is considered fair. Figure 7.13 shows results for a receiver distance of 400 mm where all other conditions are the same as previously. Again, agreement is good (within ± 1.5 dB) at all frequencies but one, where discrepancy is -4 dB at 9KHz.

In Figure 7.14 is shown the predicted and measured splitter performance, at 2KHz as a function of receiver height and distance. The performance is greater by approximately 2 dB than that of a solid barrier at almost all frequencies when there is no direct path between source and receiver. Measured results lie within + 1 dB for distances greater than 500 mm.

The relative protection is never greater than 0 dB and at small distances can be -5 dB when a direct path exists.

Figure 7.15 gives the relative protection in circumstances similar to those of Figure 7.14 for a frequency of 4KHz. Again, where there is no direct path between the receiver and the source, splitter performance compares well with that of a solid wall, except for receiver distances given by 400 mm < a < 800 mm. The protection is worse for a receiver height 250 mm where there is no barrier above the sight line. Agreement between predicted and measured results is, in general, within 2 dB in the first case and within 5 dB in the second case. All results indicate that splitters are similar to thnadners in that the sound energy is re-directed from a lower region of the shadow zone to a higher.

CONCLUSIONS AND DISCUSSION

It is possible now to give a clearer description of the shadow zone behind free-standing thnadners and splitters. In Figure 7.16 the space behind these shaped noise barriers is divided into three zones.

Where the direct sound is blocked, the relative attenuation of sound afforded by both devices varies between - 1 dB and +8 dB. This is the darkest shadow zone and lies below the sight line.

The second zone extends upwards from the vicinity of the sight line to a line from the source to a point at half barrier height. The relative protection here varies between -2 dB and -4 dB.

The third zone lies above zone two, and the relative protection varies between -5 dB and -9 dB which theoretically is a worse situation than if there was no barrier.

From this description it would appear that thnadners and splitters can be usefully employed as traffic noise barriers if the protected area lies within the first zone or at a distance greater than 20 metres from the barrier.

There is also the possibility that they can be employed as a courtyard wall, thus allowing sight and ventilation, but providing acoustic protection equal to or greater than that of a courtyard with a solid wall.

There is, in addition, the interesting possibility that they could be used as a part of a balcony in order to protect an otherwise accoustically weak facade. They might, in this case, require absorption material to be placed where the sound wave is re-directed. They could also be used as a modification to the shape of sunbreaks such that the facade would serve two purposes, that of a sound wave and solar ray attenuator.

A potential difficulty in the use of splitters is that the absorption layers may not result in a sufficient phase change. This would result in the barrier acting simply as a randomly, partially-perforated solid. The absorption material should be also of sufficient thickness to cause phase change at low frequencies and weatherability of the material used is also an important factor if the splitters are to be used outdoors. The distance between two splitter elements determines the range of frequencies that might be attenuated. Practically, this distance cannot be less than 150 mm, which corresponds to one wave length at 2KHz. Above this frequency it cannot be expected that sound will suffer much attenuation.

To overcome problems associated with the absorption material and distance between splitter elements, inclined splitters might be used. This application might act as a combined amplitude and phase gradient device and may also result in the incident sound wave suffering multiple absorptions on passing through the screen. In addition, an appreciable phase change at the lower part of the wave front may occur even at low frequencies. Absorption materials for outdoor use are now available and have been described by May *(7)* and Wirt *(8)*.

The use of splitter and thnadner screens as an integral part of a building facade will be examined in the next section.

REFERENCES

1. WIRT, L. S. "The Control of Diffracted Sound by Means of Thnadner, Shaped Noise Barriers" Acoustica (42) 1979, 2 pp.73-88.

2. MAY, D. N. and OSMAN, M. M. "Highway Noise Barrier; New Shapes" J. Sound Vib. (1980) 71(1) pp.73-101.

3. B&K "Condenser Microphones and Microphone's Preamplifier" December, 1976.

4. KURZE, U. J. and ANDERSON, G. S "Sound Attenuation by Barriers" App. Acoustics (4), 1971, pp.35-53.

5. MAEKAWA, Z. "Noise Reduction by Screens" App. Acoustics (1) 1968 pp.157-173.

6. YAGASU, M. and YAMASHITA, M. "Scale Model Experiments on Noise Reduction by Acoustic Barrier of a Straight line source", App. Acoustics (6) 1973, pp.233-242.

7. BEHAR, A. and May, D. N. "Durability of Sound Absorbing Materials for Highway Noise Barriers", J. Sound Vib. (1980) 71 (1), 33-54.

8. WIRT, L. S. "Sound Absorptive Materials to meet Special Requirements" J. Acoustic America, 57 (1975), 126.

CHAPTER EIGHT

MODEL MEASUREMENT OF BUILDING FACADES

In this part of the investigation, consideration was first given to the choice of scale factors, material, source and receiver configuration and measurement method. A description is given of the experimental procedure based on ISO 140 Part V, and the measurement of reverberation time.

Where possible, a comparison is made between the results of the scale model investigation and that of field measurements.

8.1 CHOICE OF SCALE FACTOR

In measurement of acoustic performance of full scale structures, there is little opportunity to systematically vary the control parameters such as percentage perforation facade detail, height above ground level, balcony configuration and ground absorption. A full parametric survey is possible only by use of scale model techniques the basic principles of which have been discussed in Sections 6.1 and 6.2.

The choice of scale factor in this or any investigation depends on the following:

1. The volume of available space, which ideally should offer free field conditions. The limit is therefore set by the anechoic chamber available.
2. The frequency response and physical dimensions of the transducers.
3. Air absorption which rapidly assumes increased importance with increased frequency and has a limiting effect unless sophisticated air drying apparatus is employed.
4. The full scale frequency range of measurement to be simulated.

A summary is given in Table 8.1 of the effect of the above factors in the choice of scale factor for airborne sound measurement and it can be seen that a suitable ratio lies within the range 8:1 to 10:1.

The deviation from the inverse square low within the

Constraints \ Scale Factor	2:1	4:1 5:1	8:1 10:1	20:1	40:1
Instrumentations	1	1	1	0	-1
Anechoic chamber	-1	0	1	1	1
Air Absorption	1	1	0	-1	-1
Dimensions (Cost and handling)	-1	0	1	1	1
Long stream of traffic	-1	0	1	1	1
Background Noise	-1	0	1	1	1
The output of the Noise source	1	1	1	0	-1
TOTAL	-1	3	6	3	1

1 - No effect

0 - Doubtful effect

-1 - Negative effect

Table 8.1 Factors Affecting the choise of scale factor anechoic chamber as a result of air absorption in the frequency range 20 KHz to 40 KHz has been shown not to exceed 2dB over a distance of 5m *[1]*. Since the maximum distance between the source and receiver did not exceed 2m, this deviation would not be expected to exceed 1dB. However, any distance law deviation is of little importance since in this investigation a subtractive method was adopted in which internal sound level was measured with and without each facade element. The requirement is, therefore, that air temperature and humidity, and thus air absorption, be constant throughout a measurement run.

8.2 MATERIALS USED

There are three requirements when acoustically modelling building facades and rooms:

1. The material surface must have an absorption coefficient at the scale frequency similar to that of the full scale material at the full scale frequency.
2. The transmission loss of the material at the scale frequency must be sufficiently high so that the sound field inside the model room is dominated by the direct or diffracted component.
3. The materials should allow rapid and accurate construction of models. Increased speed of construction will then allow a full parametric

survey.

The material chosen to simulate the solid part of the construction (assumed to be brickwork) was plywood of 19mm thickness. The absorption coefficient at frequencies corresponding to a full scale range of 63 Hz to 9 KHz, measured in a one-eighth reverberent chamber *[2]* has a value which lies between 0.05 and 0.1. This value is close to that of brickwork,the coefficient of which lies between 0.01 and 0.05 over the same frequency range (Figure 8.1). This difference is allowable even in room acoustics, where reverberation time measurement assumes great importance, In this investigation the absorption of the external surface of the building is not of great importance and the absorption coefficient need not be precisely simulated *[3]*. Simulated materials have been used successfully to model building facades *[4, 5, 6]*.

The airborne transmission loss of the plywood was measured directly using an impulse response technique developed by Davies and Gibbs *[7]*. In this a short duration square wave is fed to a loudspeaker. The loudspeaker microphone geometry is such that the direct and reflected signals are clearly separated in time. The direct component is captured digitally and analysed by means of a Fast Fourier Transform algorithm incorporated in the mini computer software. The process is repeated with the same speaker microphone geometry but with the addition of the intervening model wall. A simple subtraction of the new spectrum obtained from the reference spectrum, yields the transmission loss as a function of frequency.

Figure (8.2) shows the transmission loss over the frequency range of 100 Hz to 3.15 KHz,of the plywood measured by the author using the above technique. Also shown is the performance of a typical brick and plaster wall of thickness 220mm over the same frequency range. If the assumption is made that the plywood transmission-loss will increase at 5dB per octave at frequencies greater than those within the measurement range, then a notional curve of scale frequency performance can be produced and compared with the full scale performance of brickwork (Figure 8.3).

It can be seen that the transmission loss of the plywood at 2 KHz (the minimum frequency used in the scale model) exceeds 30 dB, while the maximum protection offorded by the perforated facade under consideration did not exceed 18 dB at this particular frequency; a difference of more than 12 dB. It is appropriate to point out that if the difference between two sound levels.(In this case as a result of the transmitted and diffracted paths) is more than 10 dB, than the lower contribution can be neglected.

Perspex of thickness 10mm.,was used in the construction of the facade elements including solid barriers, perforated screens and thnadner and splitter screens. The transmission loss of a sheet of perspex of thickness 13mm is shown in Figure 8.4 *[7]*. The frequency range of measurement was 100 Hz to 10 KHz and it can again be assumed that the transmitted component through the solid is negligible compared to the direct or diffracted component through any air space.

8.3 RECEIVER CONFIGURATION

Two microphones were used in measurement of facade performance. A one half inch condenser microphone (B & K 4165) was placed centrally between source and facade 300 mm from the line source and was used as a reference and a monitor of drift.

The receiver, placed inside the model room, consisted of a one quarter inch condenser microphone (B & K 4136) connected to an audio frequency spectrometer (B & K 2112) incorporating a one third octave band frequency analyser. The microphone, which could be considered omnidirectional at frequencies below 20 KHz *[8]*, occupied any one of the five positions within the model room during a test run. All positions were 100mm or more from any room surface thus eliminating reflection effects. The five microphone positions were representative of nine microphone positions if symmetry is invoked and the average of sound pressure level was obtained according to ISO 140 Part V.

The height of the microphone ranged between 100mm (1.0mm in full scale), which corresponds to the head height of a sitting person, and 200mm which is equivalent to the head height of a standing person.

8.4 THE EXPERIMENTAL PROCEDURE

The sound reduction index R θ of a facade measured according to ISO 140 Part V, in which an external loud-speaker is used *[9]*, is obtained from the formula:

$$R_1\theta_1 = L_1 - L_2 + 10 \log \frac{4\ S \cos \theta}{A} \quad dB \ ..... \qquad (8.1)$$

where L_1 is the average sound pressure level over an area equal to that of the specimen, infront of the facade, but excluding the effects of reflection. L_2 is the average sound pressure level in the receiving room obtained from at least six microphone positions. θ is the angle between the direction of the incident sound wave and the normal to the facade, S is the area of facade (or part of the facade) and A is the total absorption within the receiving room.

Let it be assumed that equation 8.1 is for the case where no facade element exists between the room and the noise source. On introducing the facade element, such as a perforated screen, the sound reduction index is now given by:

$$R_2\theta_1 = L_1 - L_3 + 10 \log \frac{4\ S \cos \theta}{A} \quad dB \ ..... \qquad (8.2)$$

Where L_3 is the average sound pressure level in the receiving room after introducing the facade element.

The acoustic protection afforded by the facade components only is therefore given by:

$$R_F = (R_1\theta_1 - R_2\theta_1) = L_3 - L_2 \quad dB \; ..... \qquad (8.3)$$

In figures (8.5) and (8.6) are shown the experimental layout and the different configurations investigated. A horizontal surface of 25mm plywood was placed in the anechoic chamber in order to simulate hard ground.

A plywood blanking wall which surrounded the model room was of dimensions 3.7m x 2.2m and was assumed sufficiently long so as to effectively eliminate the component of sound diffracted at the edges. The only significant acoustic paths between source and receiver were thus by direct and diffracted sound through perforation.

The room position, within the blanking wall, could be altered vertically in increments of 300mm, thus simulating increments of one floor level for a full scale floor to ceiling height of 3m. Difference in average levels (L_3 - L_2) was obtained at one-third-octave intervals between 2 KHz and 40 KHz, (Representing full-scale frequencies of 200 Hz and 4 KHz, respectively). Levels and level-differences were stored, for subsequent analysis on computer file, along with information on floor-height and facade-type.

Corrections for room absorption, ground reflection and air absorption are unnecessary in this measurement method since they result in an equal contribution to L_2 and L_3 which is eliminated on subtraction. The method can be regarded as a development of the 1SO open/closed method (1SO/140 Part V Appendix).

Simple computer programs allowed the calculation of an A weighted insulation or a sound insulation index rating *[10]* from the raw data. These single figure indices of acoustic performance subsequently allowed a rank ordering of facade protection (see Tables 8.2 and 8.3).

8.5 MEASUREMENT PARAMETERS

Many parameters can be listed in a discussion of the performance of a facade and it was found necessary to limit the investigation by considering of the following only:

1. Floor level.

   An increase in floor level results in an increase in source receiver distance. The percentage increase in distance from ground floor was approximately 15%. In addition, the sound incident at the facade will vary in angle from 0^o at ground level to approximately 53^o at fifth floor level where the road width is 20m. This variation is important since the relative contribution of the

Frequency KHz	Sound Levels Inside the Model					SPL Av.	SL dBA	Protection**		
	Position							dB	dBA	dBRw
	1	2	3	4	5					
2.0	42.0	40.5	40.0	41.0	41.0	40.77	59.4	12.11	16.1	16
2.5	42.5	41.0	40.5	40.5	42.5	41.27		13.28		
3.15	48.0	48.0	47.5	48.0	49.0	48.11		9.89		
4.0	56.0	56.5	56.0	57.5	56.0	56.44		8.11		
5.0	57.0	56.0	56.5	56.0	56.0	56.11		10.11		
6.3	54.5	55.0	54.0	54.0	54.0	54.27		12.66		
8.0	49.5	50.0	50.0	49.5	50.0	49.83		16.00		
10.0	51.0	49.0	50.0	50.0	50.0	50.o		15.00		
12.5	50.5	48.5	50.0	49.5	4o.5	4o.5		18.22		
16.0	50.5	4o.0	48.5	49.5	48.5	49.05		17.15		
20.0	51.5	50.5	50.0	4o.0	50.0	50.05		18.06		
25.0	45.0	43.0	43.0	41.0	41.5	42.44		20.78		
31.5	38.0	36.0	36.5	36.0	36.0	36.33		21.55		
40.0	38.0	35,5	36.0	35.5	36.5	36.11		22.89		
FACADE NUMBER 2.1*										

* Balcony without roof ** Protection = $L_1 - L_2$
Floor level: Second Walls: Partially absorptive Balcony Depth: 400mm

Table 8.2 Example of the Results

Frequency KHz	Sound Levels Inside the Model					SPL Av.	SL dBA	Protection**		
	Position 1	2	3	4	5			dB	dBA	dBRw
2.0	52.0	59.0	53.0	52.5	52.5	52.88	75.5			
2.5	55.0	55.0	55.5	53.0	59.3	54.55				
31.5	57.0	57.5	59.0	58.0	58.5	58.0				
4.0	65.0	64.5	65.5	64.5	69.0	64.55				
5.0	68.0	65.5	66.5	66.0	66.0	66.22				
6.3	67.5	67.0	67.5	65.5	67.0	66.83				
8.0	66.5	66.0	66.5	65.0	65.5	65.83				
10.0	66.0	65.0	65.5	63.0	66.0	65.0				
12.5	69.5	67.0	67.5	67.5	68.0	67.72				
16.0	68.5	65.0	67.5	65.0	66.5	66.20				
20.0	71.0	67.0	71.0	65.5	67.5	68.11				
25.0	67.0	63.0	66.5	60.0	61.5	63.22				
31.5	61.0	56.5	60.0	55.0	58.5	57.88				
40.0	63.0	57.5	60.5	56.0	60.0	59.0				
FACADE NUMBER 2.0*										

* Room only (The reference level) ** Protection = $L_1 - L_2$
Floor level: Second Balcony Walls Balcony Depth

Table 8.3 Example of the Results

reflected and diffracted components through the facade element will change. In the investigation of the effect of floor level, one model room of height 300mm was re-positioned, the rest of the facade area being uniformly blanked off.

2. <u>Balcony Depth</u>
Above ground level, an increase in balcony floor depth results in an increase in effective barrier height with respect to the source receiver vector. There is, however, also an increase in reflecting area exposed to the source and an increase in the sound reflected to the room below.

Four balcony-floor depths, ranging between 100mm to 400mm, were considered, corresponding to almost all depths in common use.

3. <u>Balcony Ceiling</u>
The ceiling was important in this investigation because it can be a reflecting or absorbing element of a building. For the case of shaped noise barriers, the ceiling may reflect the redirected sound into the room and produce a worse situation than that with no screening (Section 7.3.5).

Three types of balcony were considered with each facade element, a balcony with no ceiling, balcony with a reflective ceiling and a balcony with a particularly absorbent ceiling.

8.6 FACADE TYPES INVESTIGATED

The following factors were considered when selecting the facades for investigation:

1. The background theory of diffraction and the review of previous work on barrier performance (Section 5.2).

2. Previous work on the acoustic performance of building facades (Sections 3.1 and 3.4).

3. The design solutions, common in hot climates, for the control of solar penetration, the provision of adequate daylight and natural ventilation, and thermal insulation.

4. The field measurements which were carried out by the author, on building facades in Liverpool (Section 4.3).

5. Model and computer simulations of free standing thnadner and splitter barriers; particularly the work of the author (Section 7.3).

6. The practical consequences of installing these

facade elements in buildings with respect to appearance and durability.

The facade elements considered in this investigation are therefore as follows:-

1. <u>A Closed Balcony</u>

   Details of the closed balconies are given in Figures (8.7). The scale dimensions are typical of residential flats or offices. The balcony shown in Figure(8.7a) consisted of a rail which can be assumed acoustically transparent, while that of figure (8.7b) has a solid screen of scale thickness 10mm and is assumed to perform as a thin barrier (Section 5.3).

2. <u>Thnadner Facade</u>

   This facade, (Figure 8.8), is of 33% perforation and where measured without a ceiling can be thought to represent a courtyard with perforated walls.

3. <u>Splitter Facade</u>

   This facade (Figure 8.9), is of 35% perforation which will be seen to be sufficient for light and ventilation and is similar to that of vertical louvres used in solar control devices.

4. The Regularly Perforated Screen

A wall of 27% perforation was installed as a control (Figure 8.10). The perforation were circular of diameter, 10 mm and are often used in hot climates. Other regularly-shaped perforations need not be considered in this investigation, since the mechanism of sound reduction is the same for all of them and thus the level reduction would not be expected to vary with the whole shape, for a constant percentage perforation. Full scale usually made of brick or blockwork are acoustically reflective surfaces.

5. The Solid Barrier

A full height solid wall was used as part of a balcony without a ceiling, (Figure 8.11), and this was included, again, for purposes of comparison.

8.7 GROUND REFLECTION

During this experimental investigation, a clear dip in measured protection was observed for all facades investigated. This dip occurred at frequencies varying from 6.3 KHz, at the first floor level, where angle of incidence was 26°, to 4 KHz at the third floor level, where the angle was 43°.

Despite clear indication of the non contribution of sound transmitted through solid parts of the model (Section 8.2), it was initially thought that this was a coincidence characteristic. The mass and the stiffness of facade element and the blanking wall were altered by addition of an aluminium sheet of 5mm thickness. The transmission loss was expected to increase by approximately 7 dB, as a result of increasing the surface density from 11 Kg/m^2 to 27 Kg/m^2. The coincident frequency would also be expected to differ as a result of the sheeting. The level difference before and after inserting the facade element, and thus the measured protection was re-examined. The dip remained unchanged in magnitude and frequency and was observable even when the facade element and model room were removed. When an absorptive foam was placed upon the plywood floor of the anechoic chamber, the anomaly in the facade-protection-curves disapeared. It was clear, therefore, that the dip was due to ground reflection.

In Figure 8.12 is shown the protection offorded by a courtyard, at first floor level, with a solid thin wall. There is a dip of approximately 10 dB at 6.3 KHz, which disappears when the ground is covered with highly absorptive material. A similar improvement is illustrated in Figure 8.13 for the protection of a courtyard at second and third floor levels. These examples also indicate that the protection of any barrier is reduced by between 3 dB and

7 dB when ground absorption is introduced. This is due to ground effects, similar to those discussed in Section 5.3.2. where there are additional sound paths, between the source and receiver when above reflective ground. A phase change may also occur at the point of reflection and an interference effect be produced as a result of a change in apparent path difference between the direct and reflected rays. The presence of a ground reflected component will degrade barrier performance at a frequency dependent on source, receiver, barrier geometry, irrespective of scale. It was decided, therefore, in all subsequent measurements, the absorptive layer be removed thereby simulating hard reflective road surfaces.

8.8 EFFECT OF WINDOW SHAPE

In work carried out by Mohsen *[4]*, the effect of window shape on balcony performance was investigated. The five windows considered were of constant area but different dimensions and it was concluded that attenuation due to the screening of a balcony, varied little with window shapes If one uses the design chart produced by Mohsen, it is seen that the maximum variation in attenuation occurs at sound incident angles of 30^{o} and 60^{o}. This variation can be given as an L_{10} of 1.5 dBA. This small difference in balcony performance with different window shapes, may be due to a change in area of window screened by the balcony. Thus when, the sound incident angle is 60, 80% of a vertically long window area will be screened whereas only 50% will be screened for the case of the horizontal long shape.

It was decided in this work to use one aperture shape only namely a door in the middle of the room wall, of scale dimension 200mm x 20mm. This represents 34% of the total external wall area as compared to the 24% area considered by Mohsen. This was thought to be more representative of real situations where the need is for large apertures for daylight and ventilation, and where the need is to provide a strong visual link between the outside courtyard or balcony and the inside living area.

8.9 EFFECTS OF GLAZING

It has been stated in section (1.1) that the types of facade under consideration will be employed in hot climates where natural ventilation is desirable. It is important, however, to establish that the attenuation afforded by a facade element is not dependent on whether the aperture is glazed or unglazed.

The results of field work by Gilbert *[11]* indicated that the acoustic protection given by a solid balcony decreased by approximately 2 dB, when the window behind was opened.

Mohsen *[4]* conducted an experimental investigation, using one-tenth scale models, to study this phenomenon. A cetate sheeting was used to simulate glass and the results suggested that, again, no significant difference in balcony performance was obtained where the window was glazed or unglazed (Figure 8.14). As a result of this examination of previous work, it was decided to measure balcony-insulation with an unglazed room aperture.

8.10 Receiver-Room Absorption and Reverberation Time

A knowledge of reverberation time and thus total absorption of a model room is important, in that a comparison is possible between the performance of a particular facade-element protecting rooms of different volume and absorptive treatment.

The measurement of the reverberation-time, at scale factors of 10:1, is difficult due to the increased decay-rates, which are a function of volume and air absorption, and which increase significantly at high frequencies. There are two mechanisms of air absorption: classical and molecular, the first of which arises from the heat conduction and viscosity of the air. The absorption is proportional to the square of frequency and classical attenuation coefficient Mc is given by:

$$M_c = (33 + 0.2t) \quad f^2 \times 10^{-12} \qquad (8.4)$$

where t is air temperature (^{o}C) and f is thefrequency Hz.

The second mechanism, of molecular absorption, results from the extraction of energy from the sound waves by rotational and vibrational relaxation of the oxygen and water molecules in the air. The relative humidity of the air is thus important in determining this component *[12]*. Evans *[13]* found from measurement that at a frequency f the molecular absorption coefficient,

$$M_m = \frac{Mf}{\frac{K}{2\pi f} + \frac{2\pi f}{K}} \tag{8.5}$$

Where K is the rate of exchange between vibrating and no vibrating molecules and M is an experimentally determined temperature-dependent coefficient.

The problem can be overcome by reducing the water content of the air, provided that the scale factor is not too large *[2]*.

The present experiment does not deal directly with room acoustics and so the measurement of the reverberation-time will be used to standardize the results of the facade insulation, for use on other situations. The accuracy required, in the measurement of the reverberation-time, is not great in this method of standardization. An error of 1 second, in the measurement of the reverberation-time, will give less than a 2 dB error in insulation measurement. This will have a minor effect when an A-weighting or rating index is calculated.

Variation in temperature and humidity given by ± $4^{o}C$ dry and ± $10^{o}C$ wet, could be considered constant over any measurement period. A temperature difference of $10^{o}C$ and relative-humidity of 10% will give a 0.007 second difference in the reverberation time at 40 KHz, and this difference decreases at lower frequencies.

<u>The Procedure</u>

A small tweeter of diameter 35mm.,(Model KSN Motorola 6005A), was placed inside the room and connected to a power amplifier. The decaying sound-field was sensed by means of a quarter inch condenser microphone (B & K Type 4165), also placed inside the room and the decay curve was recorded by means of a recorder, (UHER Type 4200), with tape speeds set at 190 mm/second. The replay speed was 47mm/second and the signal was passed to a spectrometer, (B & K Type 2112), and level-recorder. The ratio of recorded to replayed speed, and thus the ratio of measured-reverberation time to real was 4. It will be remembered that the reverberation-time of a full scale room is 10 times that of the model room.

The apparatus used in the reverberation-time measurement is shown in Figure 8.15 Measurements were taken place at five source and receiver positions - and the average was taken. Measurements were taken while the door of the model room was open.

Figure 8.16, indicates the reverberation-time of the model room as a function of frequency. The reverberation time, which varies between 3 seconds it 100 Hz and 0.75 seconds at 4KHz is high when compared with a typical dwelling in a temperate climate where a national value of 0.5 seconds is given. However, rooms in hot climates are sparsely furnished with little carpeting and have large areas of reflective surfaces. This is particularly true in summer, when soft furnishings absorb too much heat. Thus, reverberation-time of a typical room in hot climates is likely to be greater than that found in cold climates. These will have higher reverberant-noise levels. The need for acoustic protection from the facade is therefore, in general, greater in hot climates than in temperate areas

REFERENCES

1. MOHSEN, E.A. "A Scale Model Investigation of the Performance of Noise Barrier" Department of Building Science, Faculty of Architectural Studies, University of Sheffield. Interior Report BS.21, February 1975, pp.8.

2. BBC Research Department. "Acoustic scaling". An Evaluation of the Proving Experiment". Report No. 1972/3.

3. DENALY, M.E., RENNIE, A.J., and COLLINS, K.M., "Scale Model Technique for Investigating Traffic Noise Propagation" J.Sound.Vib. 1978 (56), pp. 325-340.

4. MOHSEN, E.A. "The Acoustic of Self Protecting Buildings An investigation of the screening effect of Building forms with respect to noise from road traffic". Ph.D. Thesis, Department of Building Science, Faculty of Architecture, University of Sheffield, 1976.

5. ETTOUNY, S.M., and FRICKE, F.R., "Courtyard Acoustics". App. Acoustics (6), 1973, 119-132.

6. JONES, H.W., STREDNLINKY, D.C., and VERMEALEN, P.J., "An experimental and theoretical study of the modelling of road traffic noise and its transmission in the urban environment". App. Acoustics, 13 (1980), 251-265.

7. DAVIES, J.C., and GIBBS, B.M. "The oblique incidence measurement of transmission loss by an impulse method". J.Sound.Vib. (1981), 74 (3), 381-393.

8. BRUEL and KJAER, "Condensor microphones and microphones amplifier". B & K Applications, December 1976. Denmark.

9. International Organisation of Standardization. "Measurement of sound insulation in buildings and of building elements". Part V "Field Measurement of Airborne Sound Insulation of Facade Elements and Facade", ISO/140/v - 1978 (E).

10. British Standards Institution. "Method for Rating Sound Insulation In Buildings and of Building Elements". BS.5821:1980

11. GILBERT, P.H. Une étude Sur la Protection des Habitations contre les bruits Extérieurs Pénétrant Par les façades". Cahiers du C.S.T.B. (Paris) No. 103 Cahier 901, 1969.

12. KNESER, H.O. "The Interpretation of the Anomalous Sound Absorption in the air and Oxygen in Terms of Molecular Collisions" J.A.S.Am. Volume 5 (1933), pp. 122-126.

13. EVANS, E.J. and BAZLEY, E.N. "The Absorption of Sound in Air at Audio Frequencies" Acoustica, Vol. 6 (1956) 238-245.

CHAPTER NINE

MEASUREMENT AND RESULTS

A description is given of the acoustical performance of several external facades commonly used in buildings in hot climates. The measurements are obtained by means of model techniques. The facades investigated can be categorised into two main types; a courtyard and a balcony, both with and without screening walls. The traffic noise attenuation of the above is examined with respect to the room open to the balcony or courtyard. The measured performance of each facade is compared with that of a solid reference wall of equal height, all other conditions being the same. Again, this comparative method is adopted since a solid barrier is a screen with well-understood acoustical characteristics (Section 5.1). The measured acoustic protection of each facade is presented as a function of incident angle (and thus floor height), depth of balcony and position of absorption material.

9.1 MEASUREMENT PROCCEDURE

A full description of the measurement procedure has been given in Section 8.4. To summarise, sound pressure level was measured at nine microphone positions within the model room over a frequency range of 2kHz to 40kHz in one-third octave steps. The difference in room average level before and after inserting the facade element gives a measure of the increase in acoustic protection. A single figure rating was then given using the sound insulation index rating (Rw) according to the method described in Section 9.1. The Rw was thus calculated for different floor heights, and for different facade types.

In addition, a short computer program allowed the calculation of the dBA weighted protection for each facade type and for each floor level. The word 'protection' in this context means the difference of the average sound levels in dBA or dBRw before and after inserting the facade element.

The relation between the dBA and dBRw rating for all facades investigated is shown in Figure 9.1. The correlation coefficient is calculated to be 0.9934 and the slope is 0.9493 with intersection at 0.5112 (a full correlation occures if the correlation coefficient is 1 and the slope is 1 with an intersection at 0.0). The A-weighted and Rw-rated protection can be assumed equal. This result has the important advantage in that the speed and ease of an A-weighted measurement may be simply related to the Rw rating which gives insulation or protection as a function of frequency.

9.2 MEASUREMENT AND DISCUSSION

9.2.1 COURTYARD WITH A THNADNER WALL

In Figures 9.2 and 9.3 is shown the measured increase in protection of a courtyard with a thnadner wall. The floor level range from ground to fifth floor and the results are plotted at one-third octave intervals and are expressed as a function of a full-scale frequency within the range 200Hz to 4kHz. Also shown are the results of measurements for the case of a courtyard with a thin solid wall.

With the exception of the case at ground floor level, the protection afforded by a thnadner wall is, in general, greater than that of a solid wall. Even at ground floor level an improved performance was obtained within the frequency range 630Hz to 1kHz. The protection, in general, is seen to increase with increased frequency at approximately 3 dB per octave and is, at most frequencies, 2 dB greater than that for a solid wall. The dips in measured protection have been shown in Section 8.7 to be the result of destructive interference resulting from ground reflection.

A comparison of the A-weighted protection of a thnadner screen Pth and a solid wall Ps is given in Figure 9.4. The correlation coefficient was calculated as 0.80 with a confidence limit of 80% within ±2 dBA. A relation between the two is given as:

$$Pth = 0.7Ps + 5 \text{ dBA} \tag{9.1}$$

units of dB Rw can be used with equal confidence. It has been shown in Section 3.3 that Ps can be predicted using the methods of Mohsen *(1)* and Kurze *(2)* and it is a simple step to predict the performance of a thnadner courtyard by the use of equation (9.1).

In Figure 9.5 is shown the effect of courtyard depth on acoustic performance. Between the first and fifth floor levels and for courtyard depths greater than 1m there is no significant variation in protection. All values lie within ±2 dBA. This result confirms that reported by Mohsen *(1)* for the case of courtyards with solid walls.

For a courtyard depth of 1m, the protection is approximately 8 dBA (or dB Rw) less than that of a courtyard of depth 2m at first and second floor levels. At ground floor level the protection increases by approximately 3 dBA for each one metre increment in courtyard depth. This is the result of effectively moving the receiver from the illuminated zone (zone 2 in Figure 7.16) toward a darker zone (zone 1). This is also true for courtyards above street level where there is an apparent increase in the height of the solid part of the thnadner. Above ground level an increase in courtyard depth results in an increase in exposed area of solid and, again, an effective removal of receiver to the darker shadow zone 1 equal to that of a solid barrier.

The best position of courtyards, from an acoustical and economical considerations, is above ground level and for depths greater than 1 metre. This result is confirmed by Figure 9.6 where protection is given as a function of level and it is seen to be almost constant above the road level.

9.2.2 COURTYARD WITH SPLITTER SCREEN

In Figures 9.7 and 9.8 are shown the measured protection of courtyards with a splitter screen for depths 1m to 4m. The frequency range of measurement and the floor levels considered are the same as those for the thnadner wall. In general, the measured protection is greater than that of a solid wall except at frequencies less than 315 Hz and where the receiver is exposed to the direct sound path.

The protection increases by approximately 4 dB per octave with a small dip which results from ground reflection.

In Figure 9.9 are shown the results of a comparison of A-weighted measured protections. The correlation coefficient is 0.95 with a confidence limit of ±1.5 dBA at the 90% level. The equivalent to the relationship given in equation 9.1 is:

$$Psp = 0.75\ Ps + 3.8\ \text{dBA (dB Rw)} \qquad (9.2)$$

where Psp is the splitter protection and can be predicted since Ps can be calculated.

In Figure 9.10 is shown the effect of courtyard depth on performance for all levels ranging from ground to fifth floor level. The effect of change of depth is more noticeable at levels below and including 3 m; above this level the measured protection can be assumed constant. This can also be seen in Figure 9.11 where the protection is given as a function of floor level with depth as the parameter. As with the case of the thnadner screen, the splitter protection for courtyard depths 1m and 2m is increased by 6 dBA when the courtyard is moved from the ground floor to the first floor.

9.2.3 THE CLOSED BALCONY

In Figure 9.12 is shown the protection of a closed balcony as a function of floor height and balcony depth. In these measurements the balcony ceiling was covered with an absorption layer of thickness 20mm in order to reduce ceiling reflection. At first floor level, and for all balcony depths, the measured protection, which is not great, can be considered frequency invariant. This is also true for balcony depths of 1m and up to the 4th floor level. This is due to the fact that in these cases the receiver is subjected to a strong direct and reflected component.

For a balcony depth of 4m and at heights greater than the second level the measured protection increases by approximately 2 dB per octave. This frequency dependency is the result of the receiver being completely screened by the balcony floor from the direct component, although a reflected component still exists.

A comparison is given in Figure 9.13 of the measured protection in the present work using scale models with that of Gilbert *(3)* on full scale structures where a loud speaker source was used. The results of Gilbert are greater by 3 dB to 6 dB than those of the author. This is expected, however, since it has been shown previously (Section 5.2) that the protection of a barrier with respect to a line source is 3 dB to 5 dB less than that with respect to a point source. The results of Gilbert agree with those of the author in that the protection is frequency invariant when the receiver is exposed to all or part of the direct path and increases by approximately 2 dB per octave when the receiver is screened by the balcony..

The relation between balcony protection and balcony depth is given in Figure 9.14 with floor level as parameter. To a first approximation the protection increases by 3 dBA per metre increase in balcony depth and there is also an increase of 2 dBA per floor level (Figure 9.15). This is undoubtedly the result of an increase in the path difference between the direct and diffracted compounds.

In Figure 9.16 is shown the effect on balcony performance of including ceiling absorbent for balcony depths of 2m and 3m for all floor levels above the ground. For a balcony depth of 3m, and at first and second floor levels, there is no appreciable increase in protection with increased absorption. The same is true for the first to third floor levels and for a depth of 2m. The effect of ceiling absorbent becomes appreciable above the second and third floor levels for balcony depths of 3m and 2m, respectively, where, without absorbent, the increase in exposed area of balcony ceiling will increase the component of sound reflected into the room.

The effect on the balcony performance of a thin solid wall of height 1m is shown in Figure 9.17. This wall is a typical architectural detail and is employed mainly for reasons of safety. In addition, a beam at ceiling height of 500mm depth further reduced the exposed area. The improvement in acoustical performance is appreciable and varies between 6 dBA at first floor level to 2 dBA at third floor level for a balcony depth of 4 metres. The improvement is approximately 5 dBA at all floor levels to a depth of 1 metre. The wall is clearly blocking the direct sound path which is most important at the lower levels or for narrow balconies. At high levels, or for deeper balconies, there is little increase in effective barrier height and little decrease in reflective ceiling area. The net effect is a slight change of the balcony performance which cannot be assumed to be more than 1 dBA.

9.2.4.1 BALCONY WITH THNADNER SCREEN

In Figures 9.18 and 9.19 is shown the acoustical performance, as a function of floor level and balcony depth, of a thnadner screen when forming part of a closed balcony. The ceiling area was covered with an absorbent layer of thickness 20mm to eliminate or reduce any reflected component. Similar to earlier procedures, the acoustic performance of the thnadner can be isolated by comparison of the increased protection of the balcony alone with that of the balcony and thnadner screen. The result of the protection of the thnadner screen is given along with that of a full height solid barrier without ceiling.

The protection of the thnadner wall is, for most cases, 2 dB to 6 dB lower than that of the solid wall. This reduced performance is due, in part, to the existence of a partially reflecting ceiling in the former case. Sound which has been redirected by the thnadner, suffers subsequent reflection into the receiving room. The protection increases by approximately 2 dB per octave and is most significant at lower floor levels and for narrow balconies.

The relation between the contribution of a thnadner in this configuration (i.e. the difference between the protection of balcony and thnadner and that of the balcony alone) and a full height solid wall is shown in Figure 9.20. The results are given in dBA and the correlation coefficient is calculated to be 0.9142 with the protection of the thnadner being less than that of a solid barrier. The relation between the protection of a thnadner (Pth) and that of a solid wall Ps is given as:

$$Pth = Ps - 3 \text{ dBA} \qquad (9.3)$$

The difference between equation (9.1) for the case of a courtyard with a thnadner without a partially reflecting ceiling and that with a partially reflecting ceiling (equation 9.3) is approximately 4 dBA.

In Figures 9.21 and 9.22 is shown the relation between increased protection of a thnadner screen with respect to floor depth and floor level. It is seen that a thnadner, in this configuration, is most effective for a floor depth less or equal to 2m and at heights below third floor level. Maximum protection is obtained at a floor depth of 2m and at first floor level. Above second floor level, the value decreases by approximately 2 dBA per 1 metre increase of floor depth. This result is of some importance since, in general, heavily modelled and perforated facades are usually positioned one or two metres from the external windows. In addition, traffic noise is greatest and the facade is required to give maximum reduction at first and second floor levels.

The effect of ceiling reflection is shown in Figures 9.23 and 9.24 as a function of floor level and balcony depth. The reduction in measured protection which results from introducing a partially absorbing ceiling, rather than no ceiling at all, is approximately 4 dBA. The result clearly leads one to the conclusion that thnadner facades should be used without ceilings if maximum efficiency is to be obtained.

The above conclusion suggests an alternative method in which a thnadner screen is constructed at a distance of 1m to 2m from the building. The screen would be supported from the building by thin beam connectors in a similar manner to that for conventional sunbreak devices. Acoustically, they would then provide a shadow zone similar to that of a solid wall and overcome the difficulties resulting from the redirection of sound energy towards the window areas. They would also provide solar shading on the windows and doors, and might prove more economically viable than the construction of conventional balconies.

9.2.4.2 BALCONY WITH SPLITTER SCREEN

The protection of splitters as part of a balcony is given in Figures 9.25 and 9.26 for balcony depths of 2m and 4m and at the second and fourth floor levels. Results are shown for a balcony without ceiling, a balcony with partially absorbent ceiling and a balcony without roof with a 3m height solid wall. The last case is used, again, for comparison.

The protection of the splitter screen is also isolated by subtracting the protection of the balcony only from that of the balcony and splitter. The performance of a splitter screen is, in general, greater than that of the solid wall. This is true even in the presence of a partially absorbing roof and thus reflected component. Values lie between 4 dB and 12 dB for a depth of 4m and seen to increase by approximately 4 dB per octave (from 4 dB to 24 dB) for a depth of 2m.

In Figure 9.27, a comparison is given of A-weighted splitter protection with that of a solid wall. The correlation coefficient is calculated to be 0.88 and the 80% confidence limit is approximately ±1.500. A relation is given in the following form:

$$Psp = 0.5Ps + 7.5 \qquad (9.4)$$

where Psp and Ps are as before.

In Figure 9.28, the net protection of the splitter screen is shown as a function of distance from the building with floor height as parameter. It is clear that the protection varies little with floor depth greater than 2m. Above the first floor level a maximum occurs at a floor depth of 1m which is again advantageous since any perforated screen employed as a sunbreak device is likely to be positioned at this distance from the room wall.

In Figure 9.29 is shown the net protection as a function of floor level with floor depth as parameter. For depths greater than 1m a maximum protection occurs at the first and second level. This result, again, has obvious important applications.

The change in performance resulting from ceiling reflection is seen in Figures 9.30 and 9.31. The presence of a partially absorbing ceiling in this case caused an increase in net protection of approximately 2 dBA at almost all floor levels and floor depths. Thus an additional advantage of using these devices is that the ceiling, or any horizontal surface, which is an important element in solar control, does not reduce the acoustic performance of a splitter screen.

Again, if correctly designed, a splitter screen wall without balconies, or any horizontal surfaces, 1m to 2m distant from a building, will act, acoustically, as a solid wall of the same height while at the same time providing solar protection and ventilation.

9.2.5 FACADE WITH CONVENTIONAL PERFORATIONS

The protection afforded by perforated screens which did not offer an amplitude or phase gradient was, as in the case of the thnadner and splitter screens, measured as part of a courtyard and as part of a balcony.

In Figures 9.32 and 9.33, values are shown as a function of frequency for a perforated screen forming part of a courtyard. Also shown are the results for a balcony without roof or front wall and those for a courtyard with a solid wall. Courtyard depth and height were varied as in previous measurements. With the exception of the courtyard at ground floor level, the measured protection above 1 kHz is less by 2 dB to 8 dB than that of a balcony without walls. At frequencies below 1 kHz the improvement as a result of installing this perforated screen is small, and is never more than 5 dB. At ground floor level the protection is seen to decrease with measured frequency above 1 kHz and lies within the range 4 dB to 12 dB.

The measured protection in dBA as a function of courtyard depth, with floor level as parameter, is shown in Figure 9.34. Above second floor level the values with respect to the no-screen case vary between 0 dBA to -4 dBA. Any protection at first and second floor level is due to the presence of the side walls of the courtyard and, in general, results show that the presence of a conventionaly perforated screen degrades any protection given by other facade elements.

The same result can also be seen for the case of a balcony with a similar perforated screen (Figures 9.35 and 9.36). The net protection (the protection of the balcony and the screen minus that of the balcony only) ranges between +1 dBA and -3 dBA (Figure 9.37) for floors higher than third and for all balcony depths. Again, at some levels the presence of the perforated wall reduces any protection of other facade elements. There is some improvement 6 dBA to 8 dBA only at first floor level.

These results show that, in general, regularly perforated screens will result in little or no improvement in acoustic protection and should not be used as part of a building facade for noise control only. The screen may, in some cases, amplify traffic noise due to the fact that the perforated units attenuate the direct component slightly and only at low frequencies, while the reflected components, through the perforation, may increase, particularly at higher floor levels.

The model screen was of 27% perforation, as compared with 35% for the thnadner and splitter screen walls. This clearly reinforces the theory of thnadner and splitter design in that their acoustic performance is the result of shape of perforation, rather than percentage perforation.

Some comparison is given in Figure 9.37 of field measurement result, (Section 4.5) with that using the scale models. The comparison can only be given for the first floor level where sound was incident at an angle of approximately 30°. However, there is fair agreement and where the mean of three measurements of the full-scale structure was 6 dBA, the mean of two model measurements was 6.5 dBA.

9.2.6 INCLINED SPLITTER SCREEN

It was suggested in Section 7.4 that if inclined splitter elements were used then the devices might act as a combination of phase change device and amplitude gradient device. This configuration might also block the direct sound and force part of the sound wave incident to suffer multiple reflection, and thus absorption on passing through the screen. To investigate this effect, the splitters were turned at 45° to the normal, while the distance between the splitter elements was kept constant at 20 mm. The results shown in Figures 9.38 and 9.39 for a courtyard compared with those for the ordinary splitter wall. The protection is less than ordinary splitters at most frequencies and the difference being greatest at higher frequencies. This is unexpected since it would be thought that the increased absorption of the inclined splitter surface would increase the shadow zone. The discrepancy is 4 dB at 1.25 kHz and 12 dB at 40 kHz. This is also despite the fact that the inclined splitters are now blocking the direct component more effectively.

The above result has two implications: first, it supports the theory of the splitter screen in that its mechanism is that of differential change of phase with height of the wave-front (amplitude remaining constant), and not by attenuating the sound wave through absorption and opacity. Secondly, the inclined splitter screen cannot be considered a combination of splitter and thnadner device. However, a proper combination of amplitude and phase change gradient may be achieved by using a thnadner with differential thickness of absorption.

SUMMARY

The protection afforded by different facades and facade elements can be summarized in Tables 9.1 and 9.2. In Table 9.1 is shown the protection afforded by a courtyard with different screens as functions of floor level and courtyard depth. In table 9.2 is shown the same as in Table 9.1 but for the case of a closed balcony. It is clear that there is no significant difference between the protection of a solid, thnadner or splitter wall as part of a courtyard or a balcony.

Floor Level	Court-yard Depth	SOLID		THNADNER		SPLITTER		PERFORATED UNITS		COURTYARD 2 SIDE WALLS	
		c	n	c	n	c	n	c	n	c	
Ground Floor	1	16	16	8	8	10	10	2	2	0	
	2	21	21	13	13	13	13	5	5	0	
	3	21	21	16	16	18	18	6	6	0	
	4	22	22	19	19	19	19	8	8	0	
First	1	20	20	13	15	17	17	4	4	0	
	2	23	19	22	18	22	18	7	3	4	
	3	22	15	22	15	23	16	16	7	7	
	4	24	13	26	15	26	15	15	4	11	
Second	1	19	18	17	16	17	16	4	3	1	
	2	22	16	25	19	23	17	10	4	6	
	3	24	13	24	13	22	11	14	3	11	
	4	24	8	26	10	24	8	19	3	16	
Third	1	22	17	21	16	19	14	8	3	5	
	2	24	11	26	13	22	9	13	0	13	
	3	23	4	24	5	23	4	15	-4	19	
	4	24	5	26	7	24	5	19	0	19	
Fourth	1	22	17	22	17	23	18	8	3	5	
	2	22	8	24	10	23	11	12	-2	14	
	3	23	5	24	6	24	6	15	-3	18	
	4	24	4	25	5	22	2	18	-2	20	
Fifth	1	22	13	23	14	22	13	12	1	9	
	2	24	9	25	10	25	10	11	-2	15	
	3	24	5	25	6	26	7	17	-2	19	
	4	24	4	25	5	27	7	18	-2	20	

c: Combination with the courtyard
n: Net protection of the wall

Table 9.1 Protection afforded by a courtyard with a solid, a thnadner, a splitter and a conventional perforated wall.

Floor Level	Balcony Depth m	BALCONY		THNADNER & BALCONY		SPLITTER & BALCONY		CON. PERF. & BALCONY	
		Roof	No Roof	Roof	No Roof	Roof	No Roof	Roof	No Roof
First	1	2	0	11	15	16	17	4	4
	2	3	4	20	22	20	22	9	3
	3	6	7	20	22	21	23	14	7
	4	10	11	21	26	24	26	15	4
Second	1	1	1	10	17	17	17	6	3
	2	6	6	20	25	23	23	7	4
	3	11	11	19	24	26	22	6	3
	4	15	16	22	26	25	24	5	3
Third	1	5	5	19	21	20	19	6	3
	2	12	13	20	25	25	22	2	0
	3	12	19	20	24	22	23	-2	-4
	4	16	19	23	26	23	24	0	0
Fourth	1	5	3	19	22	17	23	6	3
	2	12	14	20	24	21	25	-1	-2
	3	15	18	21	24	24	24	-4	-3
	4	19	20	26	25	24	22	-1	-2
Fifth	1	8	9	18	23	22	22	2	1
	2	11	15	19	25	21	25	-1	-2
	3	16	19	21	25	26	26	-2	-2
	4	19	20	19	25	26	27	-3	-2

Table 9.2 Protection of a balcony, balcony and splitter screen, with thnadner screen and with concentional perforated screen

REFERENCES

1. OLDHAM, D. J. and MOHSEN, E. A. "The Acoustical Performance of Self Protecting Building" J. Sound Vib. (1979) 65 (4) pp. 557-581.

2. KURZE, V. J. "Noise Reduction by Barriers" J.A.S.A. (1974) 55(3), 504-517)

3. GILBERT, P. H. "Une etude sur la Protection des Habitations Contre les bruits Exterieurs Pentrant par les Facades" Cahiers due C.S.T.B. (Paris) No. 103 Cahier 901, 1969.

CHAPTER TEN

PERFORMANCE OF THNADNER AND SPLITTER SCREENS WITH RESPECT TO OTHER ENVIRONMENTAL FACTORS

Having described splitter and thnadner screens as noise barriers, they will now be examined with respect to other environmental factors. The discussion will not be of all aspects of environmental control, but will be restricted to their use as external shading devices, daylighting apertures and ventilation control units. Other factors, such as fire resistance and structural stability, will not be examined. The analysis involved the use of standard techniques, described in the literature, and allowed a relative comparison of the performance of an unscreened balcony and one with thnadner or splitter screen.

10.1 THE SCREENS AS SOLAR CONTROL DEVICES

The performance of the screens as solar control devices was examined using a method described in the literature

(1,2,3) each stage of which is itemised below;

1. It was decided to fix a geographical point for the study. The point chosen was that of Amman in Jordan, which exists at Latitude 32° North (Longitude is unimportant).

2. In Figure 10.1 is shown a simplified chart indicating the period which can be assumed to be of excessive solar gain, with respect to time of day and year, in the City of Amman. External air temperature within this zone (Fig. 10.1) in general, exceeds 24°C and solar radiation incident on a vertical surface exceeds 200 w/m^2.

3. The shading angles, illustrated in Fig. 10.2 were calculated for West, East, Southwest and South orientations (Fig. 10.3). The vertical shading angle (ε) varies between 22° and 40° for all cases. The equivalent horizontal shadow angle lies between -10° and -50° for an East-facing wall and between -50° to +70° for a South-facing wall, assuming that the vertical angle is fixed at 70°. If a horizontal solar device only is to be used, then it should be of

a width such that adequate shading is provided for the minimum vertical angle (Fig. 10.3). A combination of horizontal and vertical elements, which are perpendicular to the shaded wall, should be such that shading occurs at the maximum vertical angle within the range of horizontal angles.

4. In using the above information, two building elevations were considered, one orientated towards the South and a second orientated towards the Southwest or Southeast.

In Fig. 10.4 is shown three facade elements, which were orientated towards the Southeast. They consist of an unscreened balcony of depth 1 m or 2m, a balcony with a thnadner screen and one with a splitter screen. For the case of the balcony only, the vertical shadow areas are 25% and 42% of total wall area for balcony depths 1 m and 2 m respectively. The thnadner screen shaded area increases to 87% and 90% respectively. For the case of a splitter screen, a perfect shadow zone was created, even for a balcony depth of 1 m and where the spacing between splitters is 600 mm (the maximum distance allowed when employed as an acoustic screen).

In Figure 10.5 is shown the shading performance of thnadner and splitter screens of part of a balcony oriented towards the South. The increases in the shaded areas provided by the thnadner screen were 51% and 29%, compared with a balcony only of depths 1 m and 2 m. Again the splitter screen provided a perfect shadow for balcony depths of 1 m and 600 mm spacing between the splitters.

Thnadner and splitter screens will not only reduce or eliminate the direct path between the sun and the interior wall, but also reduce indirect and reflected components. In Figure 9.6 is shown the percentage solar gain of the protected wall, calculated by methods described by Olgyay et al *(1)*. The use of a thnadner screen results in a reduction in solar gain from 77% of that available (for a 1 m depth) to 37.5% and from 52% (for a 2 m depth) to 22.5%. The reduction is of the order of 67% more when a splitter screen is used as part of a balcony.

10.2 THE SCREENS AS DAYLIGHTING CONTROL

The method used to evaluate the screen performance with respect to daylighting is valid only in overcast sky conditions where the whole of the sky hemisphere acts as a light source *(4, 5, 6)*. It is possible, however, to justify its use in a hot climate, such as at Amman, since there the sky during Winter (November to April) is, in general, overcast. In addition, the evaluation is comparative and external conditions can, and must, be fixed.

There are three main components which determine the daylight factor, defined as the percentage ratio of the internal illumination to the illumination simultaneously available outdoors *(6)*. Daylight factor is the sum of sky component SC, the externally reflected Component ExC and the internally reflected component EnC. The internally reflected component is a function of the room size and surface treatment and will be assumed constant at 0.5% for this discussion.

The sky component and externally reflected component were calculated using the 'pepper-pot' method of Hopkinson *(11)* since it has the advantage of allowing speedy calculation when the aperture is irregularly obstructed. The sky and reflected components were calculated for a room of dimensions 4 m x 4 m and 3 m height with one external wall with aperture of dimension 2 m x 2 m (the same room modelled for the acoustic investigation). The cases were considered of an opening without any obstruction; with a closed balcony of depth 2 m, with a thnadner screen as part of the balcony, and with splitter screen as a part of the balcony. The daylight factor was calculated at the centre of the room and 1 m from a side wall on a horizontal plane at height 1 m. Both points were at a distance of 1 m from the rear wall. The results are given in Table 10.1 and in order to relate the above information to the internal illumination, two other factors must be considered: the minimum task lighting levels required for different activities and the external natural illumination, in lux, which is available. The levels recommended by the CIE *(4)* are 150 lux, 300 lux and 700 lux for ordinary, medium and severe tasks, respectively. The external illumination for 90% of normal working hours throughout the year is approximately 10,000 lux at Latitude 32° North *(4)*.

As can be seen from Table 10.1, the thnadner screen gives higher internal illumination compared with that of the splitter screen. It is also seen that under the circumstances considered, thnadner screens allow sufficient natural illumination at the working plane for ordinary tasks (rough bench, machine work and intermittent work). For the case of a splitter screen, additional artificial lighting is necessary. For the case of medium and severe tasks, additional artificial lighting should be provided even for the case of the aperture without any obstruction. In general, for 'tolerable minimum conditions' (CIE recommendation) daylight illumination is not sufficient for the case of severe tasks in all weather conditions and for any aperture size or orientation.

10.3 VENTILATION FUNCTION OF SPLITTER AND THNADNER SCREENS

Ventilation in buildings is important for the supply of fresh air, the increase of heat loss from, and thus thermal comfort of, the occupants, and cooling the structure. In

FACADE TYPE	Daylight Comps. Point (1)			Day Light Factor (1)	Daylight Comps. Point (2)			Day Light Factor (2)	Illumination Lux Average of Points (1) & (2)
	SC	ExC	ExC		SC	ExC	ExC		
Door without obstruction	1.8	-		2.3	1.5	-		2	210
Door and a balcony	1.2	0.06	0.5%	1.76	1.1	0.04	0.5%	1.64	170
Door obstructed by a thnadner screen as part of a balcony	1	0.02	Assumed	1.52	0.9	0.02	Assumed	1.42	147
Door obstructed by a splitter screen as part of a balcony	0.5	0.07		1.07	0.8	0.03		1.33	121

Table 10.1 Comparison of daylighting provided by the facade elements considered

general, an increase in the air velocity in and around buildings, results in an increase in convective and evaporative heat losses *(8)*.

There are several factors which contribute to air movement to and through a perforated enclosure which can be categorised into external and internal factors *(7,8,9)*. The former involves climatological effects such as wind velocity and direction, the dimensions of the building and the position with respect to the site plan. The latter is affected by window size, cross-ventilation, location of openings and the existence of perforated screens. The present discussion, will be confined to the effect of external aperture size and sunshade geometry.

10.3.1 SIZE OF OPENING

In model work carried out by Givoni *(10)* to investigate the effect of opening size on ventilation, it was concluded that the ventilation depends to a great extent on the degree of room cross-ventilation and not on the size of opening. In Table 10.2 is shown the effect of window size and orientation with respect to wind, in a room without cross-ventilation and average air velocity. It can be seen that the only significant effect is obtained when wind direction is oblique to the window. When wind direction is perpendicular an increase of window size from one third to two-thirds of the wall area results in no significant change in air velocity inside the model.

From the case of a cross-ventilated room, the air velocity increased significantly. This effect can be seen in Table 10.3 where air velocity increased by a factor of 3. It is also seen that for the case of a cross-ventilated room and perpendicular wind direction an increase in window size results in a decrease of air velocity. The increase in window size has, in general, no significant effect for the case of oblique wind direction. The relation between average indoor velocity $\bar{V}_i$, ratio of window area to wall area X, and outdoor wind speed V_o is given by:

$$\bar{V}_i = 0.45\ (1 - e^{-3.84X})\ V_o \qquad (10.1)$$

The above formula is only applicable in restricted circumstances.

In relating the above information to splitter and thnadner screens, which are one third perforation, it is clear, fortunately, that this size of perforation is an optimum for ventilation for both cases, that for cross and non cross-ventilation.

10.3.2 EFFECT OF EXTERNAL FEATURES

It was concluded from a wind tunnel study by Givoni *(10)* that the use of screens as part of a balcony resulted in

Direction of Wind with respect to Window	Width of Window: Width of External Wall 1/3	2/3	3/3
Perpendicular	13	13	16
Oblique in front	12	15	23
Oblique from rear	14	17	17

Table 10.2 Effect of window size in room without cross ventilation on average air velocity (Percentage of external wind velocity)

Wind Direction	Outlet Size	Inlet Size		
		1/3	2/3	3/3
Perpendicular	1/3	36	34	32
	2/3	39	37	36
	3/3	44	35	47
Oblique	1/3	42	43	42
	2/3	40	57	62
	3/3	44	59	65

Table 10.3 As Table 2 for the case of cross ventilated room

improved ventilation conditions compared with the case of screens positioned at the opening. The balcony acts as a mediator between the external air and the aperture. The air penetrates the screen through a large area, without speed reduction, and then contracts towards the small opening. Under the above circumstances, splitter or thnadner screen improve the ventilation conditions inside the room and there will be no noticeable difference between the performance of the two screens.

REFERENCES

1. OLGYAY, V. and OLGYAY, A. "Solar Control and Shading Devices"Princeton University Press, Princeton, N.J. 1957.

2. HARKNESS, E. L. and MEHTA, M. L. "Solar Radiation Control in building" App. Science Publications Ltd., London, 1978.

3. KOENIGSBERGER, O. H., INGERSOLL, T. G., MAYHEW, A. and SZOKOLAY, S. V. "Manual of Tropical Housing and Building" Part One, Climatic Design. Longman Group Ltd., London, 1974.

4. INTERNATIONAL COMMISSION ON ILLUMINATION (CIE) "Daylight, international recommendations for the calculation of natural daylight". CIE publications, No. 16 (E.3.2) 1970.

5. LYNES, J. "Principles of Natural Lighting" Elsevier, Co. Ltd., London 1969.

6. HOPKINSON, R. G., PETHERBRIDGE, P. and LONGMORE, J. "Daylighting" Heinemann, London, 1966.

7. MARSH, P. "Thermal Insulation and Condensation" The Construction Press, London 1979.

8. GIVONI, B. "Man, Climate and Architecture" App. Science Pub. Ltd., London 1976.

9. THRELKELD, J. L. "Thermal Environmental Engineering" Prentice-Hall Inc., Englewood Cliffs, N.J., 1962.

10. GIVONI, B. "Basic Study of Ventilation Problems in hot countries" Bldg. Res. Stn., Haifa, 1962.

11. HOPKINSON, R. G. Architectural Physics: Lighting. London HMSO, 1965.

12. WISE, A. F. E., SEXTON, D. E. and LILLYWHITE, M. S. T. "Urban planning research: studies of air flow around Buildings" A. J. 141, May, 1965. pp. 1185-1189.

13. SZOKOLAY, S. V. "Design of Building for Equatorial Highland Climate" M.Sc. Thesis, Arch. Dept. Univ. of Liverpool, April, 1968.

14. OLGYAY, V. "Design with climate" Princeton Univ. Press, Princeton, N.J, 1963.

CHAPTER ELEVEN

CONCLUSION, DISCUSSION AND SUGGESTIONS FOR FUTURE WORK

The acoustic performance of two types of building facade, in common use in hot climates, namely a courtyard and a closed balcony, was measured. Three types of screening element were introduced individually to the above facades and investigated, namely a thnadner screen, a splitter screen and a conventionally perforated wall. The investigation involved field meaurement, computer simulation and one-tenth scale model techniques. The following observations are made.

11.1

Field measurements of a high-rise building in Liverpool, containing conventionally perforated elements were carried out according to ISO/140, Pt. V. The building chosen was similar to those in common use in hot climates.

It was found that a facade with a regular perforated screen gives a measured protection of approximately 7 dBA at lower floor levels (i.e. for incident angles less than 30°) but the protection decreases with increased height.

In most field measurements it is difficult, if not impossible, to vary the measurement conditions such that the important parameters can be isolated and assessed. Therefore, it was decided to continue the research programme in a more controlled environment.

11.2

A scale model system was designed with a scale factor of 10:1. This factor was an optimum set by the limitations of the dimensions of the anechoic chamber, air absorption and the frequency response of the acoustic sources and receivers.

11.3

A line source which consisted of a linear array of equally-spaced point sources with random phase characteristics was designed and constructed. This proved to be a good approximation to a heavily used road in that it generated a cylindrical sound wave, the axis of which was the road axis and was small such that it did not perturb the sound field within and around the model. The output was constant with respect to time and fairly flat within the frequency range of measurement and, although the frequency spectrum was not similar to that of traffic noise. It gave sufficient signal to noise at all frequencies and microphone positions. The source was long and could be assumed infinite.

11.4

A computer simulation was produced of the acoustical protection of free-standing perforated barriers of unusual geometry which give either an amplitude gradient (thnadner) or phase gradient (splitter). The results indicated that, in certain circumstances, these devices gave an acoustic protection similar to, or greater than, that of a solid thin barrier of the same height.

11.5

The results of the scale measurement for the case of free-standing, solid thin barriers compared well with those of previous work in which similar techniques were used and with theoretical prediction.

11.6

For the case of free-standing thnadner and splitter barriers, the scale measurements compared well with computer simulation. The results showed that these devices gave equal, or better protection, than that of a solid thin barrier for a wide range of frequencies if the direct sound path is blocked. Maximum protection is achieved at distances less than five metres from the barrier which, fortunately, corresponds to typical dimensions of balcony or courtyard spaces.

The protection decreases with increased height above the sight line and can give negative protection (i.e. at sound levels greater than when no barrier is present). Thnadner and splitter barriers re-direct, rather than absorb, sound energy and must, therefore, be positioned carefully when employed as noise reduction devices.

11.7

The results of the scale model measurements on thnadner and splitter walls, as part of a courtyard house, show that the protection obtained is similar to that of a courtyard with a solid wall of the same height. The protection is greater above the first floor level and for courtyard depths greater than two metres, and can be assumed constant at 20 dBA when the direct path is screened, irrespective of courtyard depth or height.

It is now possible to predict, using both simple empirical formulae and the diffraction theory for thin solid barriers, the protection of courtyards incorporating a thnadner or splitter wall (Eqs. 9.1 and 9.2).

11.8

The model measurements show also that a balcony, open to the street but enclosed on all other sides, does not afford good acoustic protection when the balcony depth is less than two metres and/or the floor level is such that the sound incident angle is less than 30°. The value lies within 2 dB and 8 dB and is frequency invariant. The protection increases with increased incident angle and balcony depth and becomes frequency dependant since the direct path between source and receiver is now screened. The performance is, however, degraded by reflection of sound from the ceiling. This effect is more noticeable at incident angles greater than 40° and for balcony depths greater than three metres. The use of a solid partial height barrier of 1m as part of the balcony considerably improves acoustic performance for balcony depths less than three metres and for sound incident angles less than 40°.

This protection is constant at approximately 16 dBA at sound incident angles greater than 40°, irrespective of balcony depth. In general, the protection measured by the author, using scale models, compared well with full scale measurements of other workers.

11.9

The measured protection of a closed balcony is considerably improved when a thnadner screen or splitter screen is installed. The performance of a thnadner screen in this configuration is within 3 dBA of that of a solid wall while a splitter screen can be assumed equal in effect to that of a solid wall.

The maximum protection (16 dBA) of the above screens is obtained at first and second floor and at balcony depths of two metres distance or less. The acoustic protection of the above configuration can be predicted by use of simple empirical formulae and diffraction theory (Eqs. 9.3 and 9.4).

11.10

The acoustic protection of a regularly perforated screen, both as part of a courtyard or balcony, was also measured by means of scale models, for comparison. The measured values never exceeded 3 dBA for balcony depths greater than 1m and in the case where the sound incident angle was greater than 40°.

A maximum of 8 dBA reduction was obtained where the screen is combined with a courtyard of depth four metres at first floor level.

The opportunity to compare tenth-scale and full scale measurement was limited but the measured protection on scale models compared well with that of field measurements where the noise source is traffic.

The measured protection of thnadner and splitter screens of 35% perforation is greater by approximately 16 dBA than that of a conventional, less perforated screen (27%). This is clear evidence of the importance of perforation geometry, rather than percentage perforation.

11.11

The measured protection of a 'turned' splitter screen (45° to the normal) used as a part of a courtyard or a balcony, was unexpectedly worse than that of a perpendicular splitter screen. Values were 2 dB less at 2 KHz and 12 dB less at 40 KHz. A turned screen cannot, therefore, be considered as an optimum combination of amplitude and phase gradient.

11.12

A courtyard, which is often throught to provide the most comfortable internal environment in hot climates, also provides the darkest sound shadow of all types of building facade investigated.

11.13

The splitter and thnadner screens were also assessed with respect to solar radiation, daylight penetration and natural ventilation, by use of standard techniques. The results show that the screens, if correctly designed, can provide a perfect solar shadow zone and thus reduce solar gain during the overheated period by 40% to 70%. They also allow adequate daylighting for ordinary tasks (150 lux) and sufficient air ventilation.

11.14

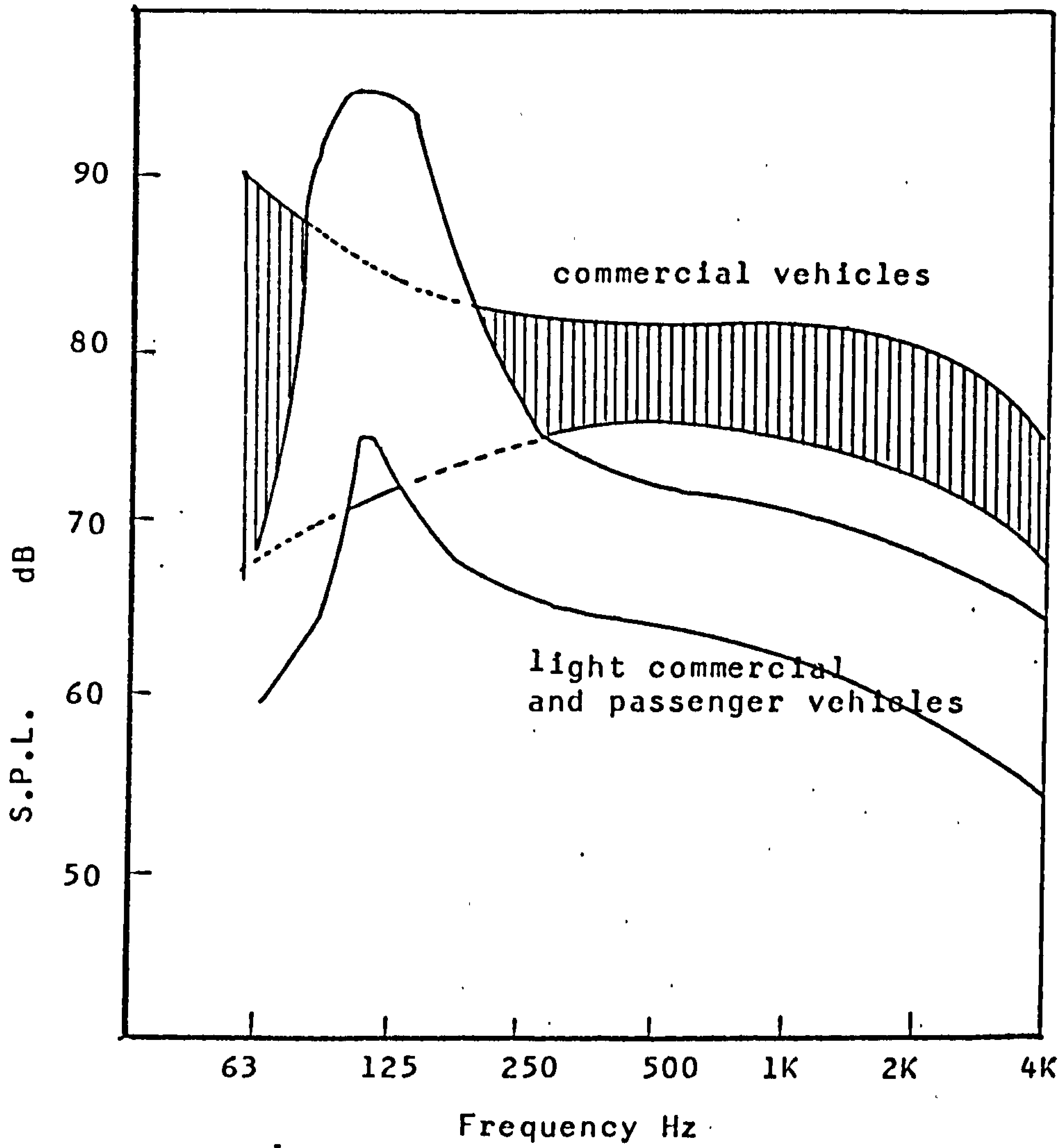
The thnadner screen can be constructed easily from any building materials, precast or in-situ, but the splitter elements require a covering of absorbent material, which must resist weathering. The splitter screen also occupies a large area compared with a thnadner screen, but it has the advantage of being less affected by sound reflection at the ceiling.

Suggestions For Future Work

1. The application of amplitude and phase gradient attenuation can now be extended to include other perforation geometries such as that of a perforated screen in which the holes gradually increase in area with the screen height. It is suggested that the boundaries of the holes might be knife edges, so as to avoid any redirection of sound towards the shadow zone.

2. Other commonly occurring building facades might be investigated using the methods described, such as those where the elevation is stepped backwards with respect to the road. In this case, thick barrier theory should also be employed in a description of acoustical performance.

3. Much field work is required on traffic noise in urban areas in hot climates. This should include field measurements and social survey of the subjective reaction of occupants. This would, it is hoped, lead to design and control criteria more suitable to that environment.



Typical spectrum zones for road traffic after (25) Chapter 2.

Fig. 2.1

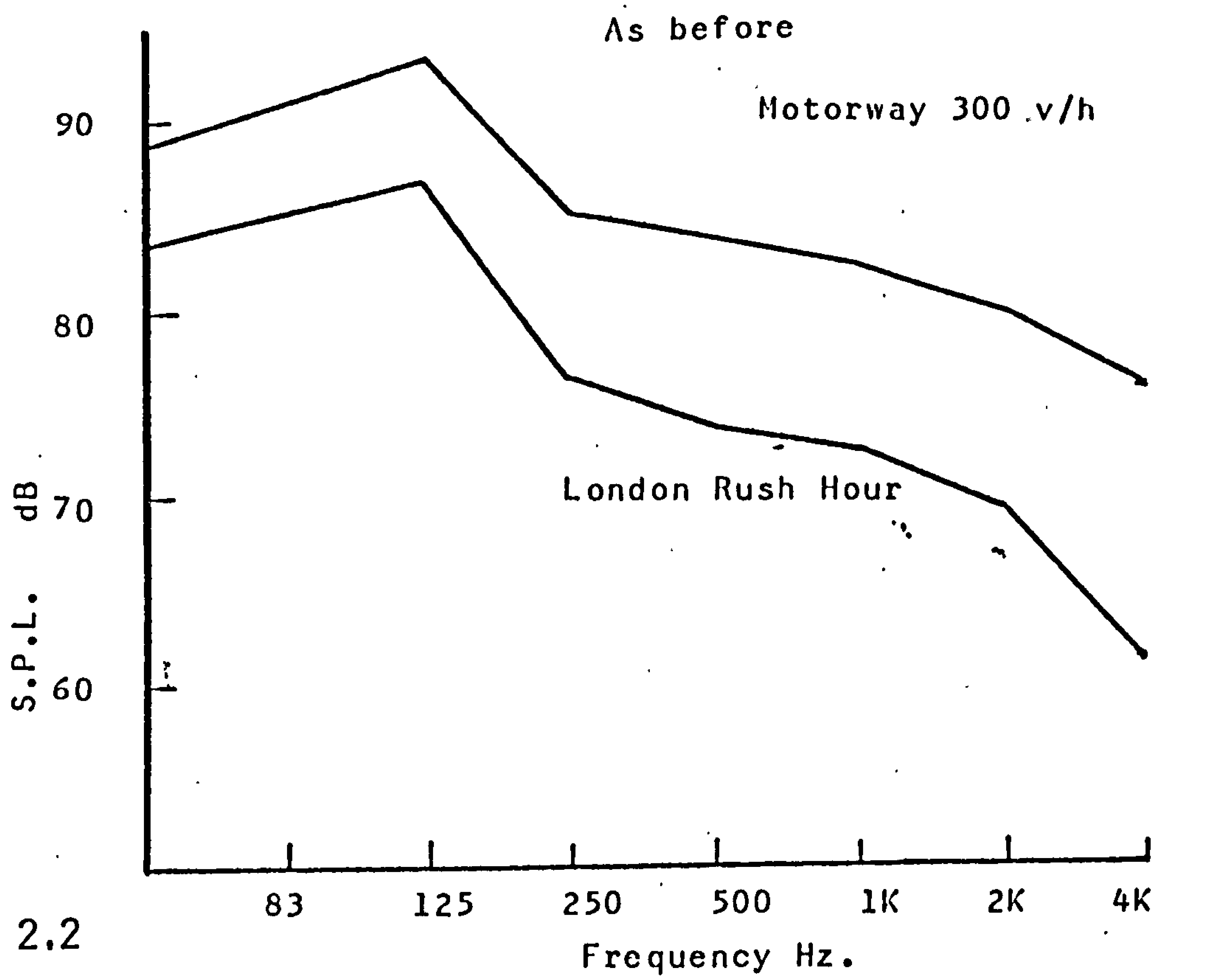
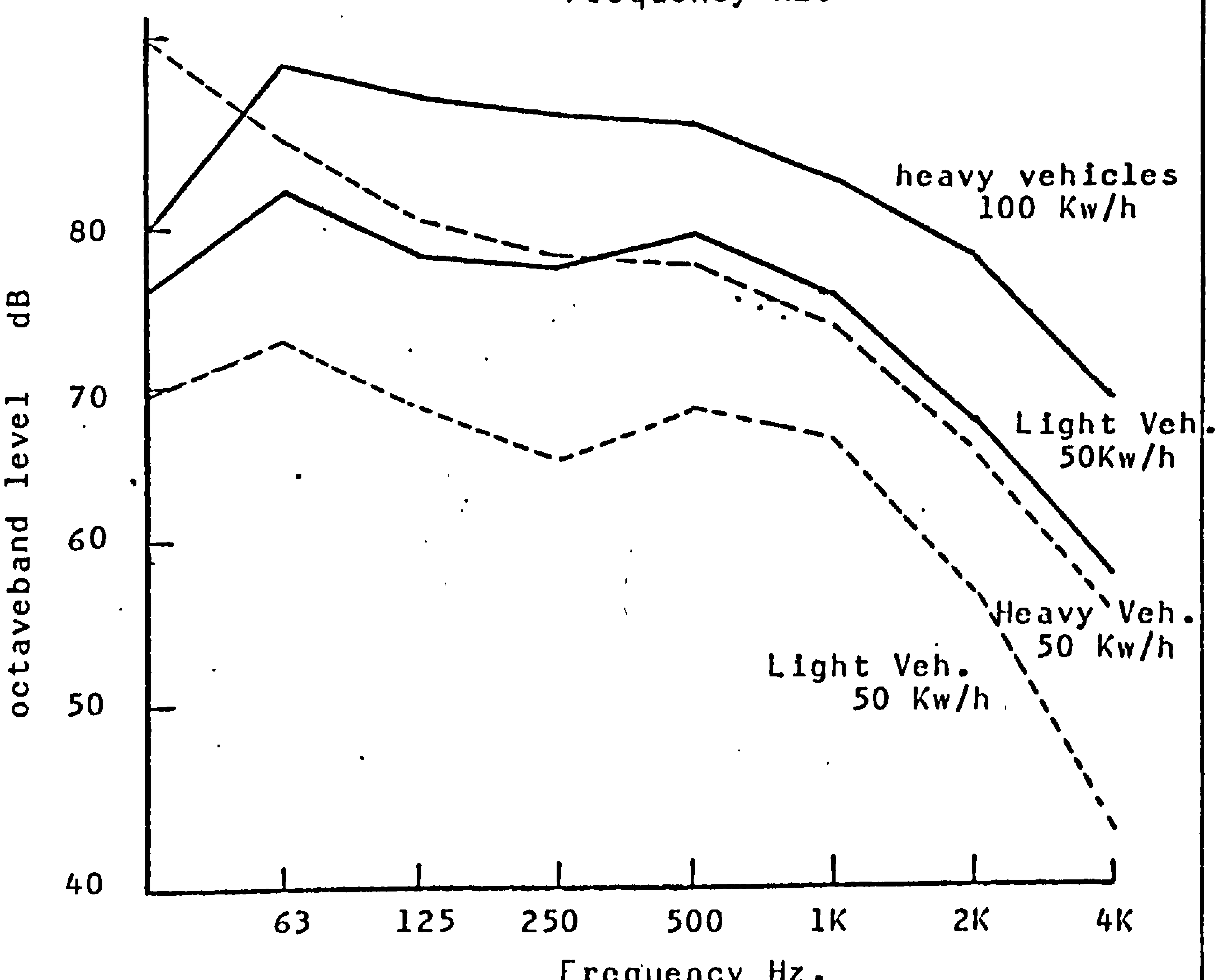
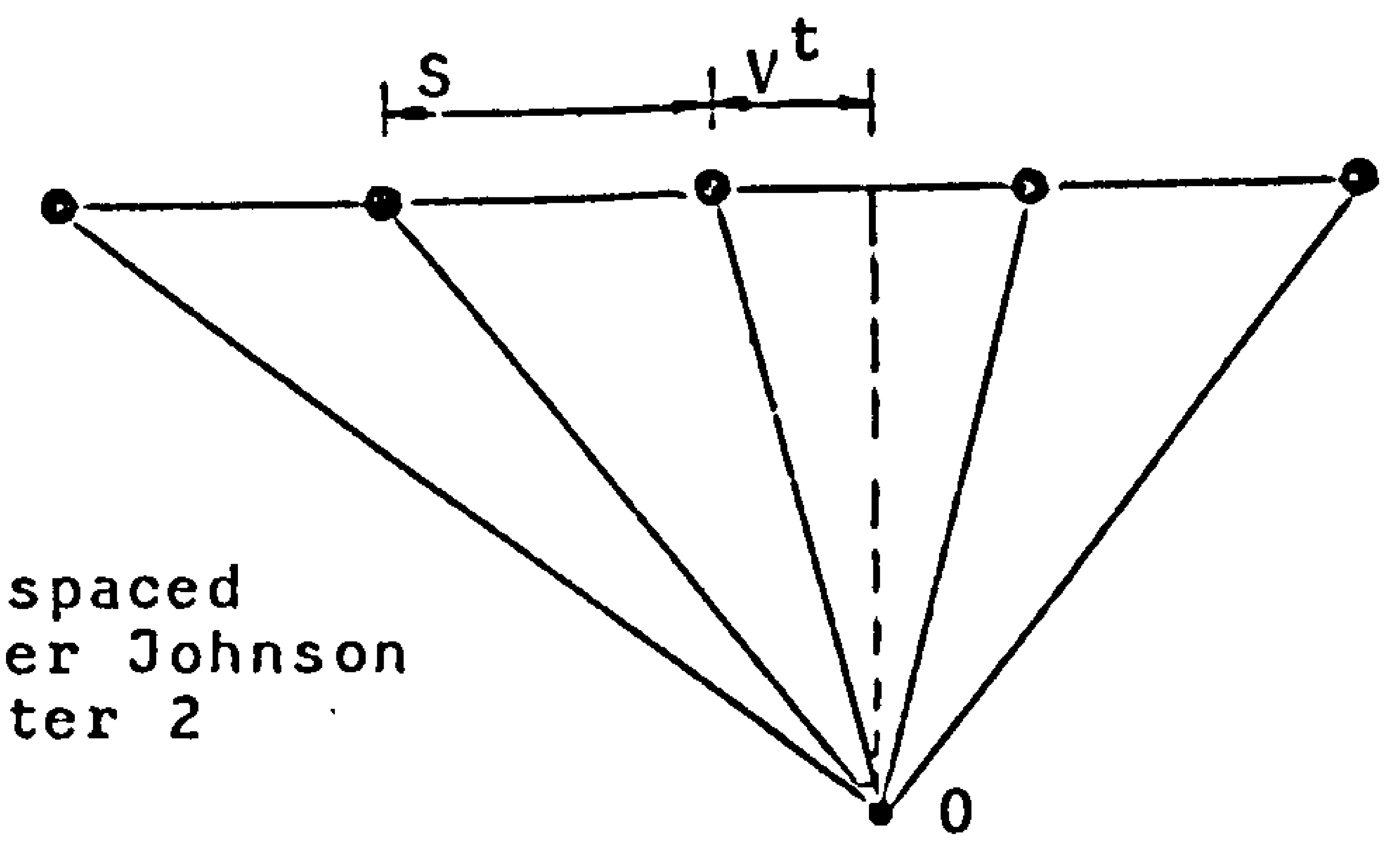


Fig. 2.2



The effect of speed on the spectrum after Lewis (25) Chapter 2.

Fig. 2.3



Array of equally spaced point sources after Johnson et al., (12) Chapter 2

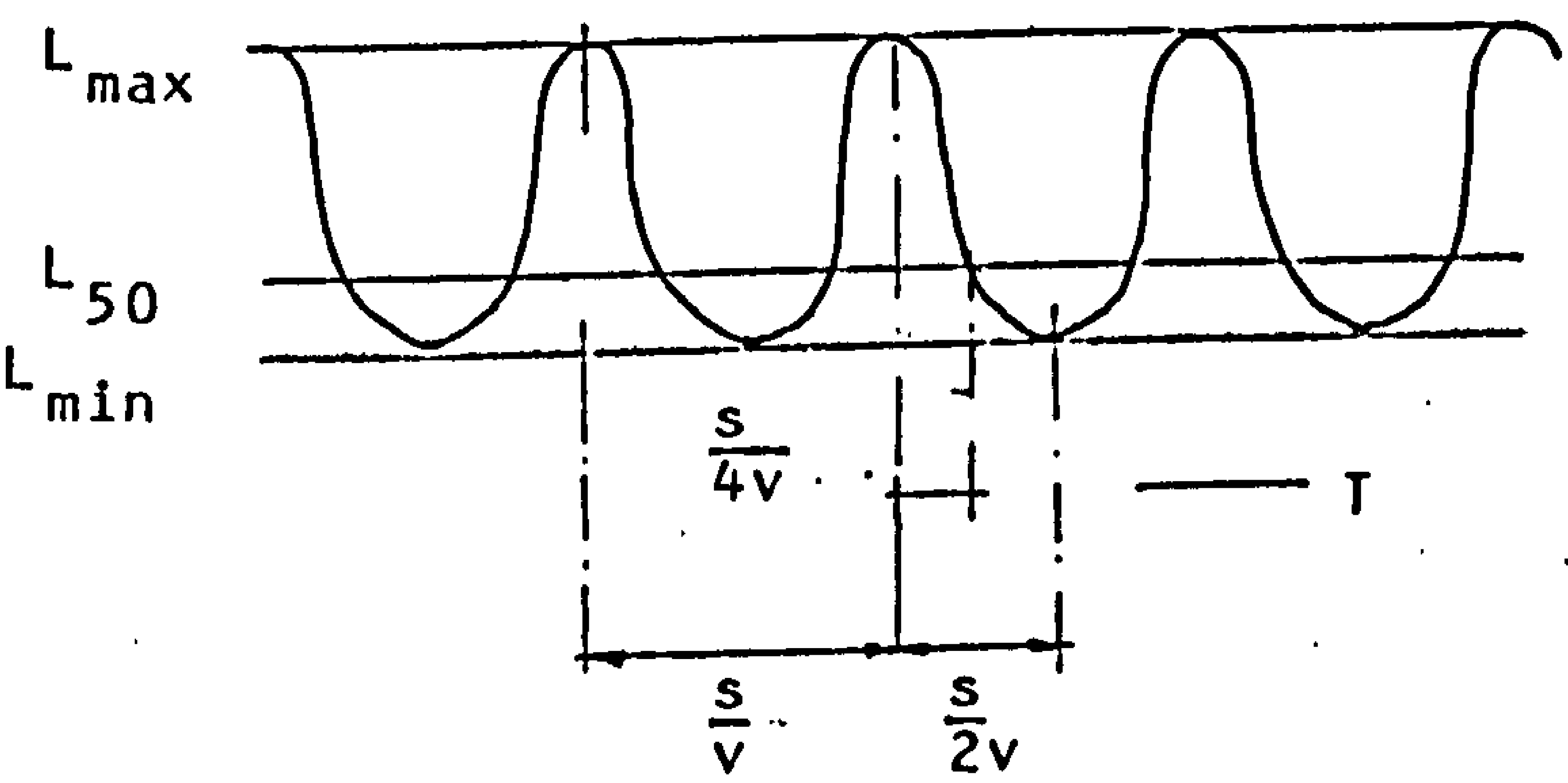
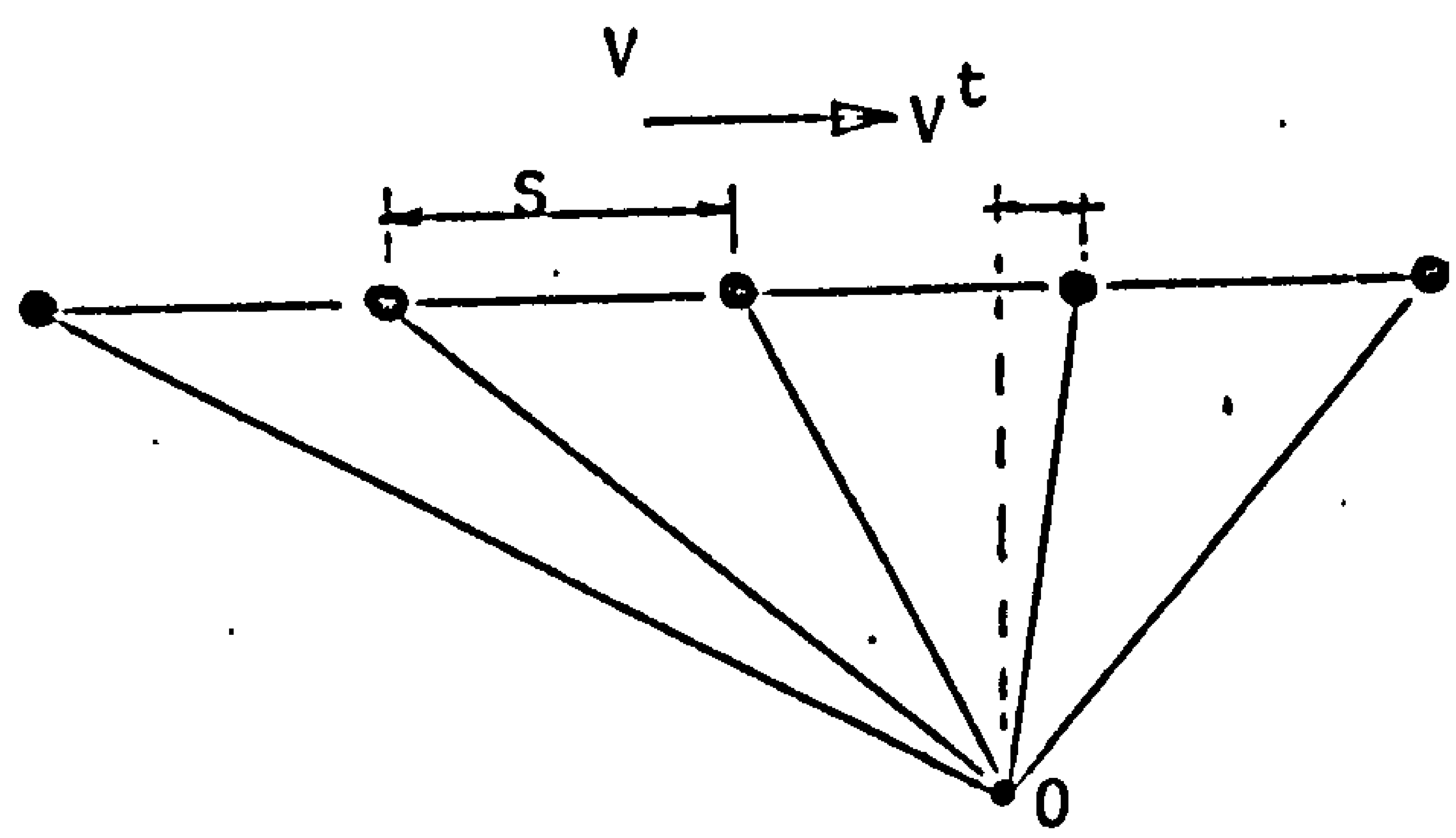


Fig. 2.4



Array of equally spaced point source after BLitZ (34) Chapter 3.

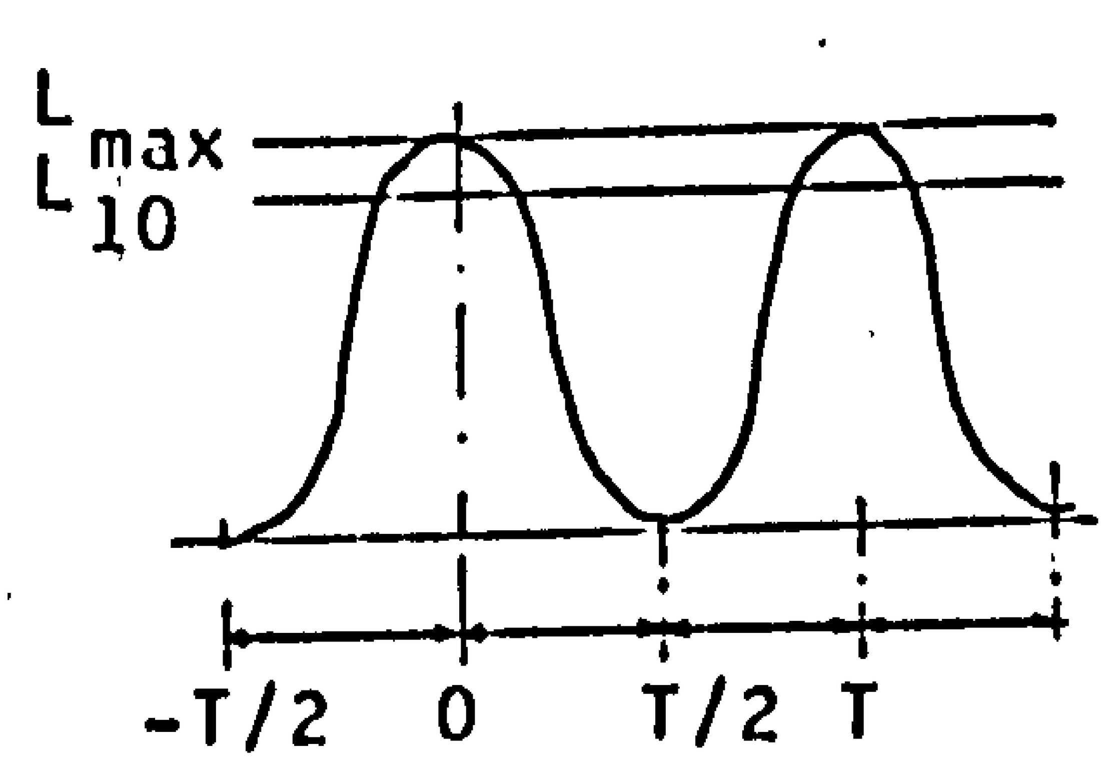
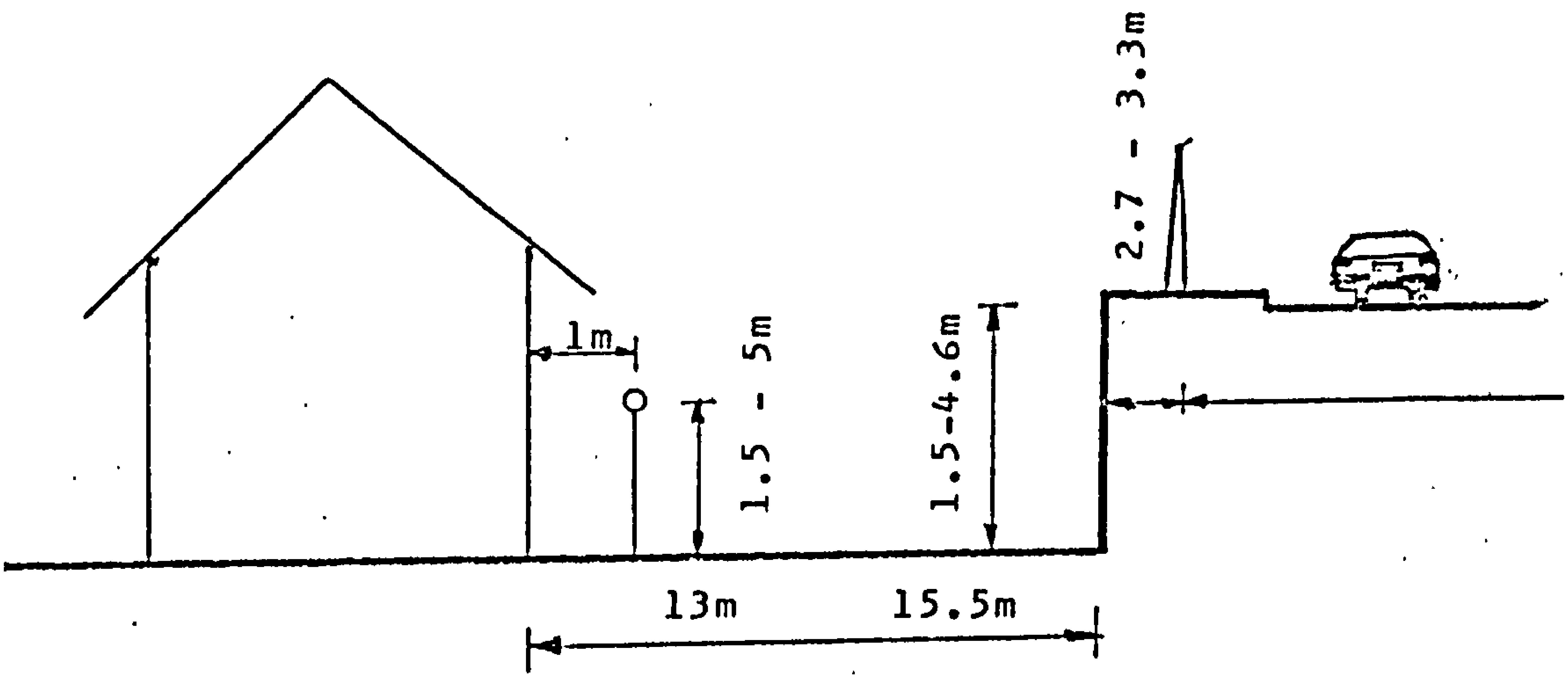
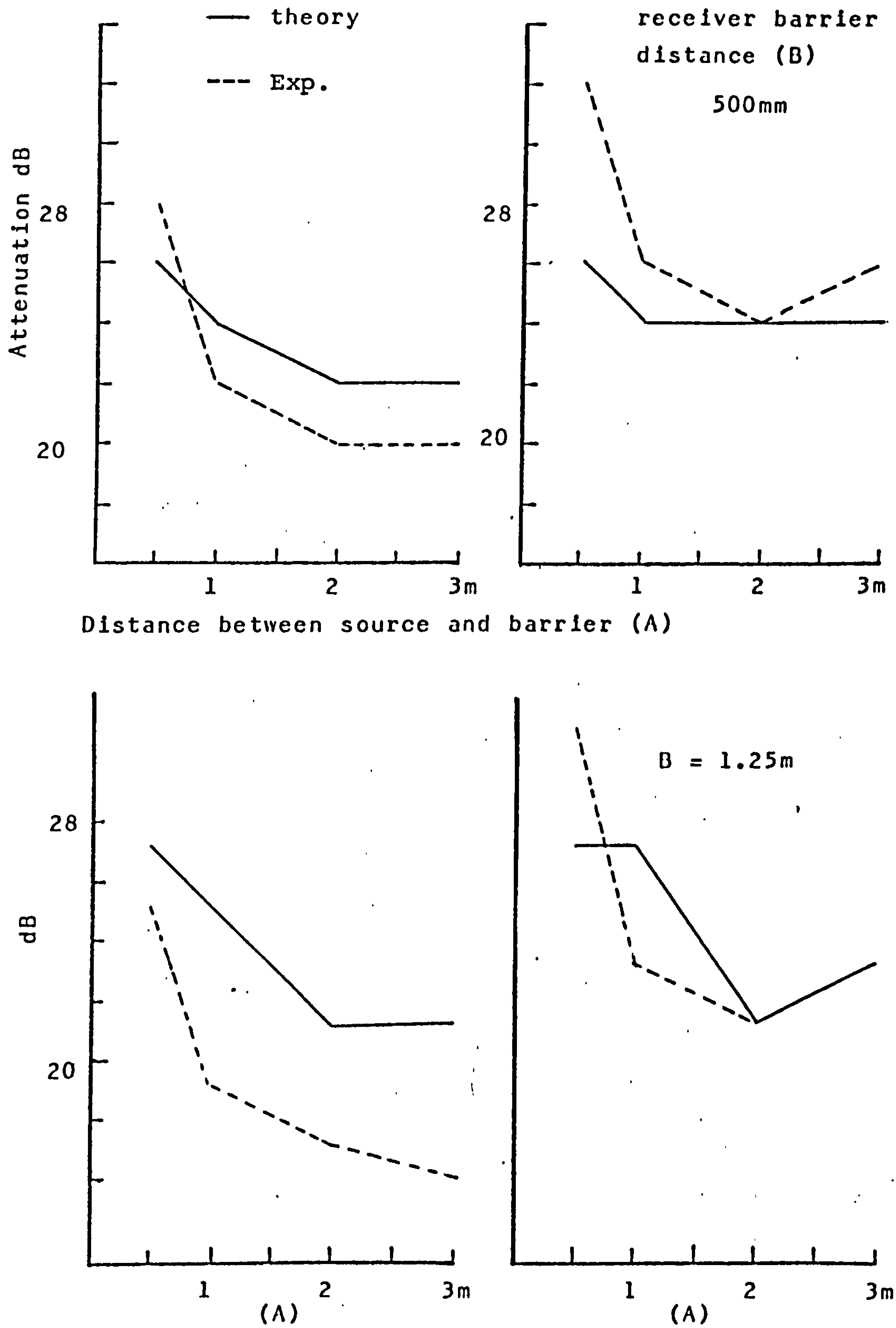


Fig. 2.5



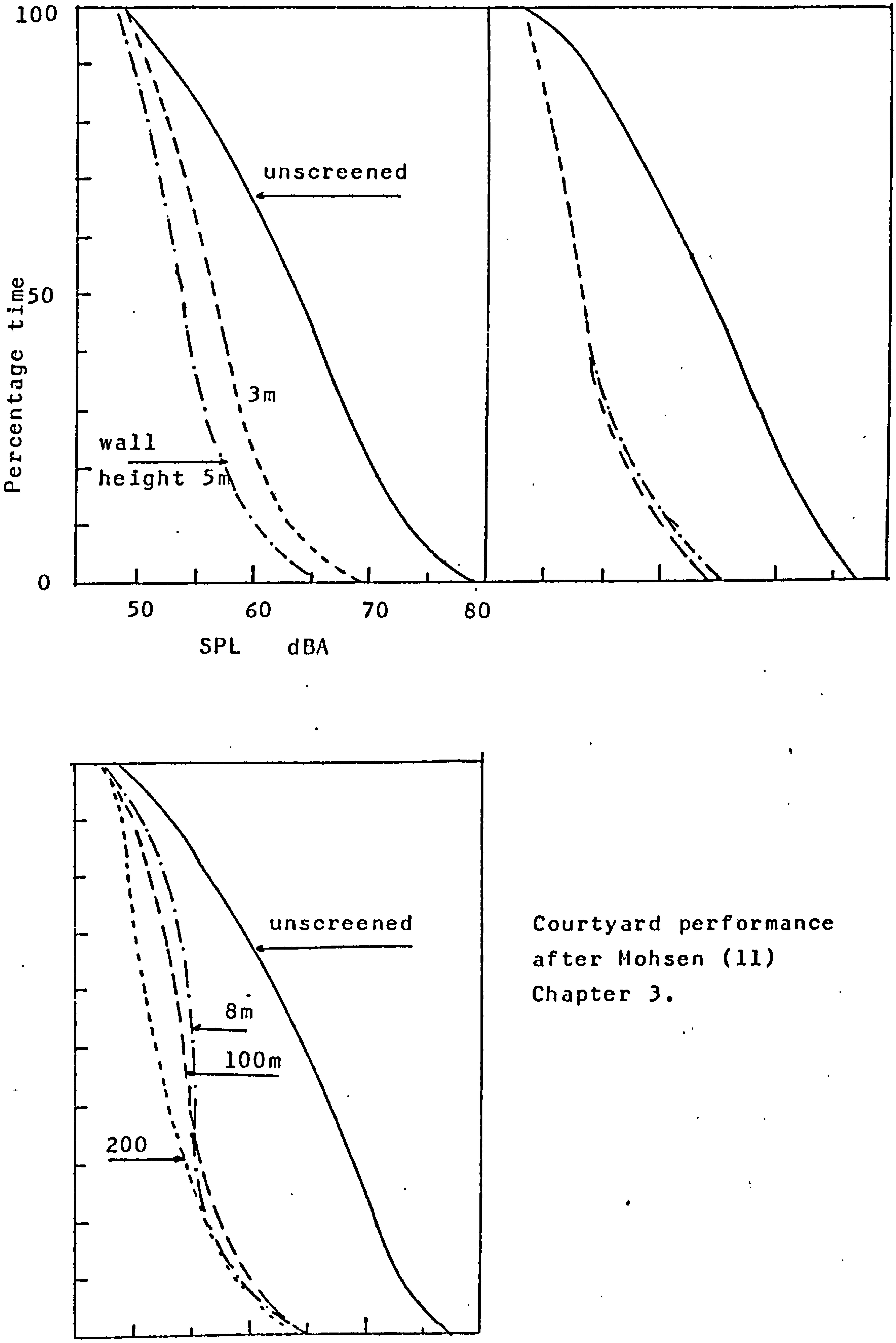
Barriers configuration.
After Scholes *et al.*, (2) Chapter 3.

Fig. 3.1



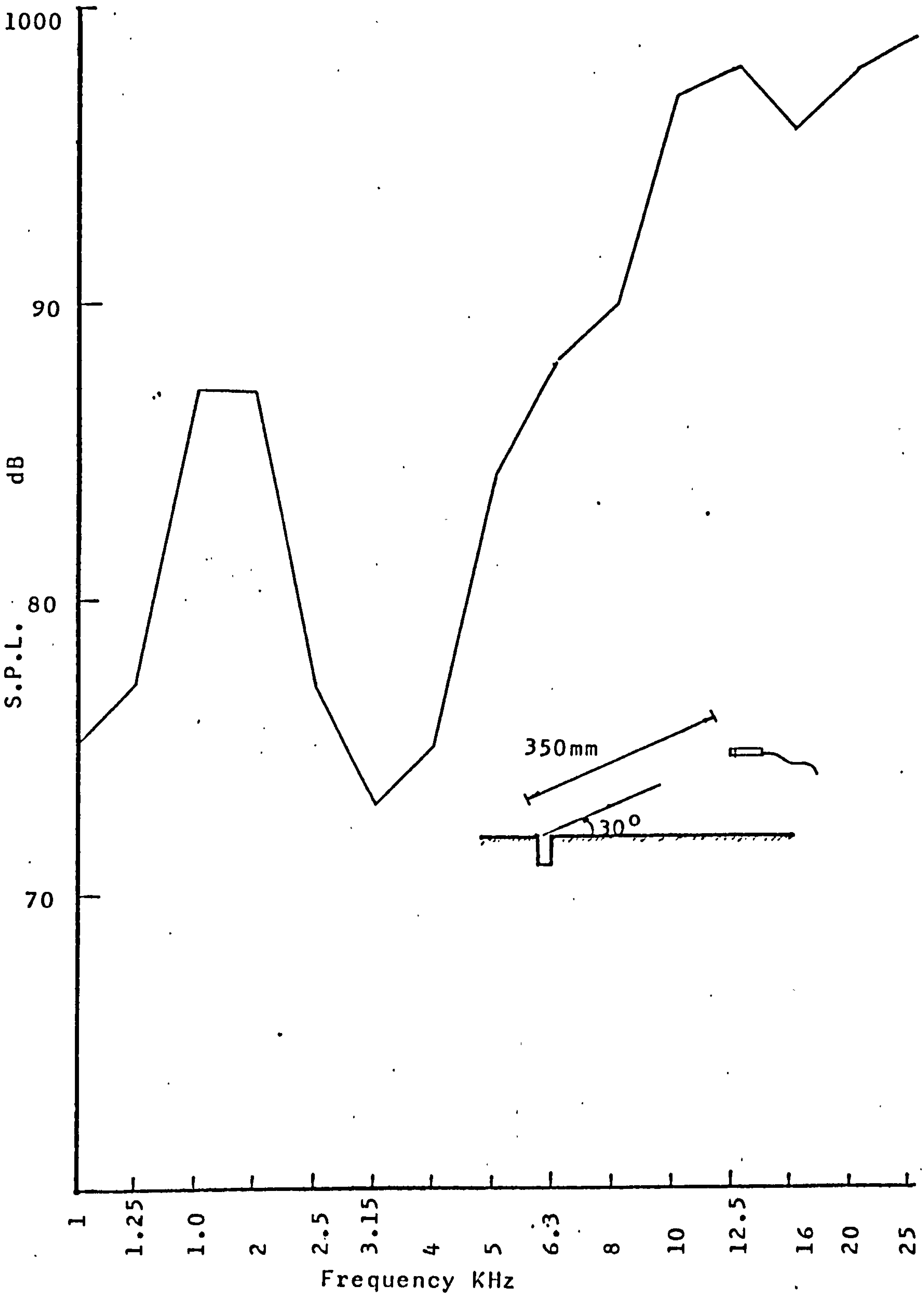
Attenuation of a courtyard after Ettouney (1) Chapter 3.

Fig. 3.2



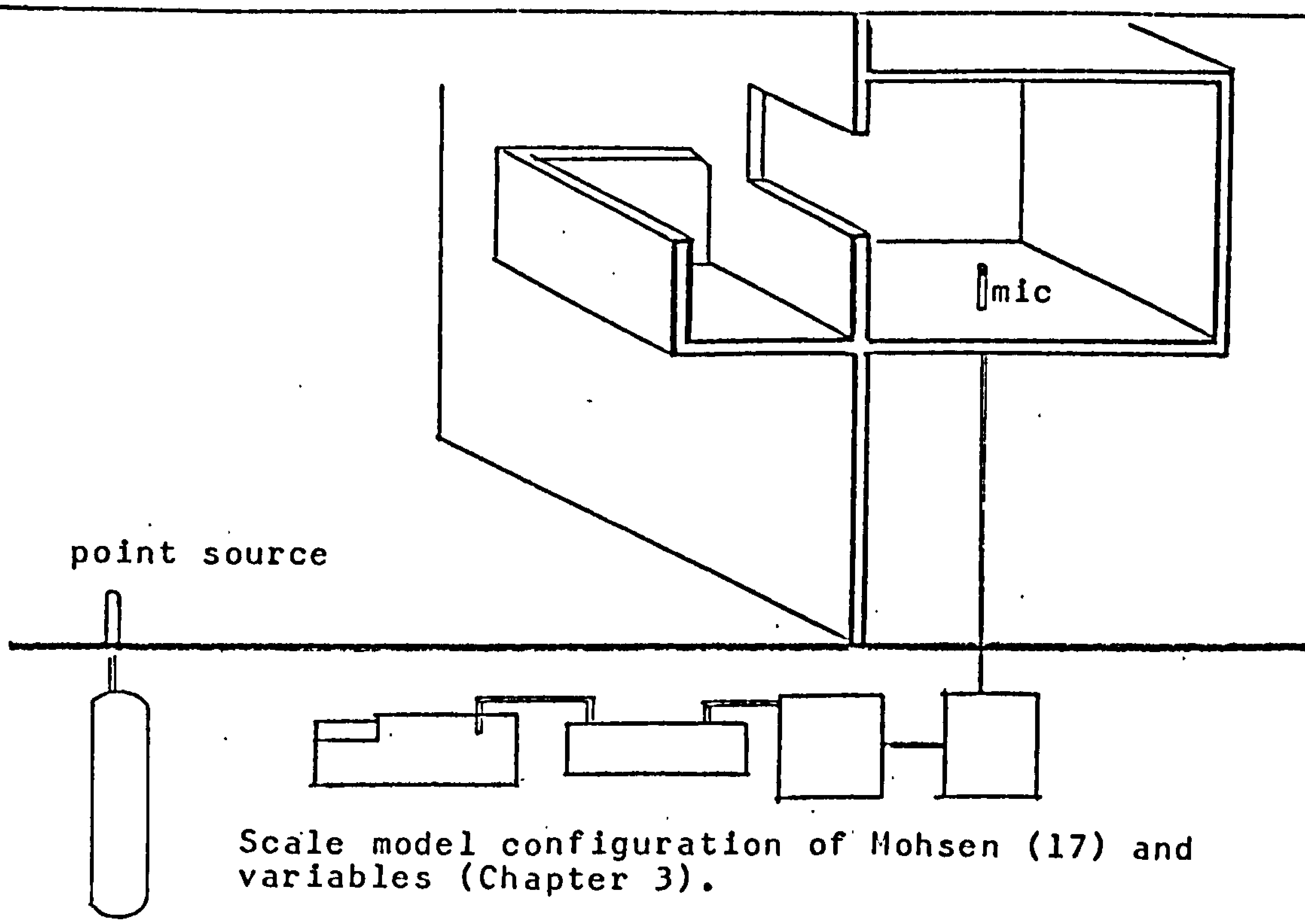
Courtyard performance after Mohsen (11) Chapter 3.

Fig. 3.3



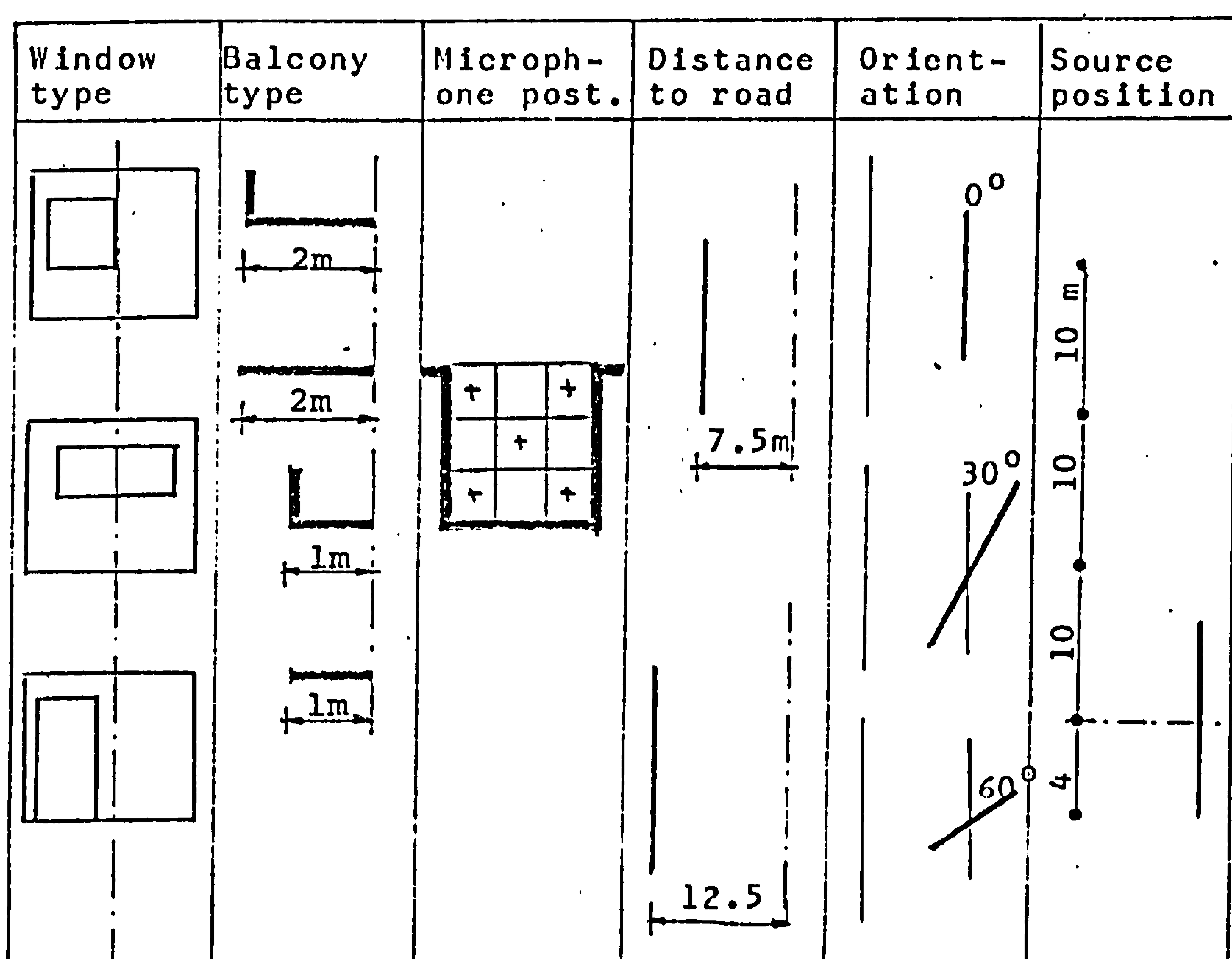
The spectrum of Mohsen'ssound source (11) Chapter 3.

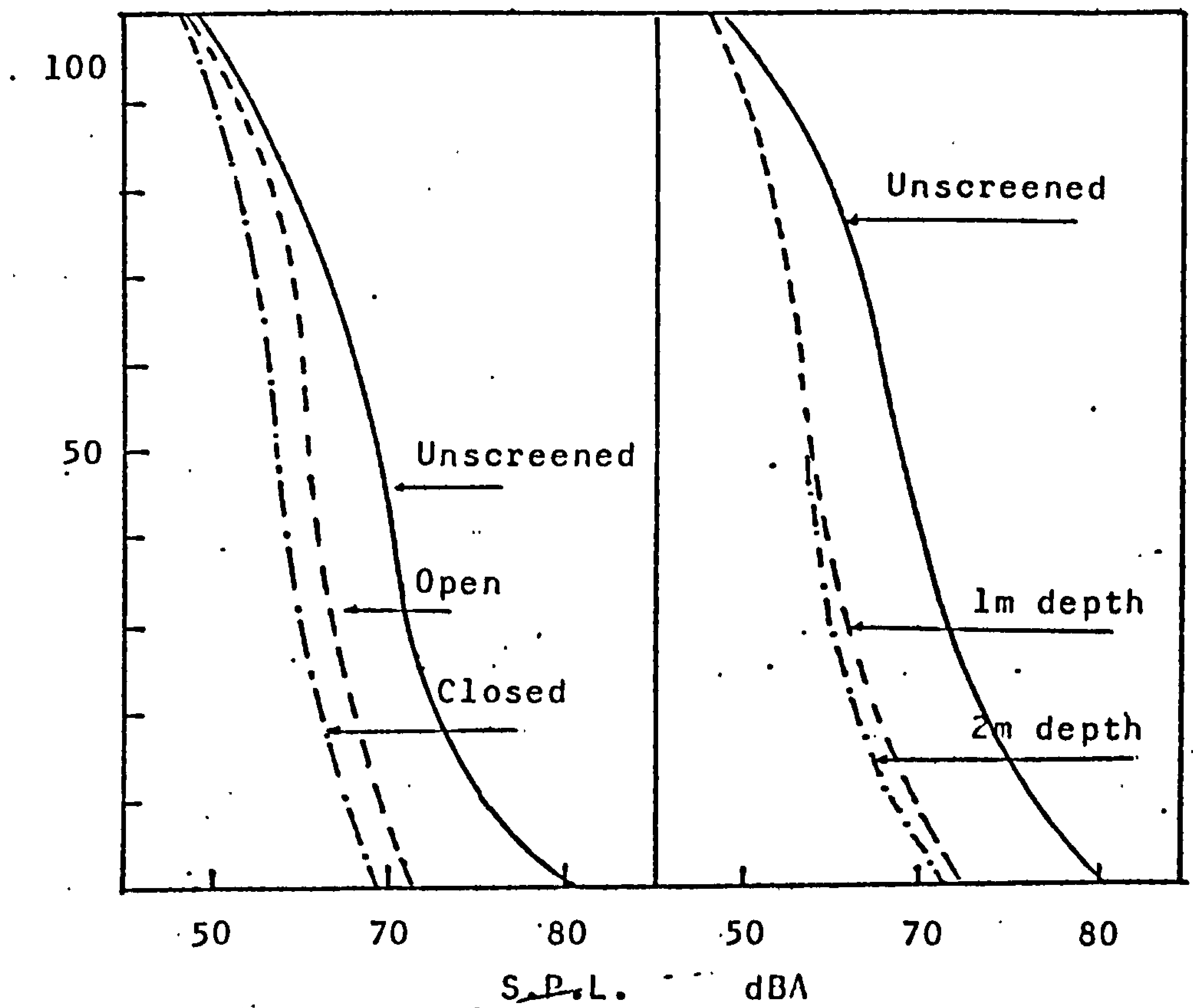
Fig. 3.4

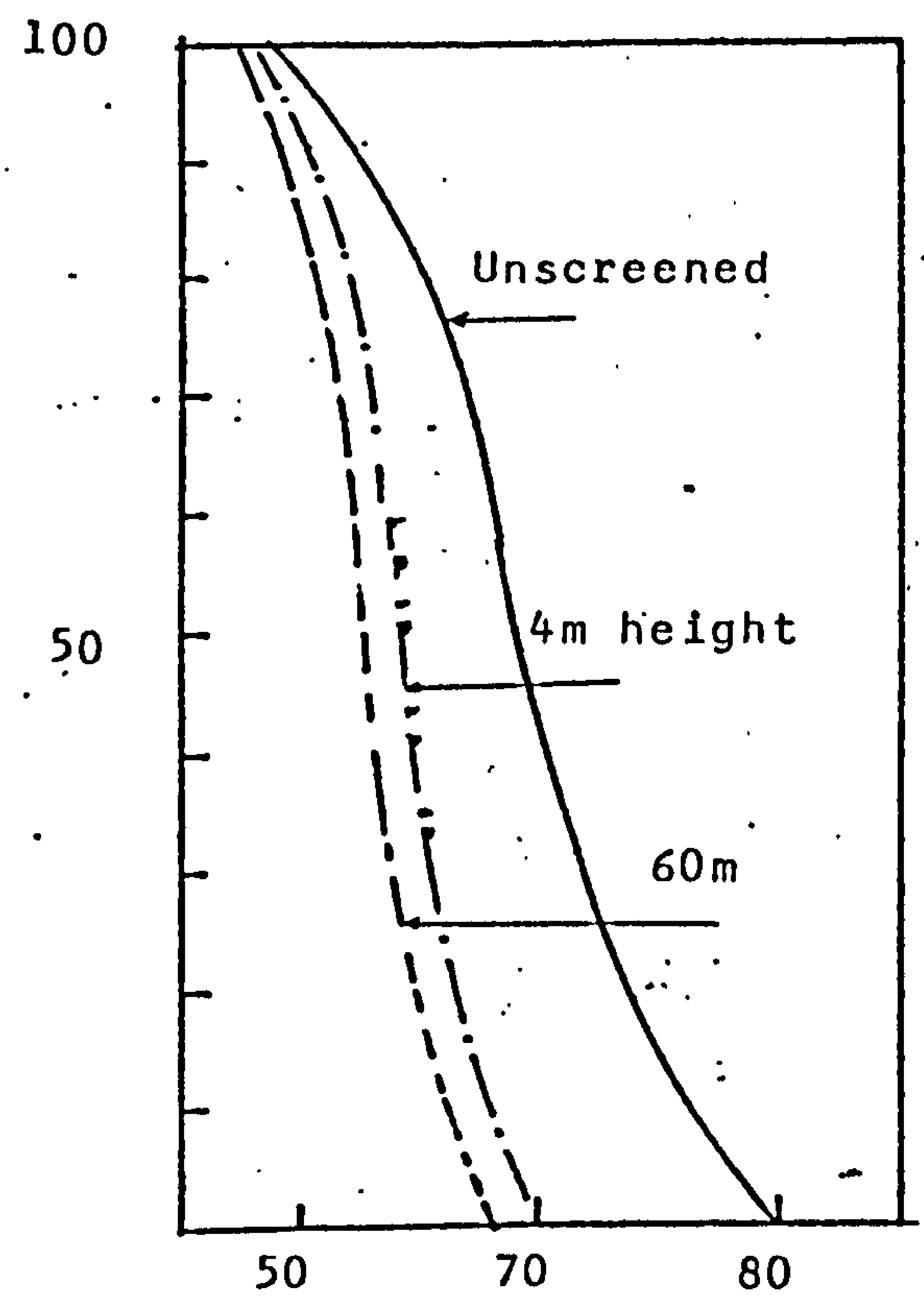


Scale model configuration of Mohsen (17) and variables (Chapter 3).

Fig. 3.5







Balcony Performance
after Mohsen (17)
Chapter 3.

Fig. 3.6

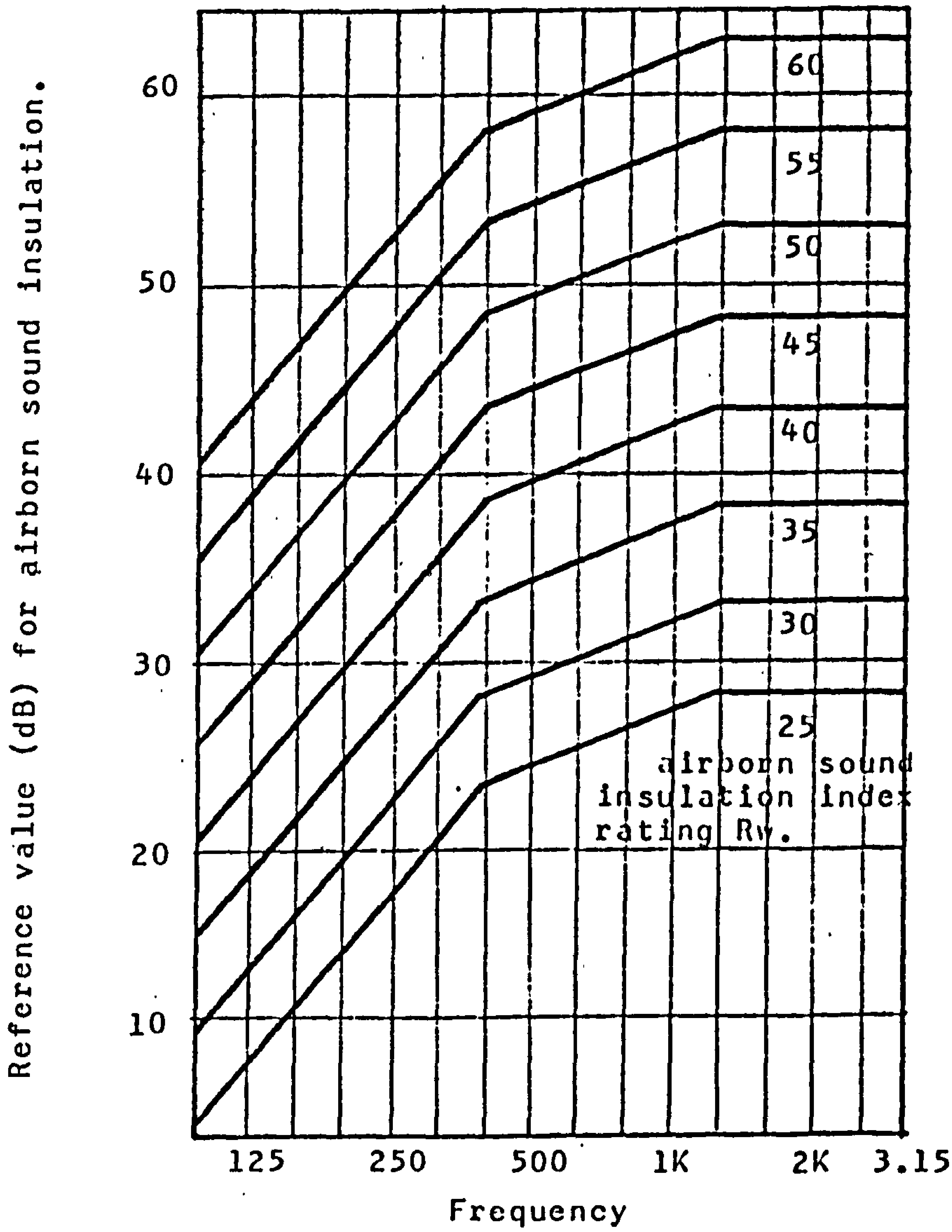


Fig. 4.1

Example of graph for deriving weighted sound reduction index Rw.

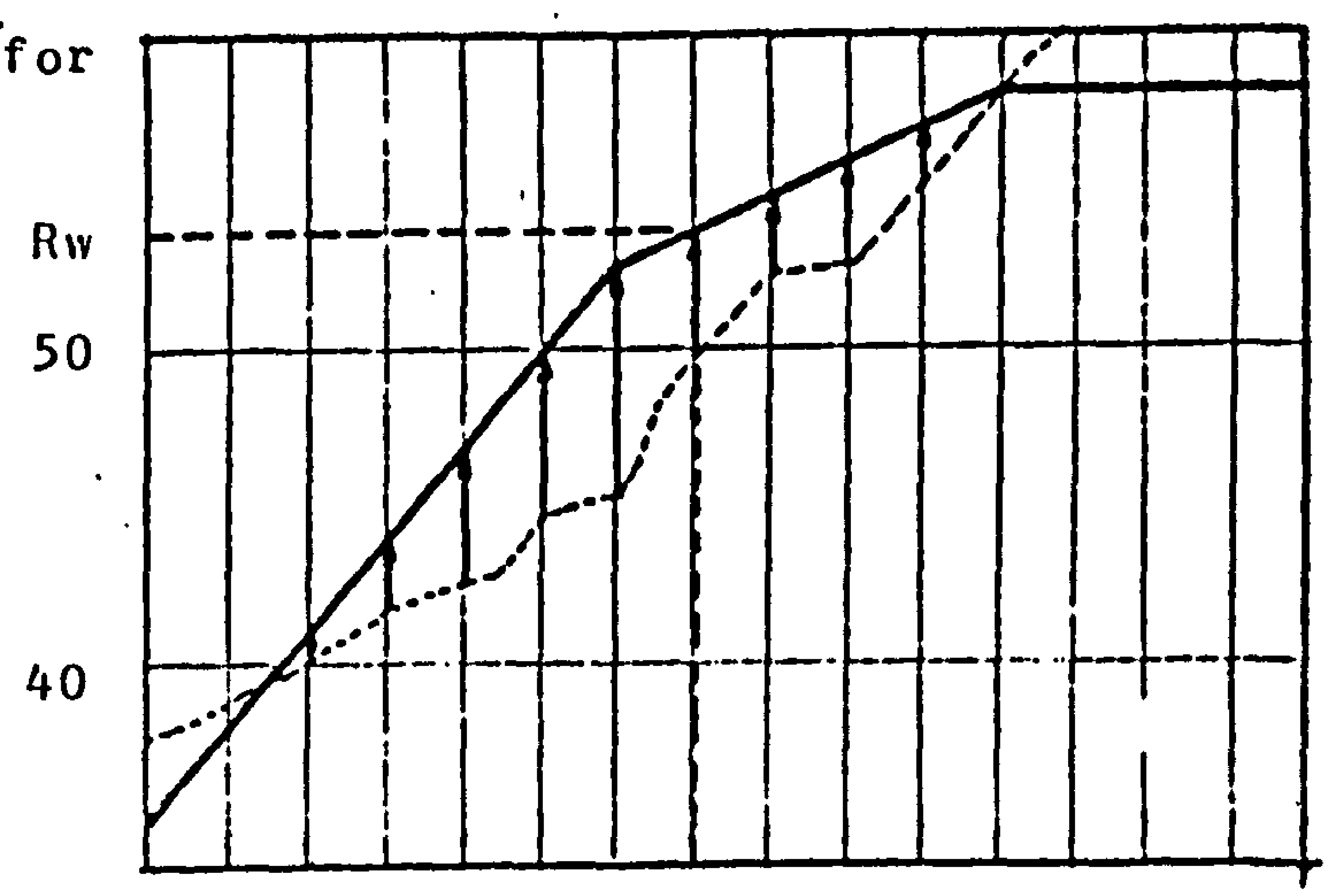


Fig. 4.2

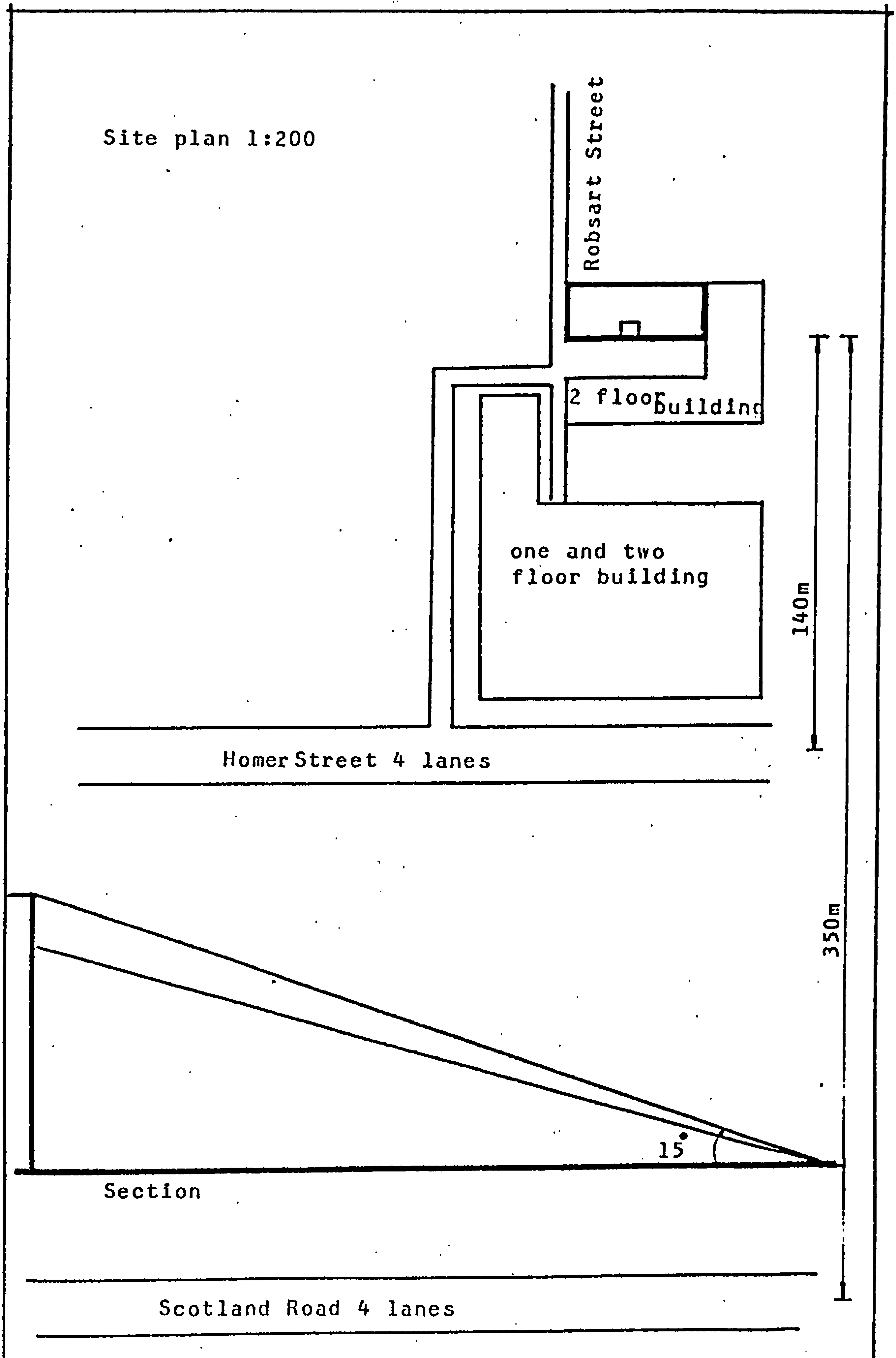
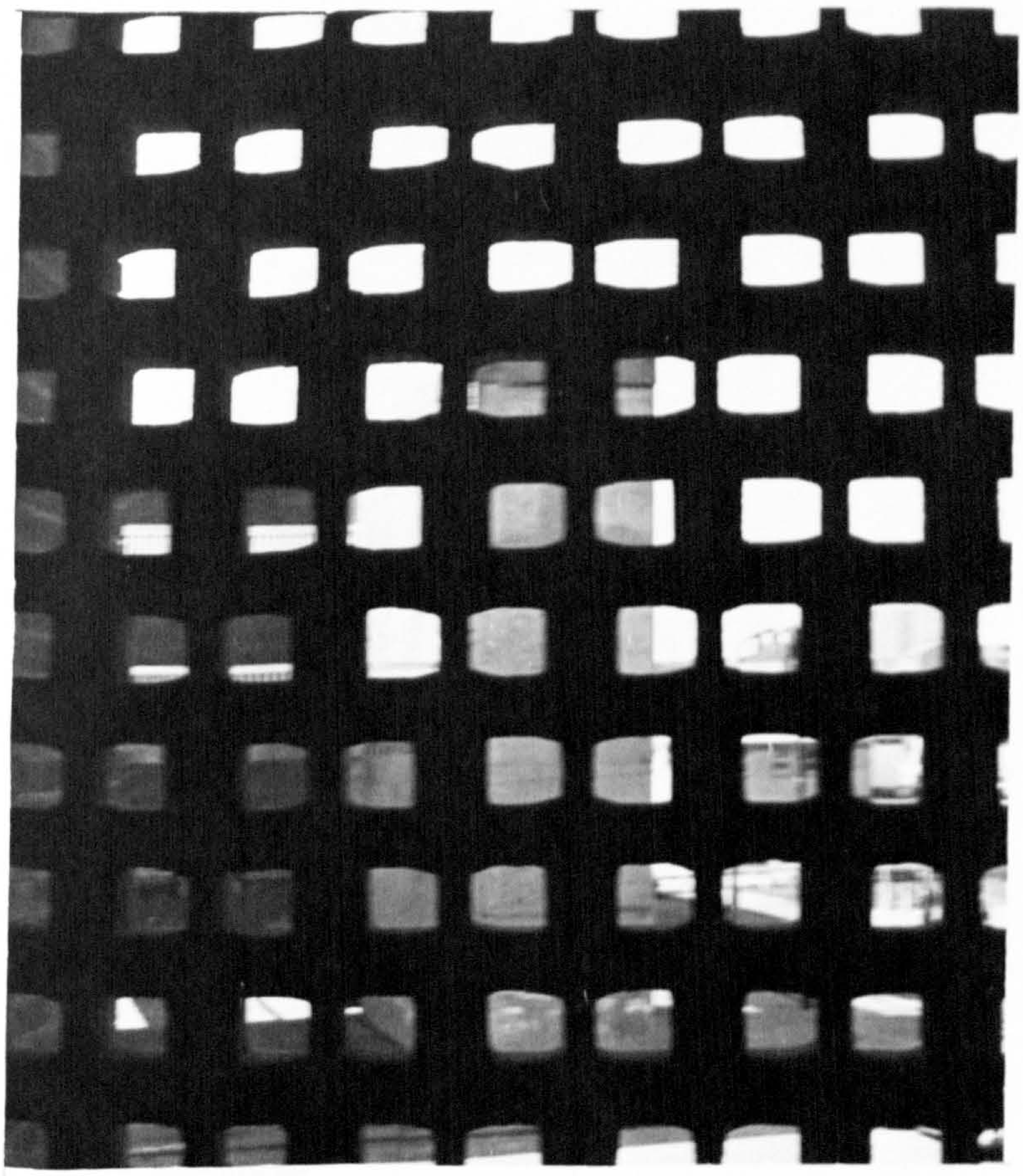

Site plan 1:200
Robsart Street
2 floor building
one and two floor building
140m
Homer Street 4 lanes
350m
15°
Section
Scotland Road 4 lanes

Fig. 4.3

DETAIL OF THE EXTERNAL FACADE



VIEW FROM INSIDE


wind screen
rotating
½" condenser microphone
3.00m
wind screen
1" condenser microphone
2m
section
sound level metre
tape recorder
sound level metre
Experimental layout
2.5m
0.75m
2.8m
1.25m
360mm
200mm
200mm
120mm
40 40 40mm
Plan of the access area
Perforated unit

Fig. 4.5

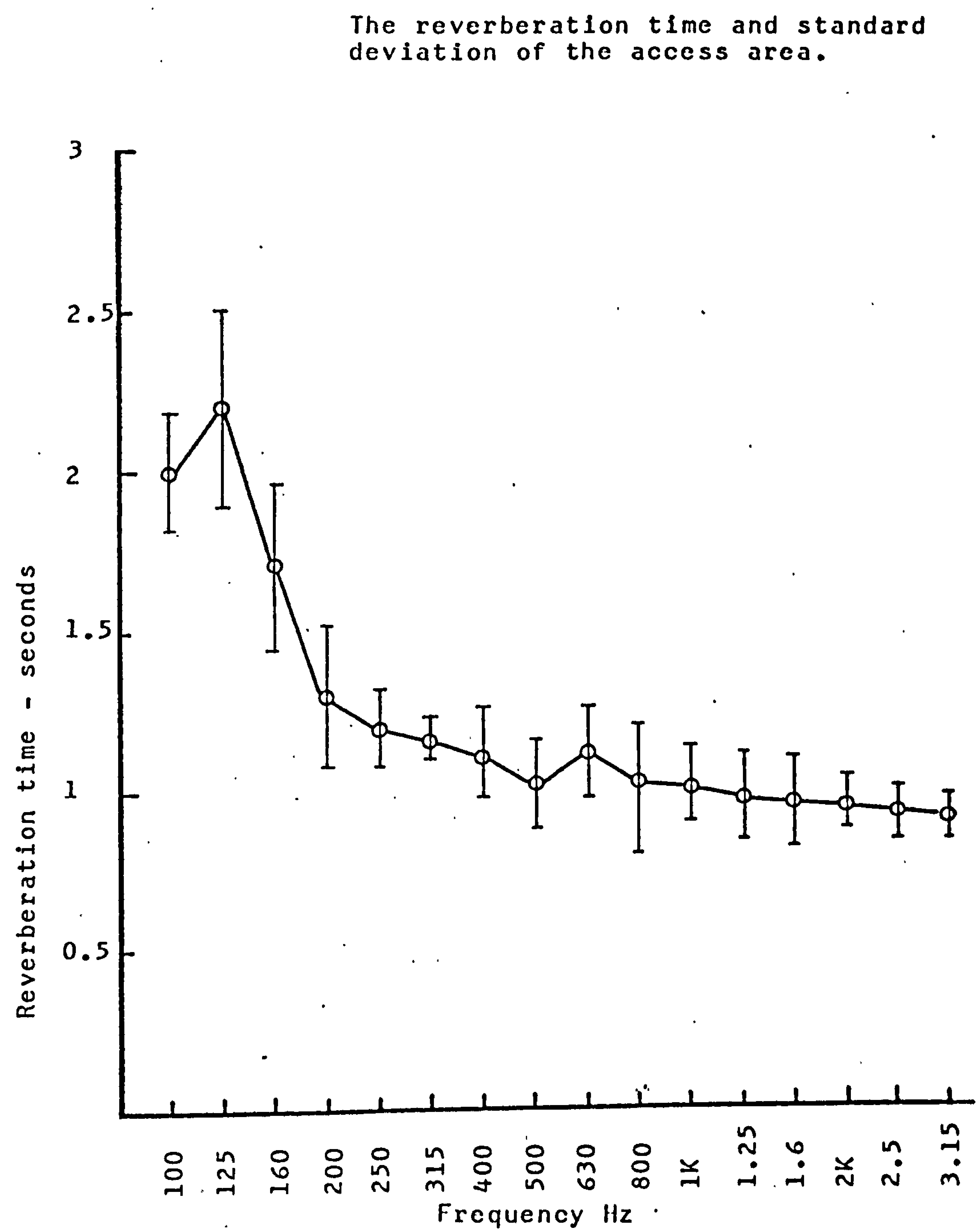
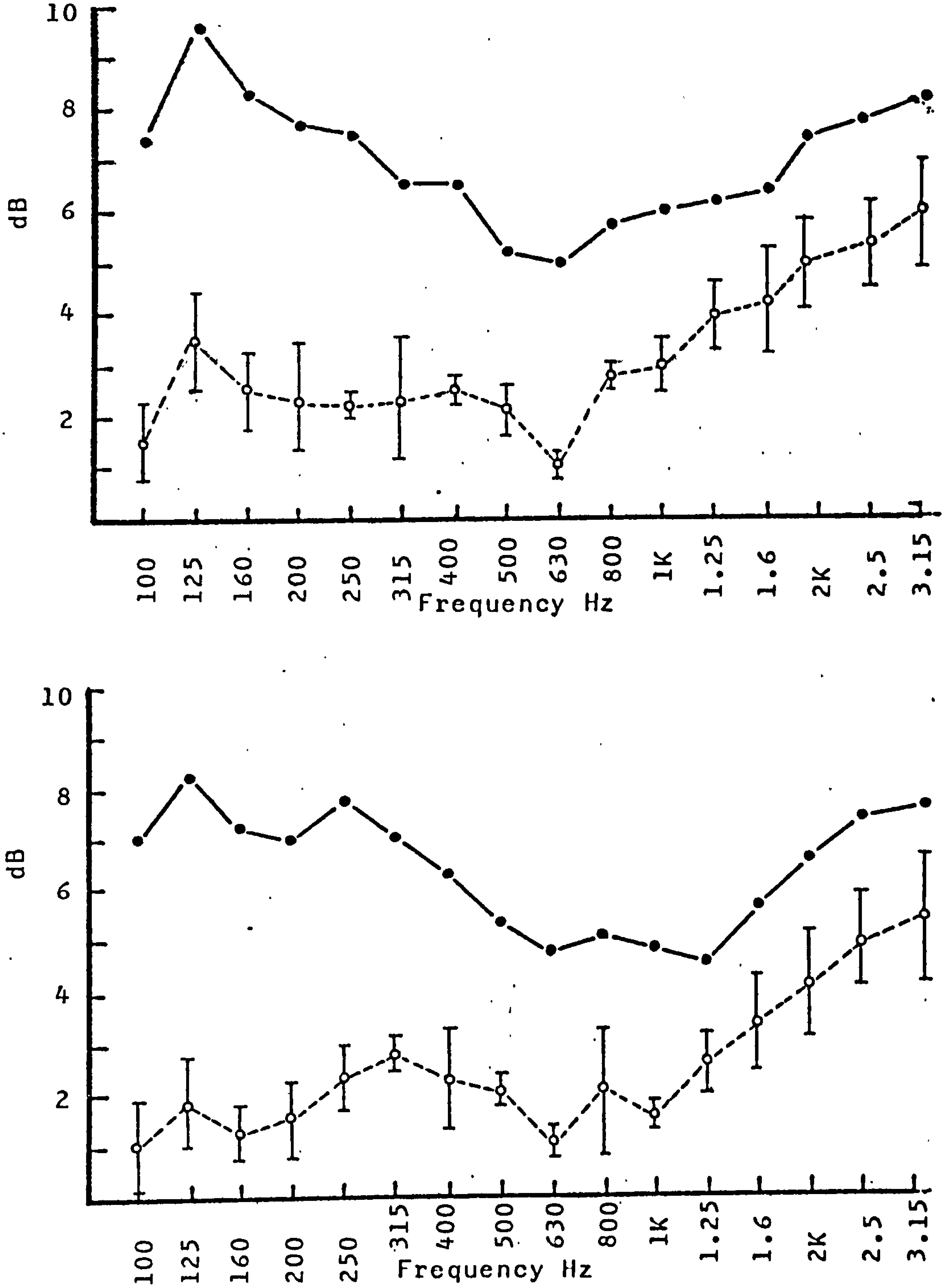

The reverberation time and standard deviation of the access area.
Reverberation time - seconds
3
2.5
2
1.5
1
0.5
100
125
160
200
250
315
400
500
630
800
1K
1.25
1.6
2K
2.5
3.15
Frequency Hz

Fig. 4.6

Field measurement of building facade.

- Sound reduction Index Rtr,
- o the equivalent sound pressure level difference (Leq_1-Leq_2) and the standard deviation.



As above at 11th floor level.

Fig. 4.7

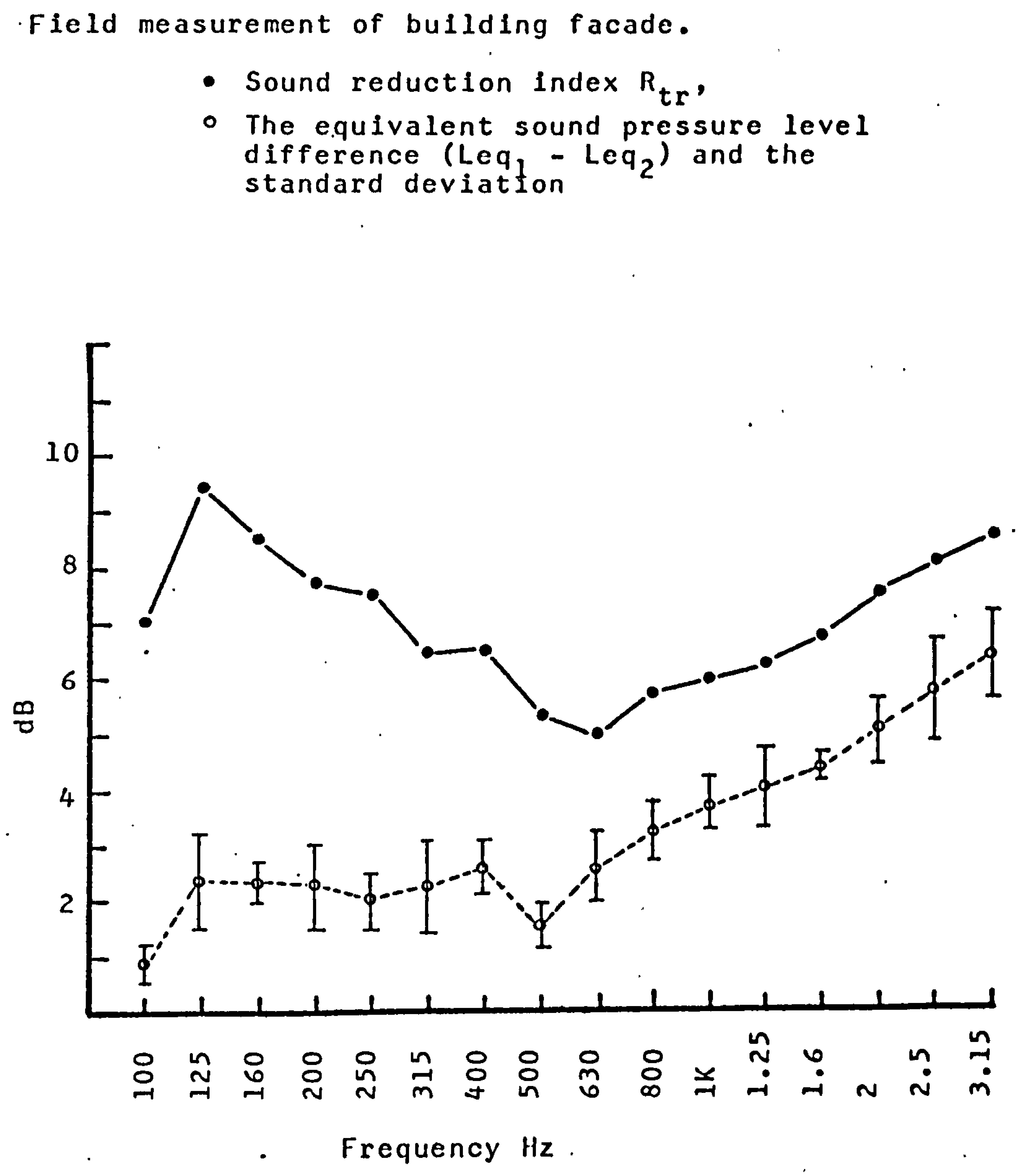

Field measurement of building facade.
• Sound reduction index R_tr,
○ The equivalent sound pressure level difference (Leq1 - Leq2) and the standard deviation
dB
10
8
6
4
2
100
125
160
200
250
315
400
500
630
800
1K
1.25
1.6
2
2.5
3.15
Frequency Hz

Fig. 4.8

Field measurement of building facade.

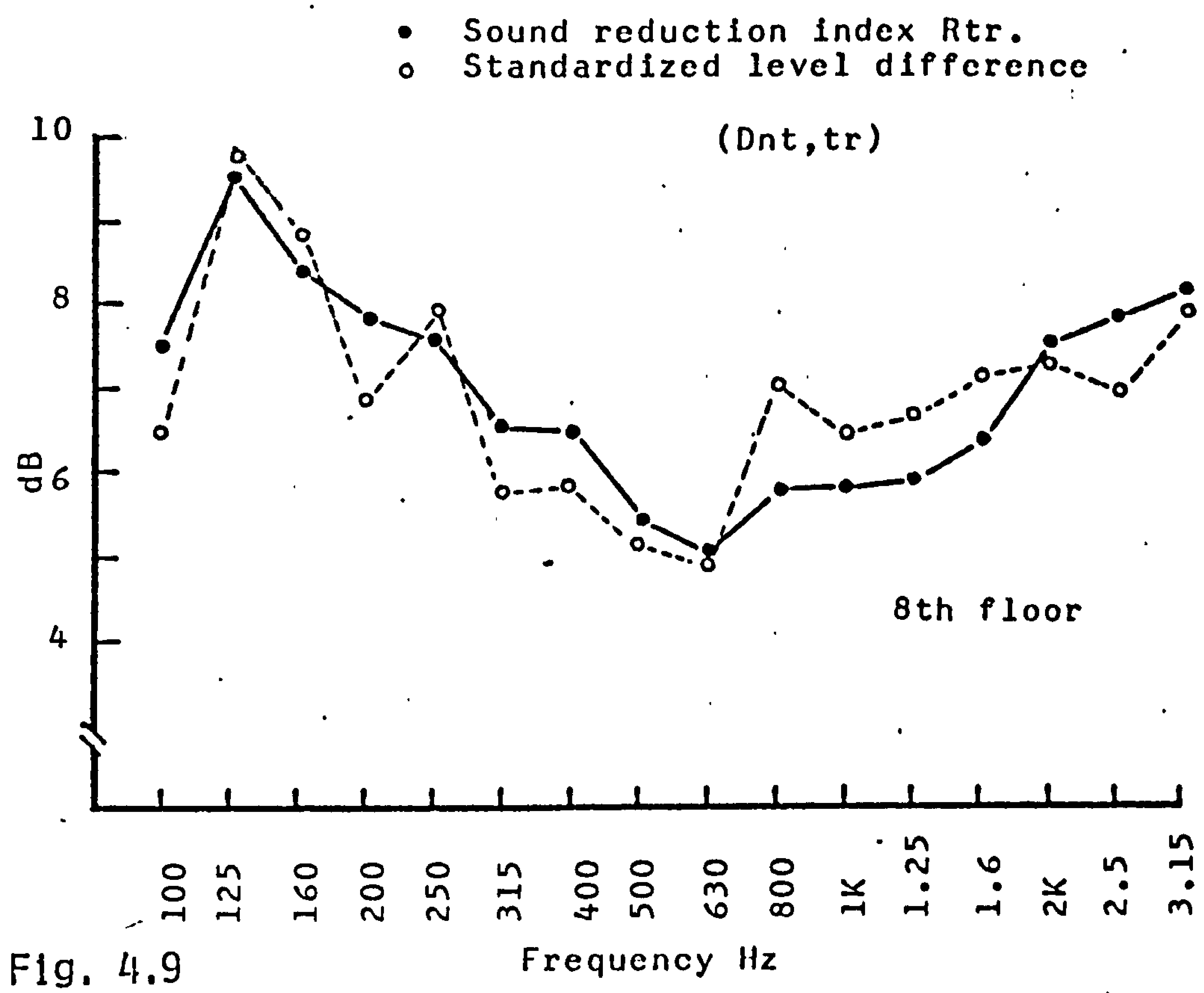


Fig. 4.9

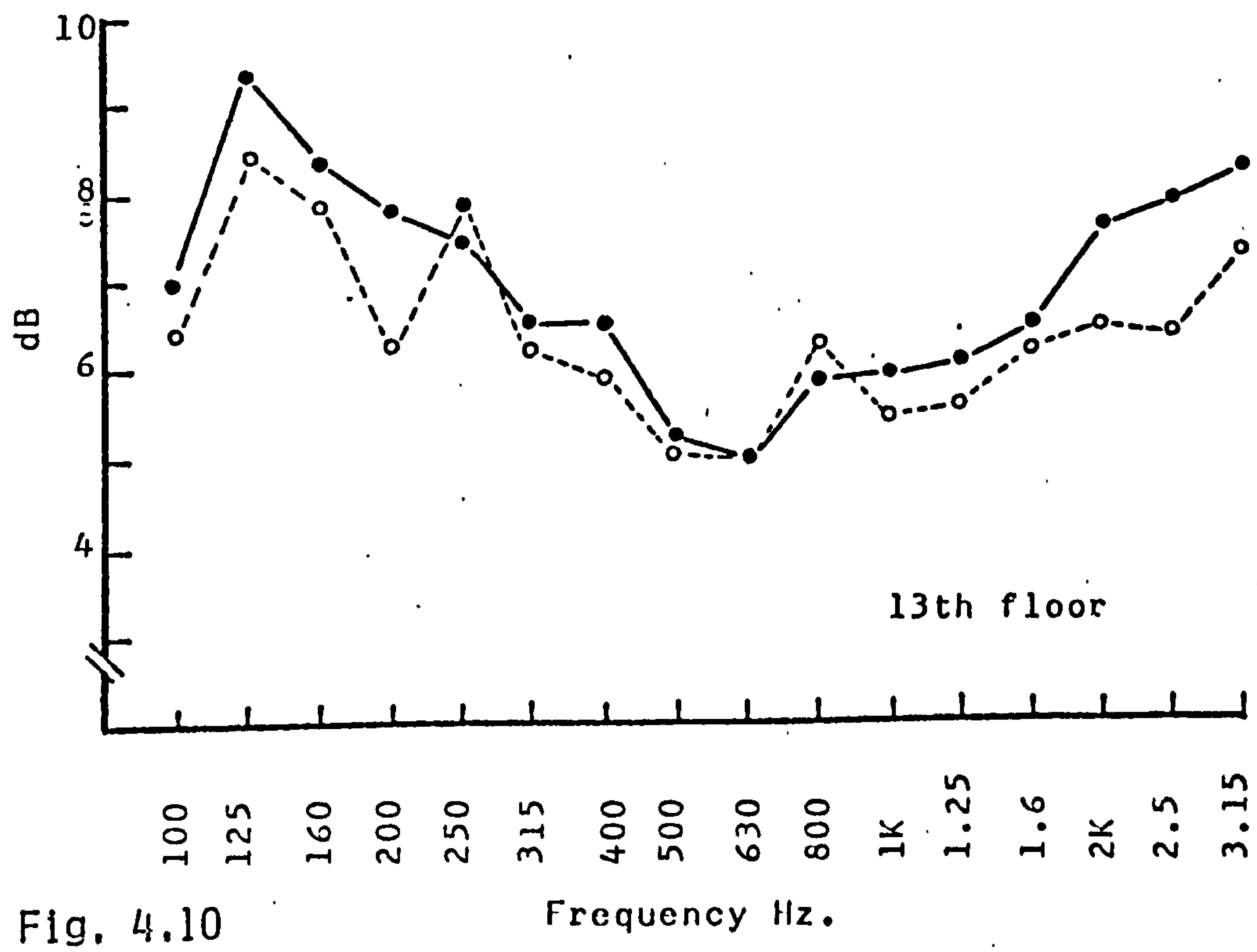


Fig. 4.10

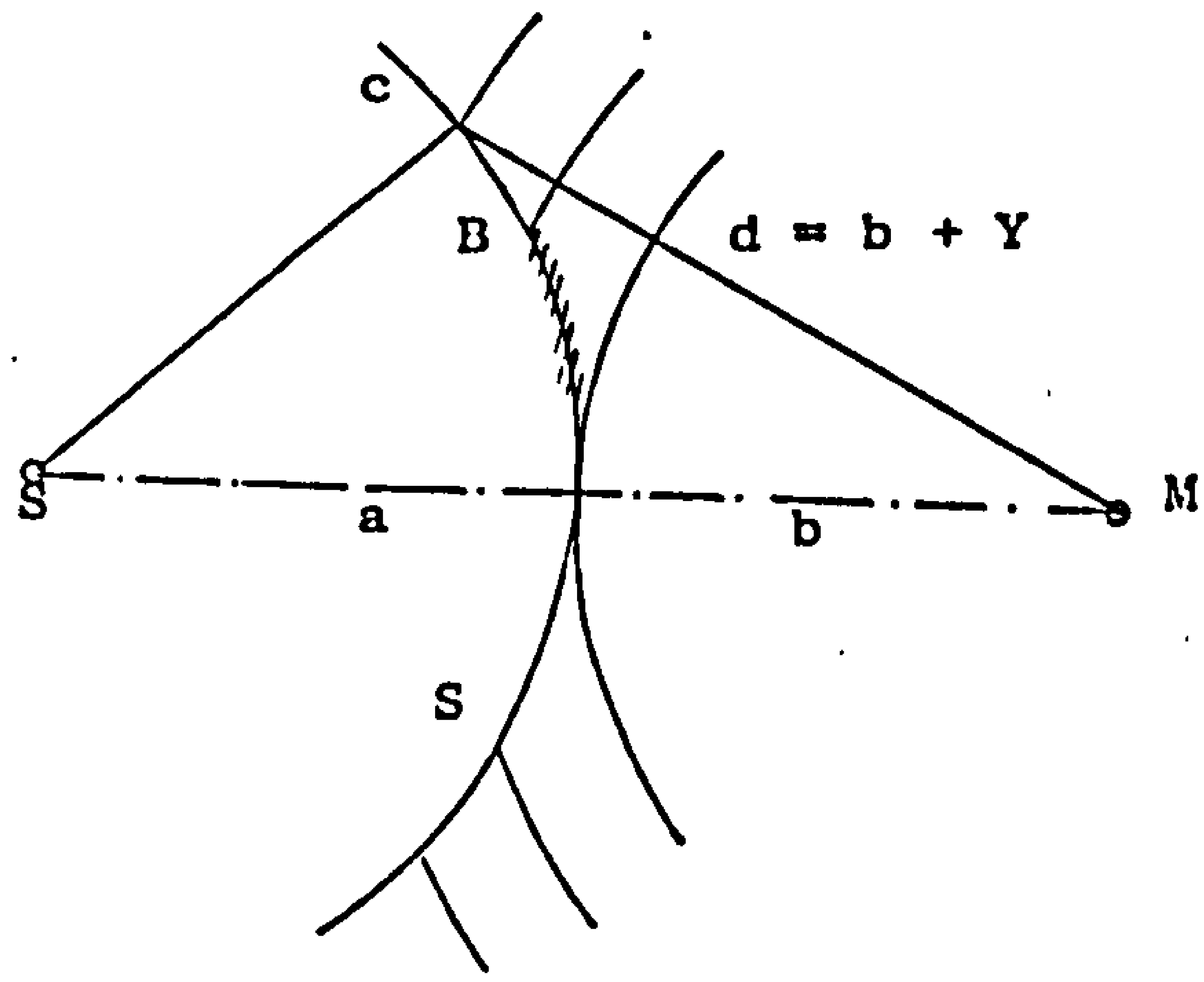


Fig. 5.1 Subdivision of a cylindrical wave front.

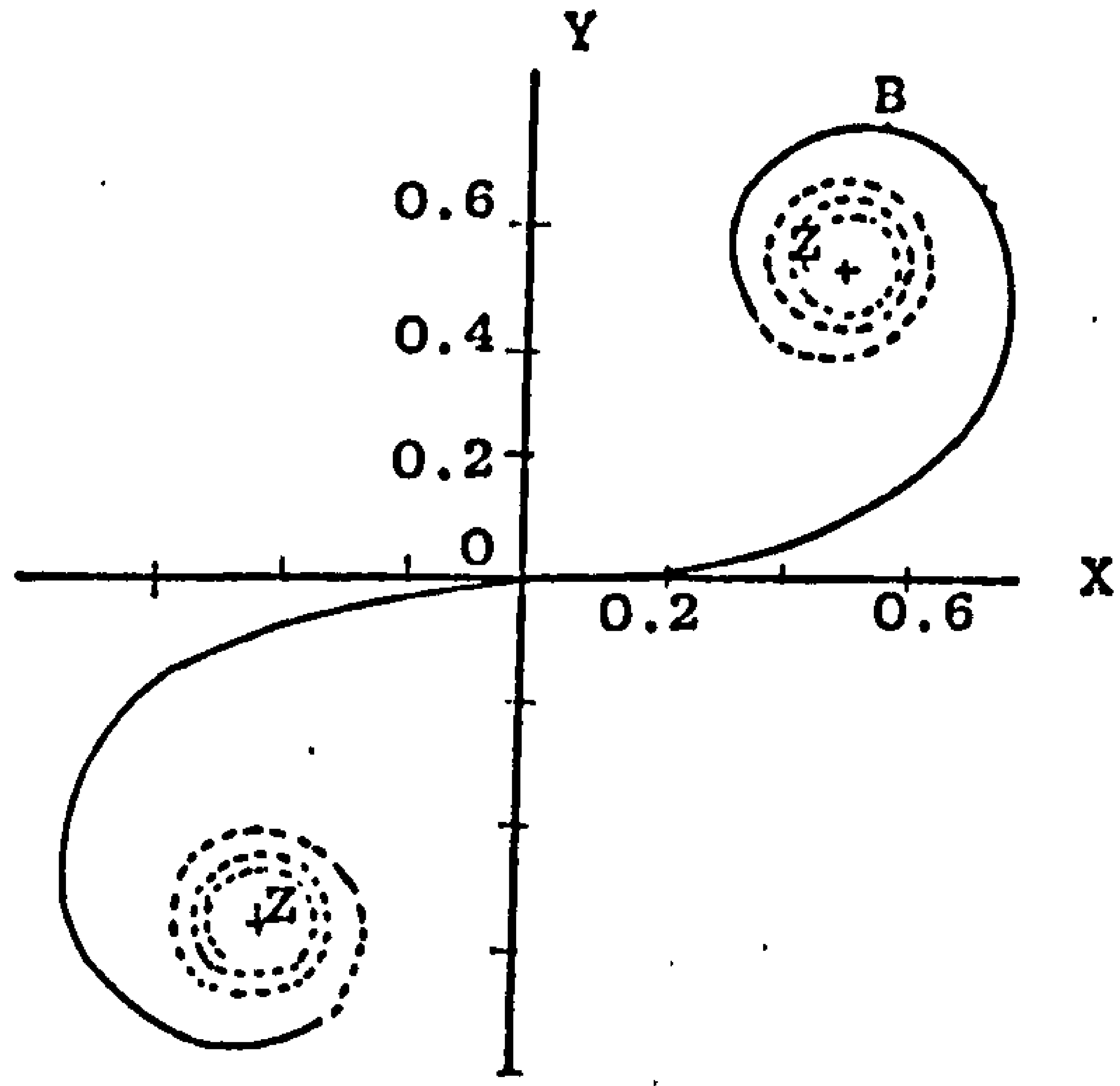


Fig. 5.2 Cornu's spiral, a plot of the Fresnelintegrals

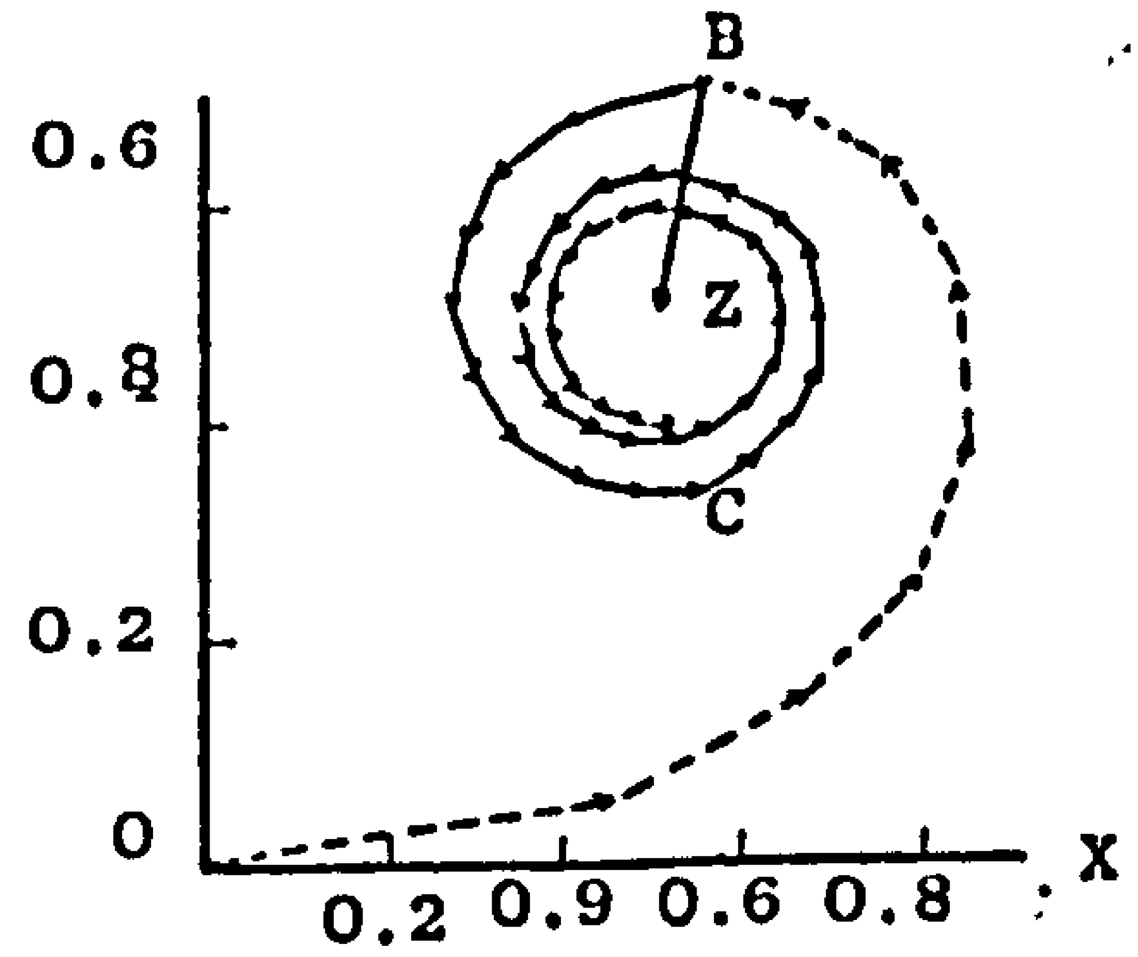


Fig. 5.3 Vector diagram for a wall blocking the first half period zone.

Redfearn's Chart

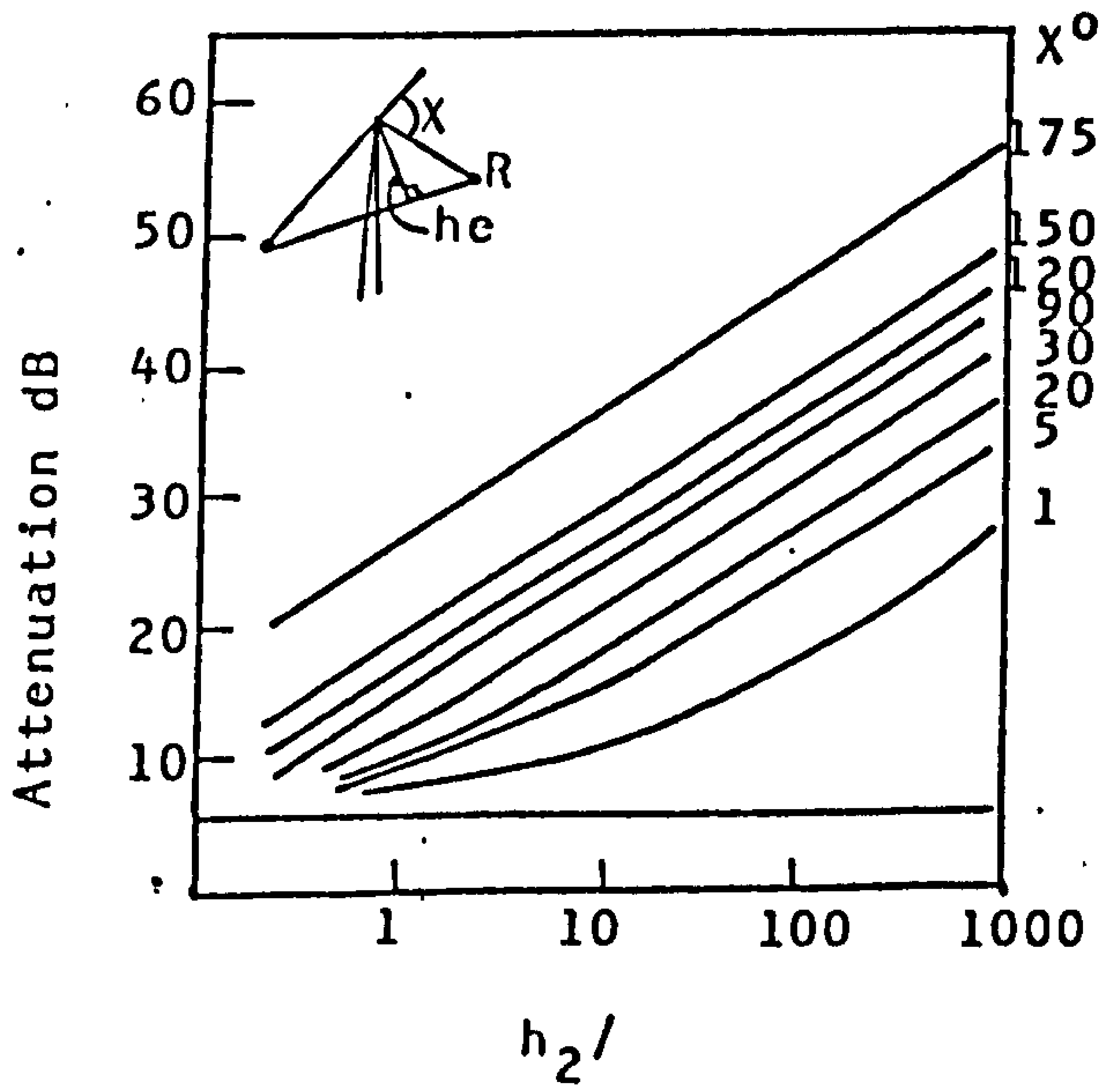


Fig. 5.4
Purcell's design chart

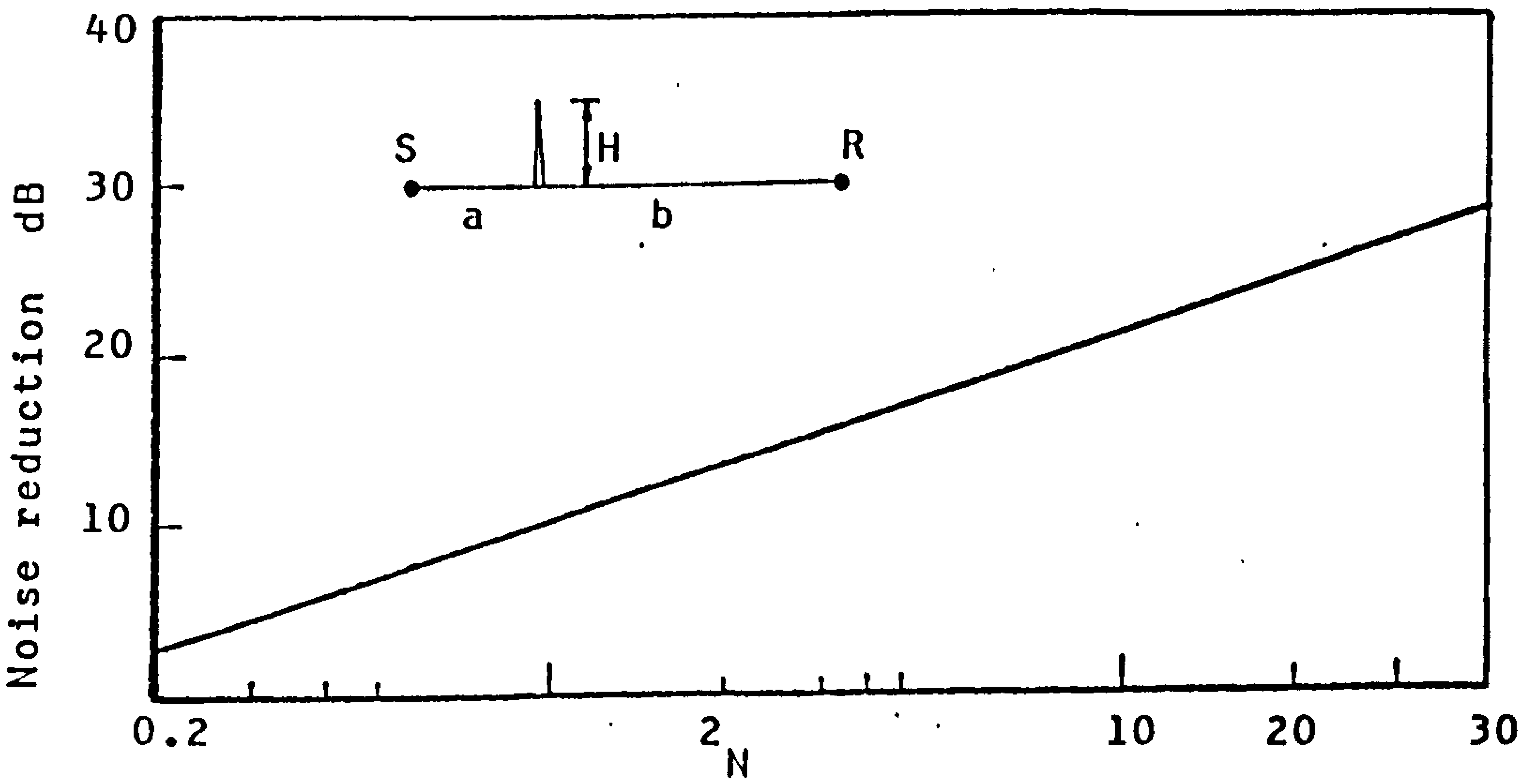


Fig. 5.5

Fehr Chart
Equation 12
Equation 13

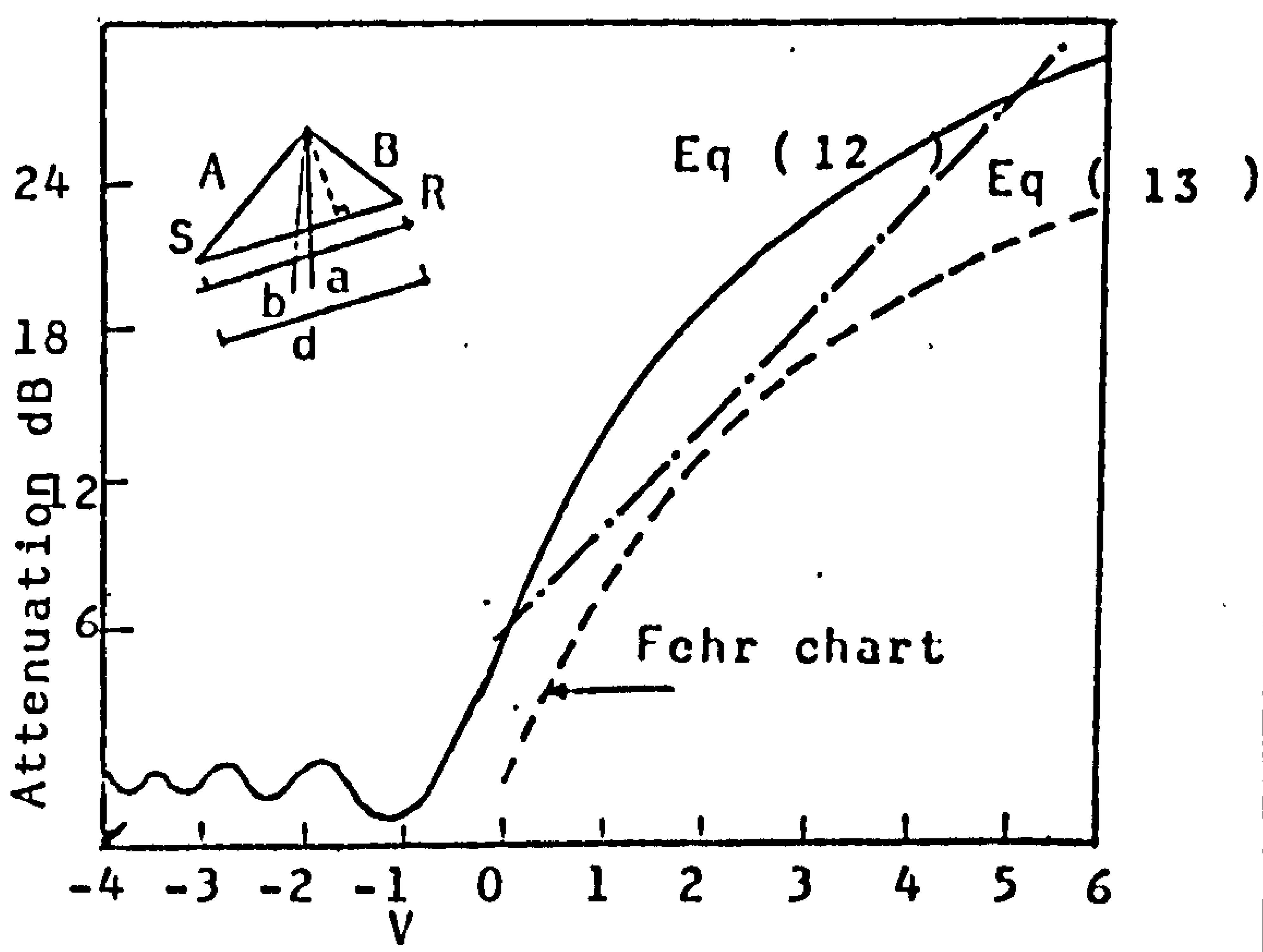
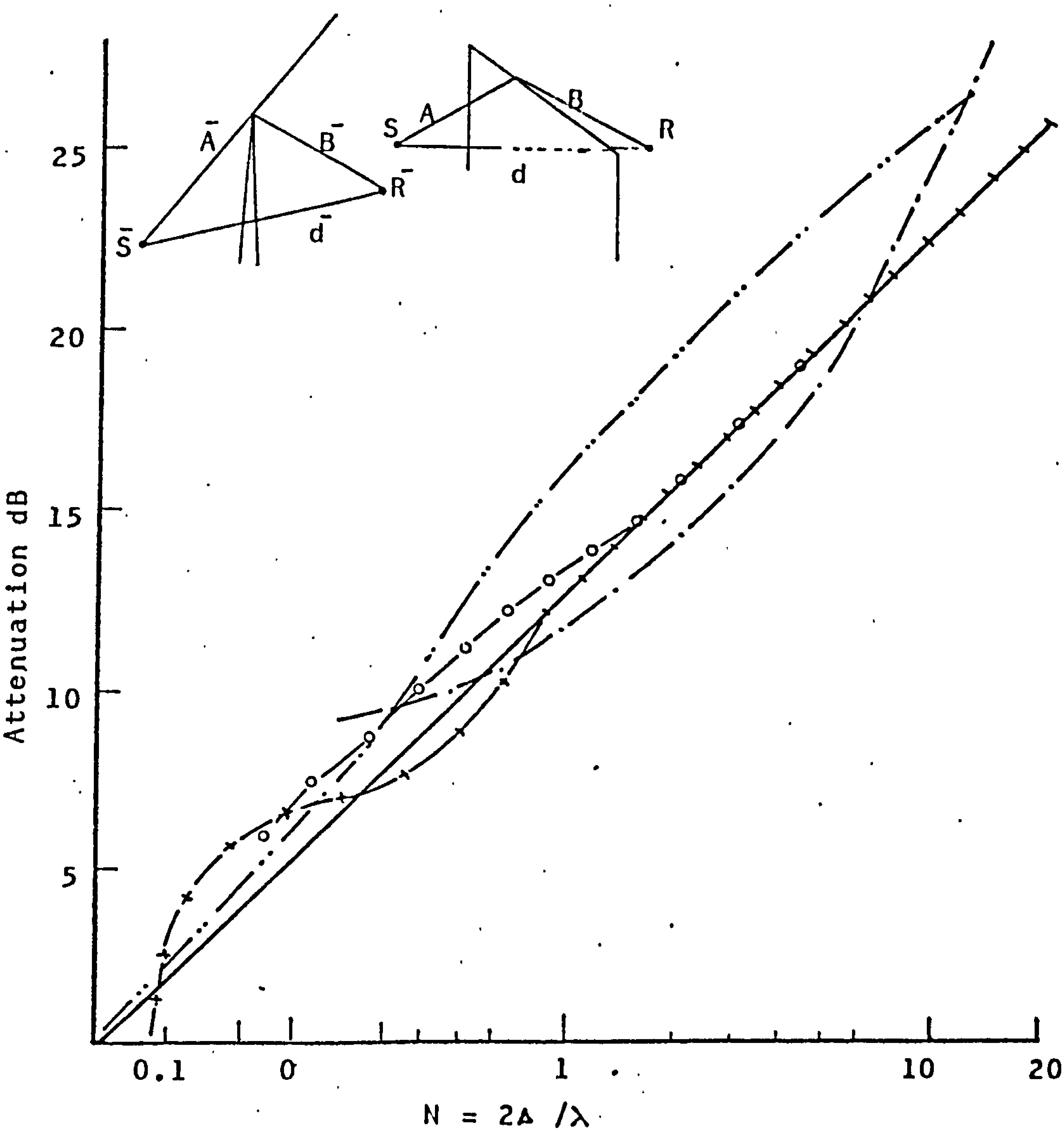


Fig. 5.6



Free standing Barrier

Comparison between different formulae and measurement

—— Mae kawa
—·— Stanly
+—+ Kurze
o—o Pierce

Fig. 5.7

As before

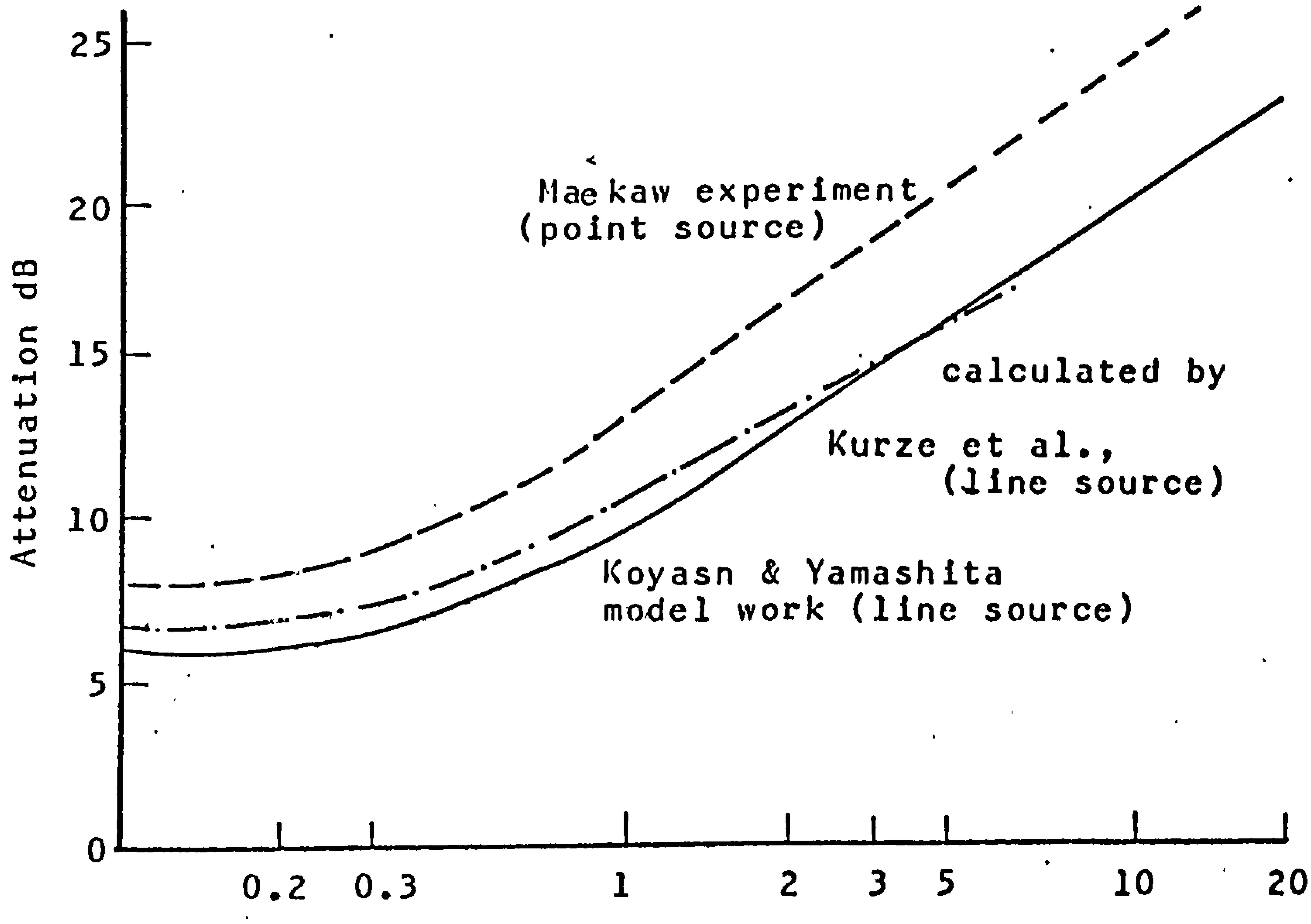
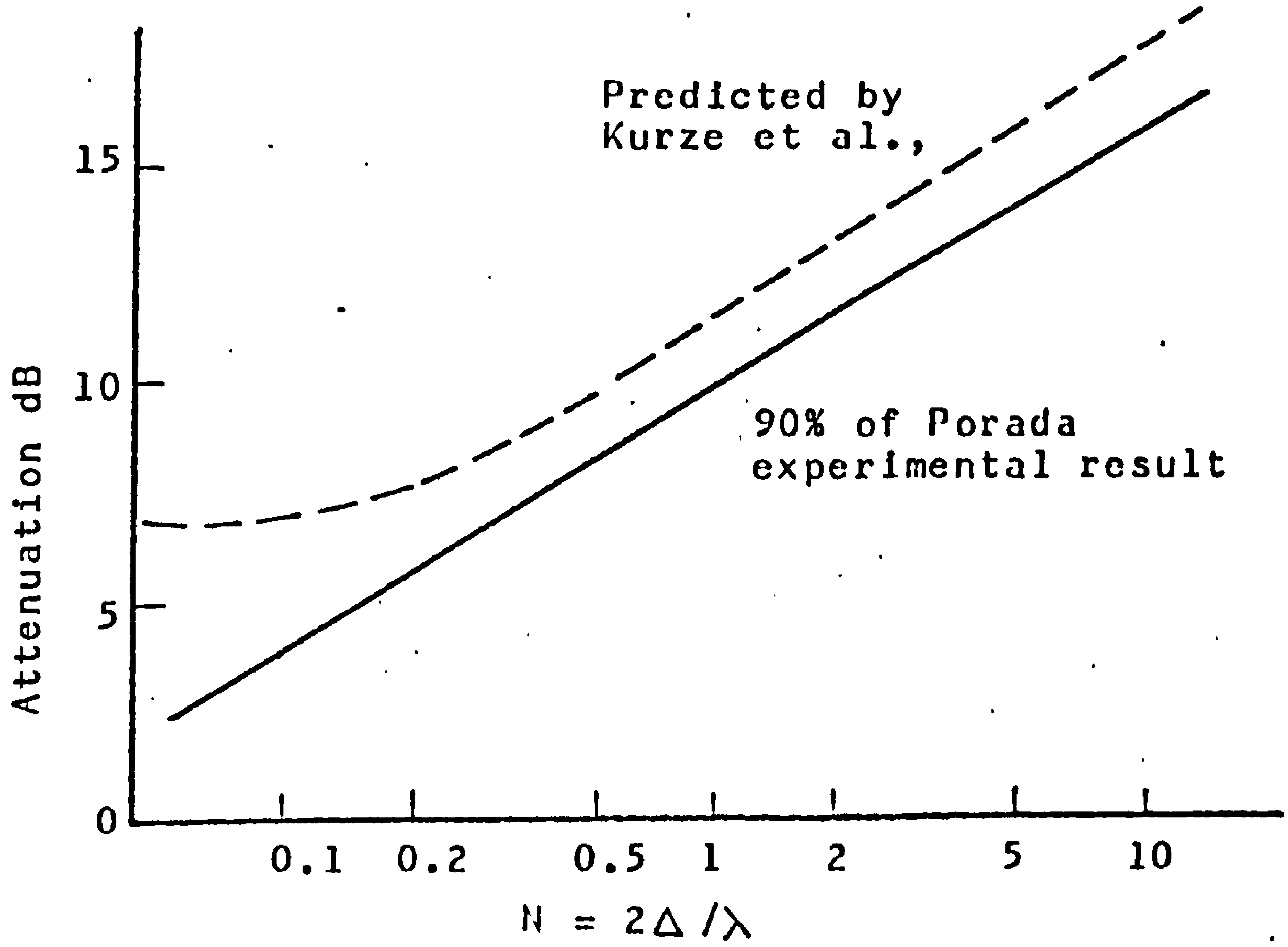


Fig. 5.8 N = 2Δ /λ



As before

Fig. 5.9

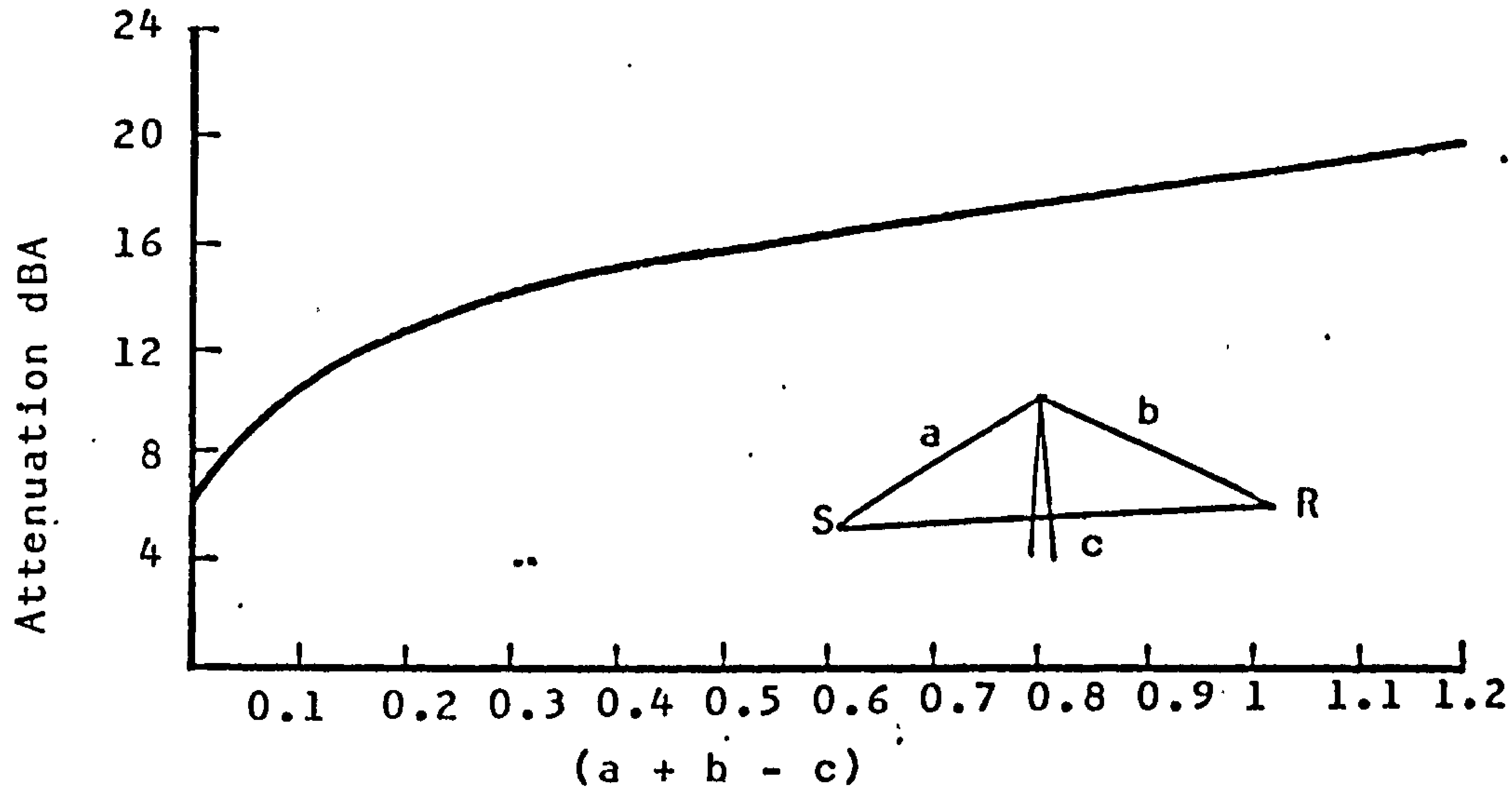


Fig.5.10 Reduction of road traffic noise L10 by a very long barrier.

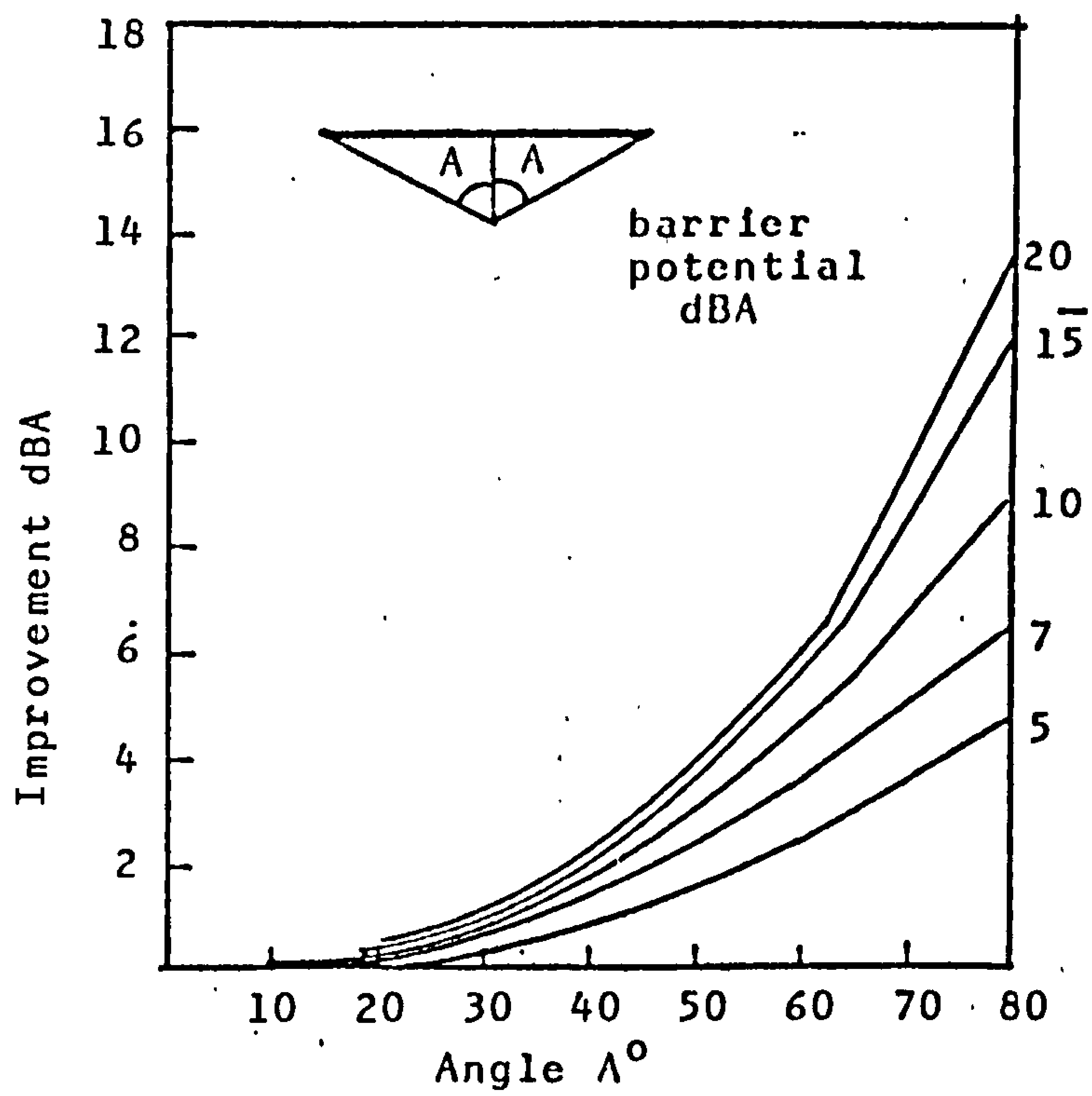
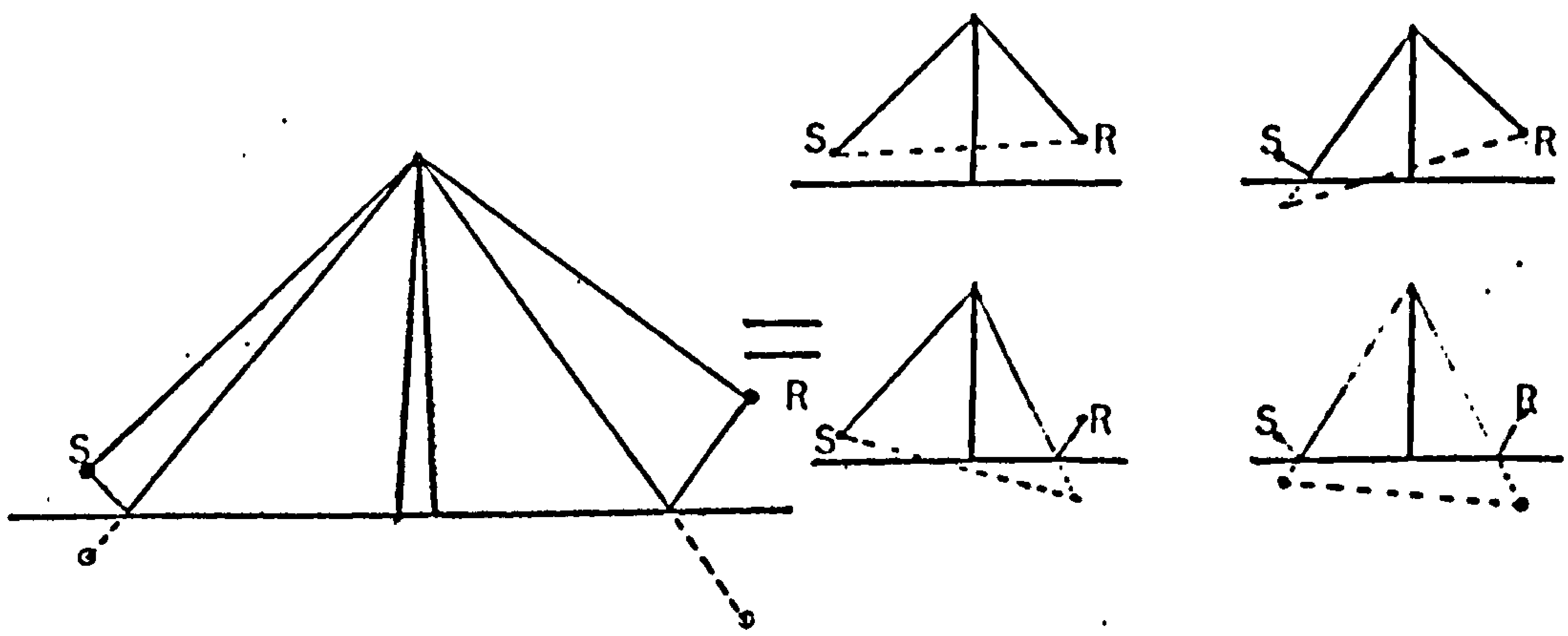
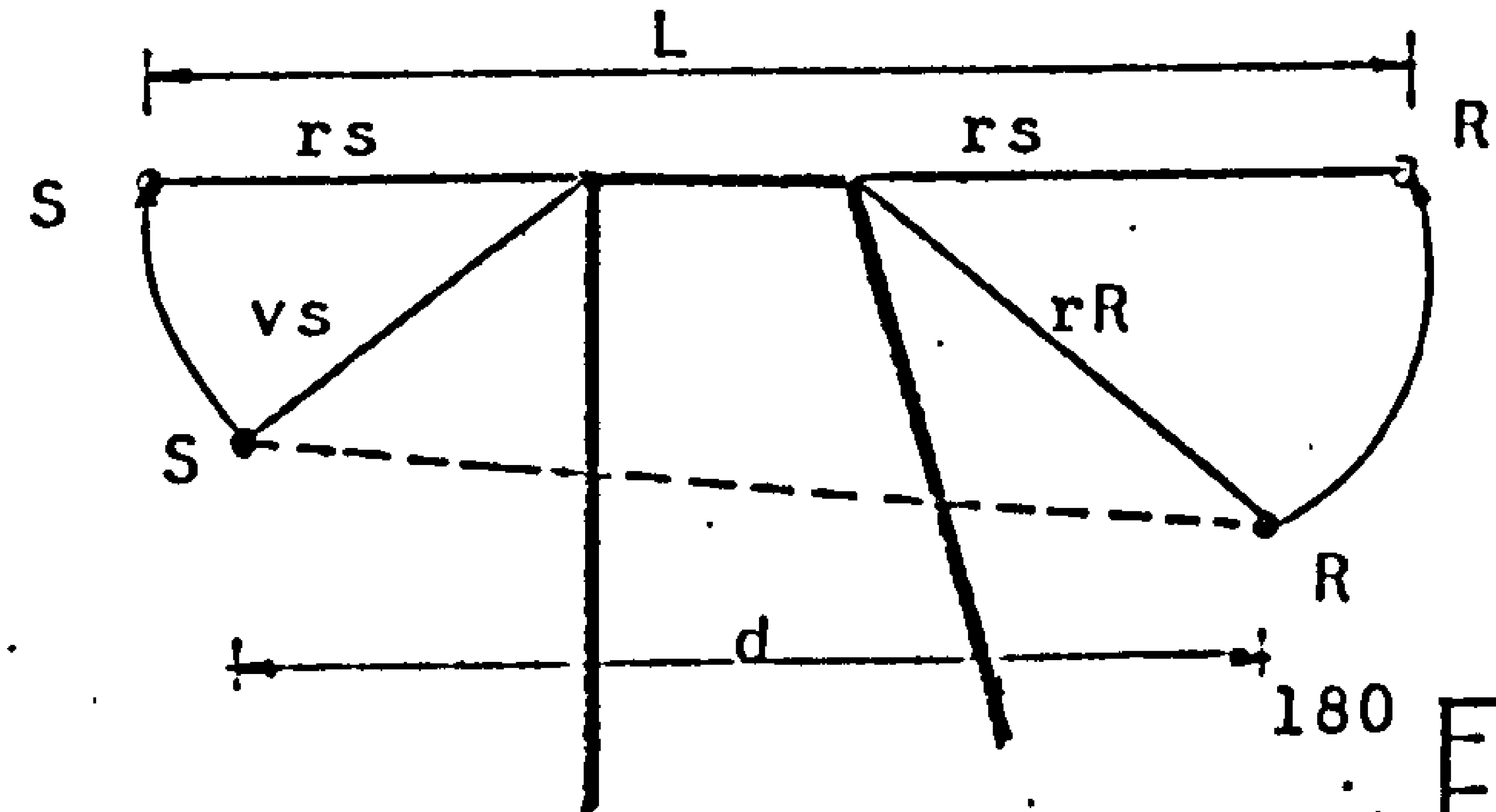


Fig.5.11 Free standing barrier symetrical partial screening.



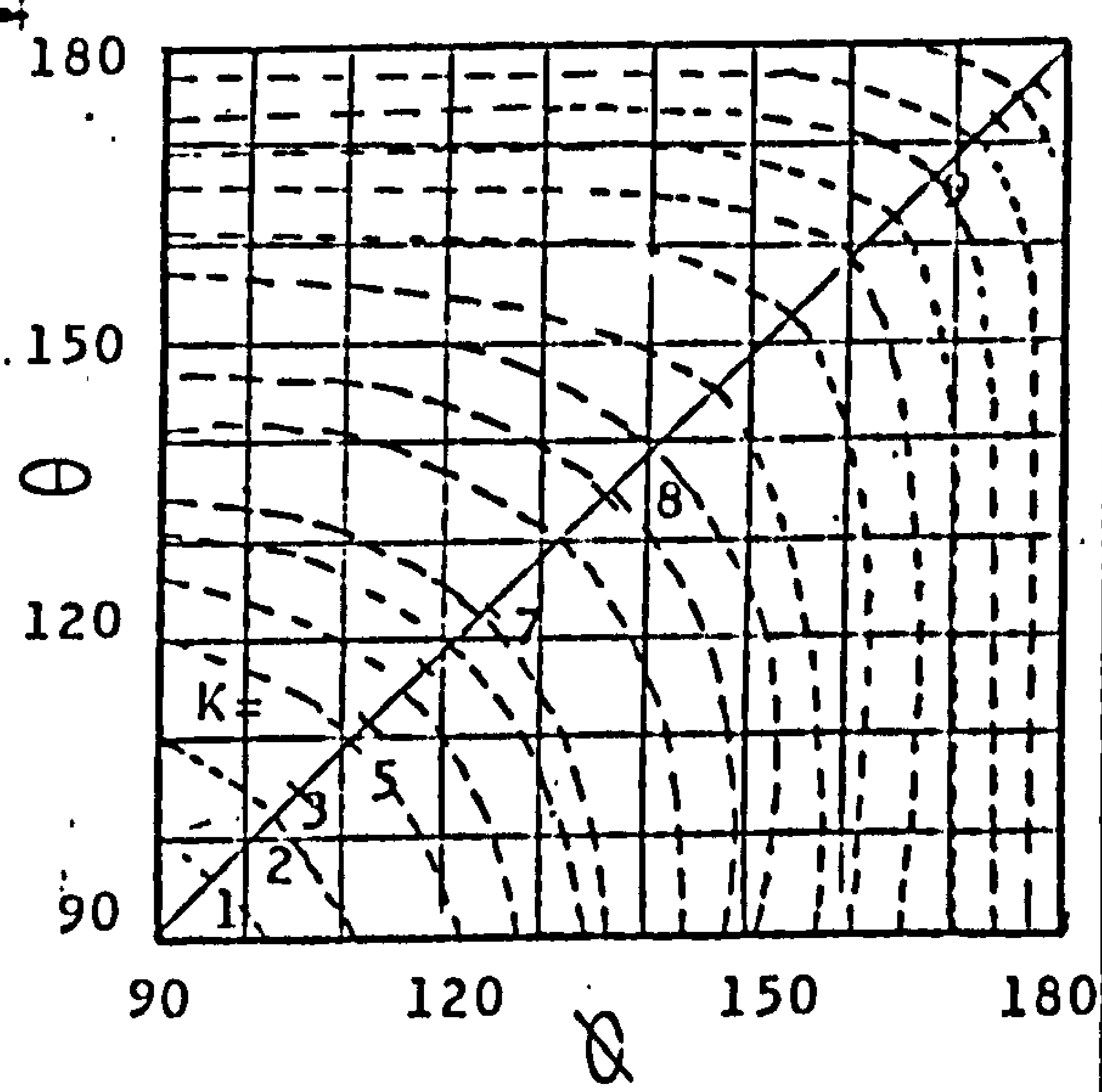
The different paths of different rays on a reflected ground.

Fig. 5.12



The geometry of a thick barrier.

Fig. 5.13



Values of the inclination lines

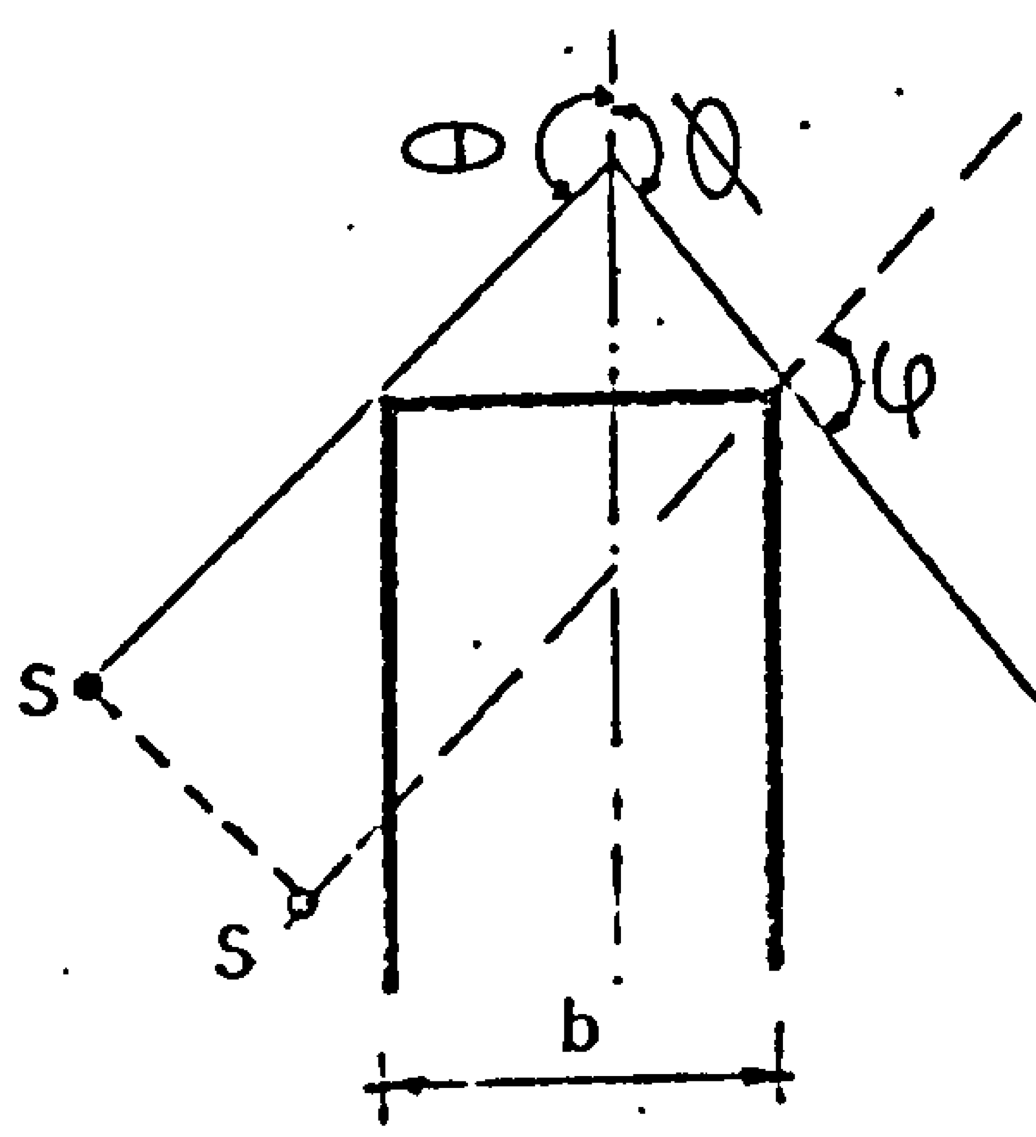


Fig. 5.14

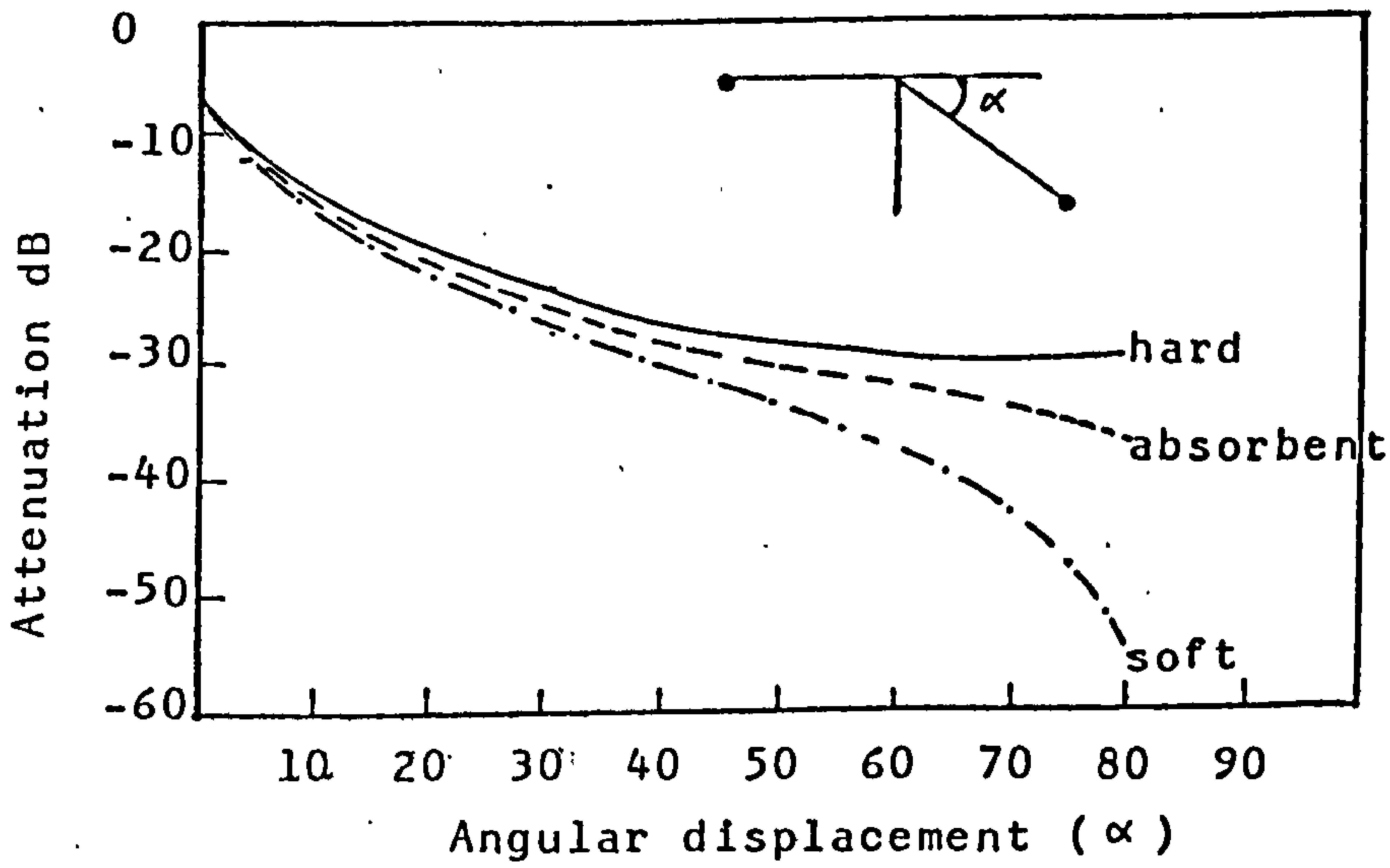


Fig.5.15 Attenuation of free standing semi-infinite barrier for hard, soft and absorptive boundary condition

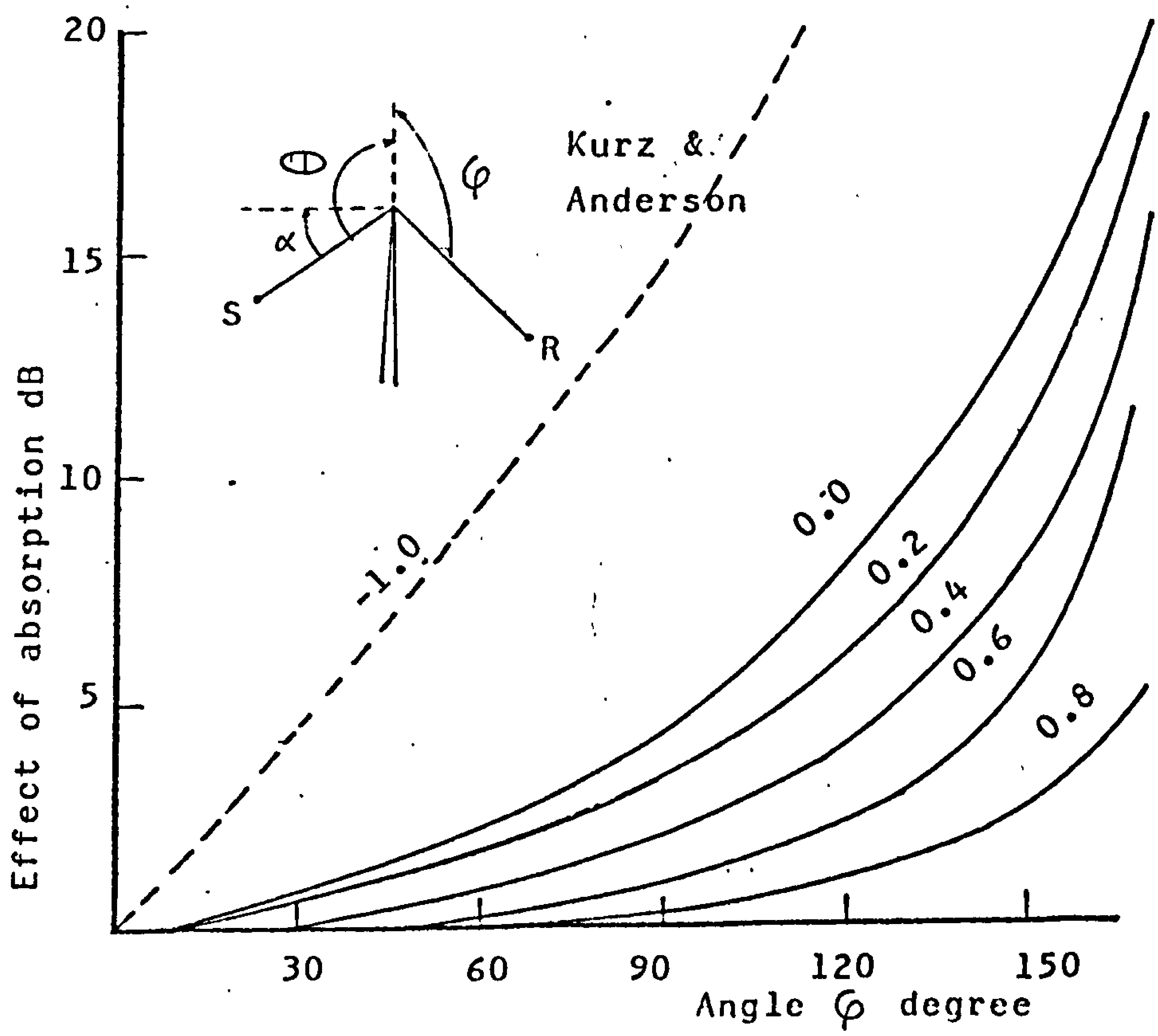


Fig. 5.16

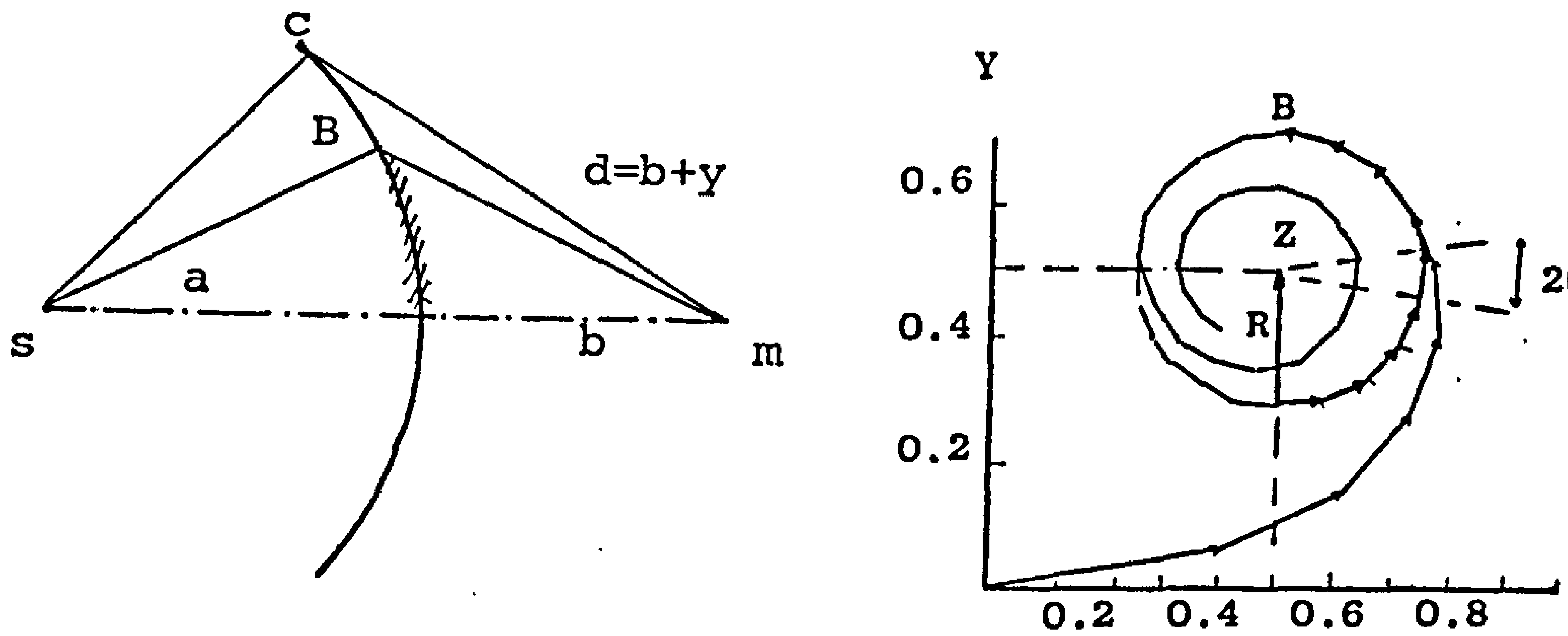


Fig. 5.17 Graduated attenuation of the first nine sub-zone vectors [24] Chapter 5.

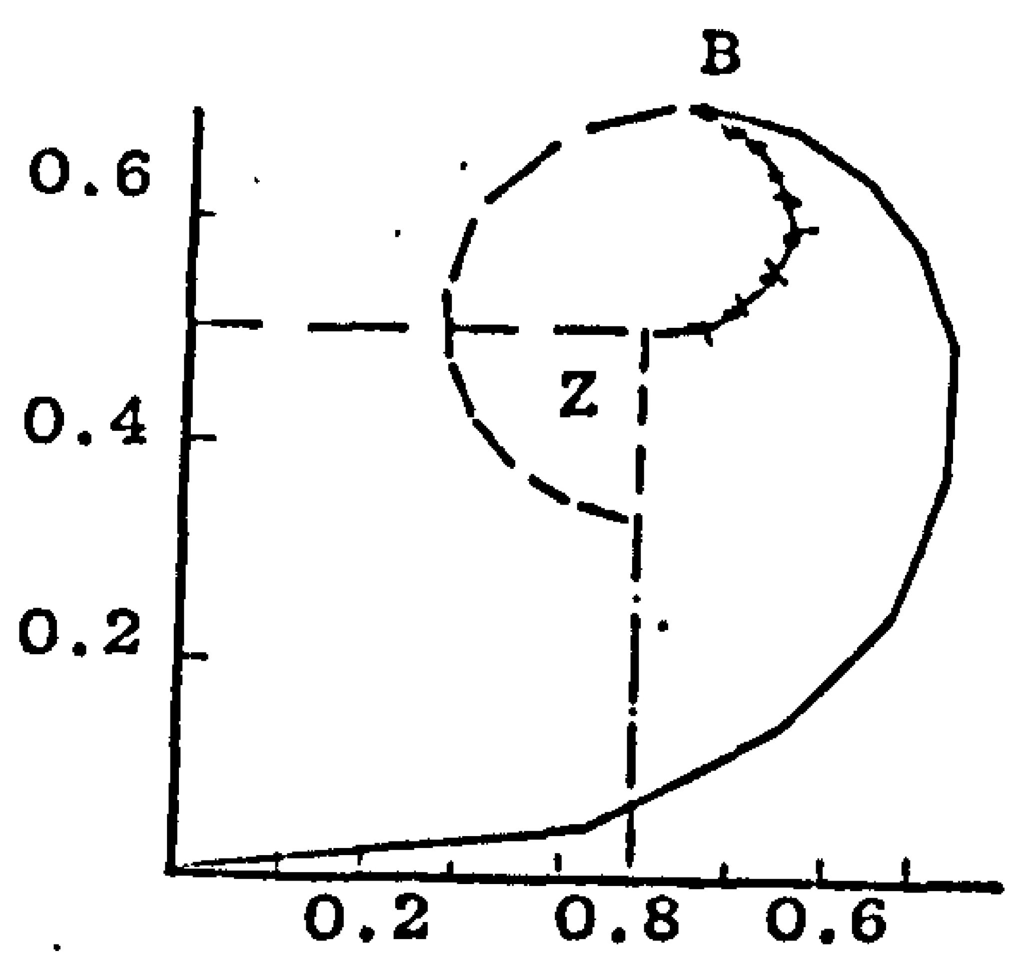


Fig. 5.18 Example of the use of graduated attenuation of the first nine-zone vectors to generate a perfect shadow.

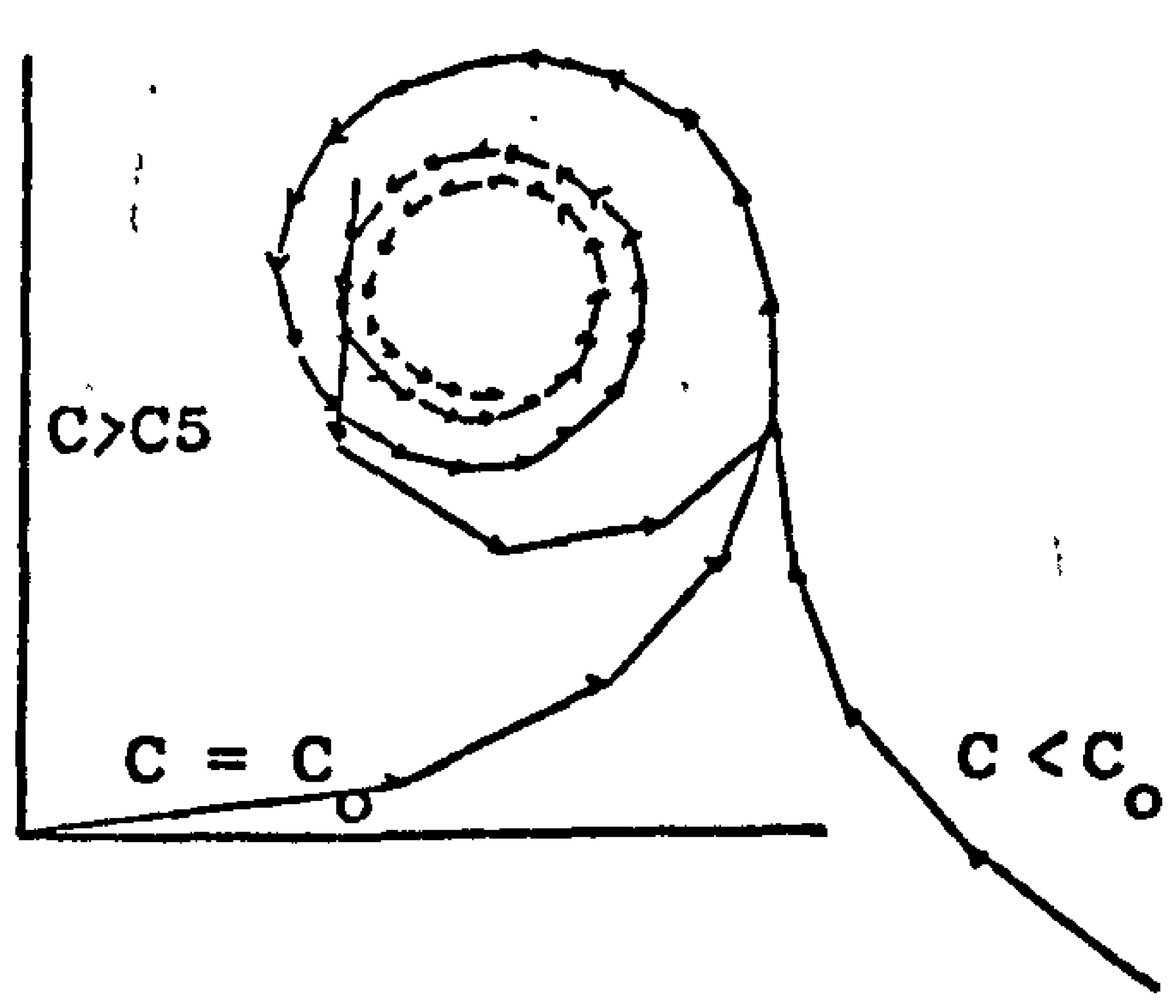


Fig. 5.19 The effect of phase advancement and retardation.

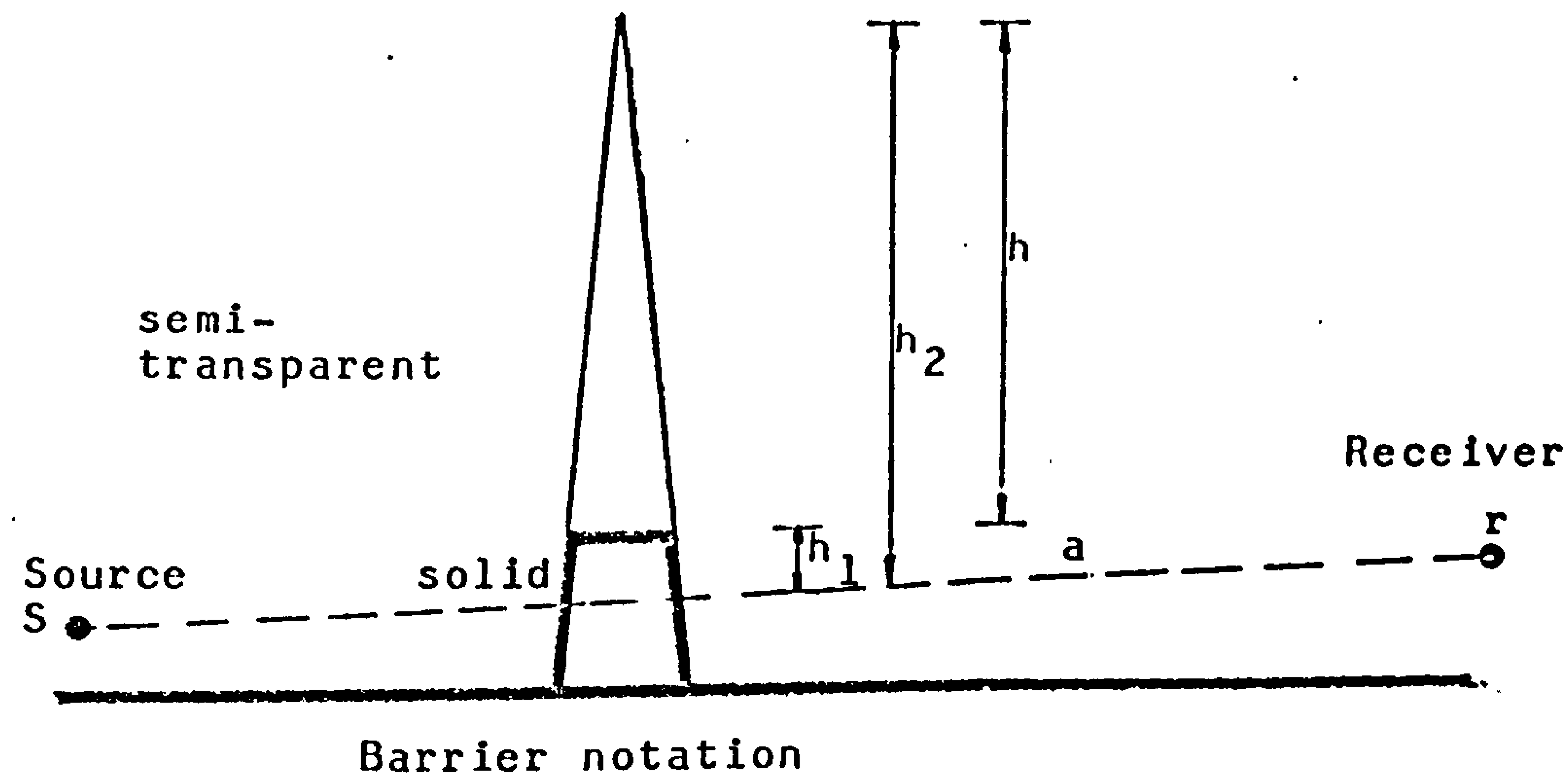


Fig. 5.20

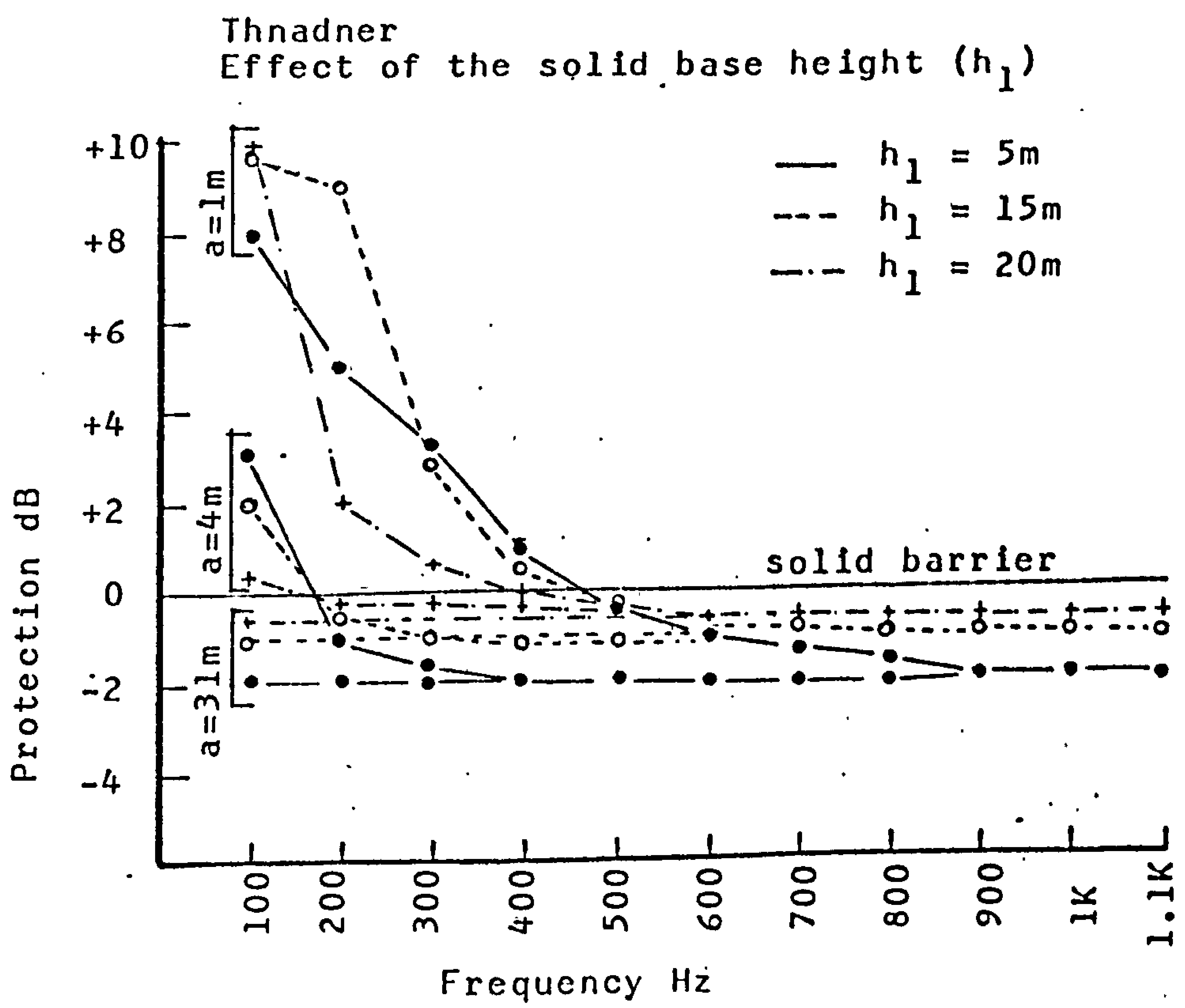


Fig. 5.21

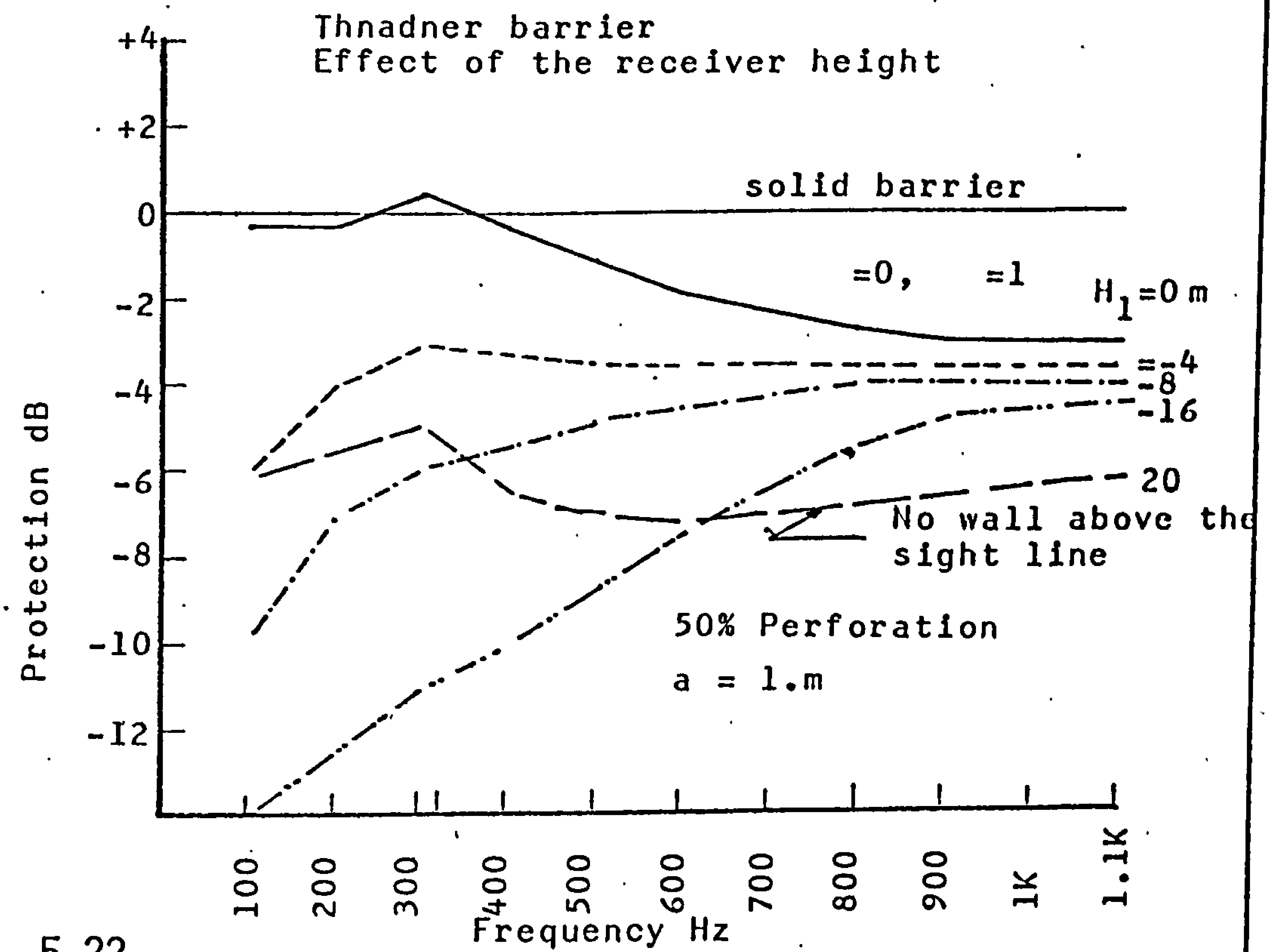
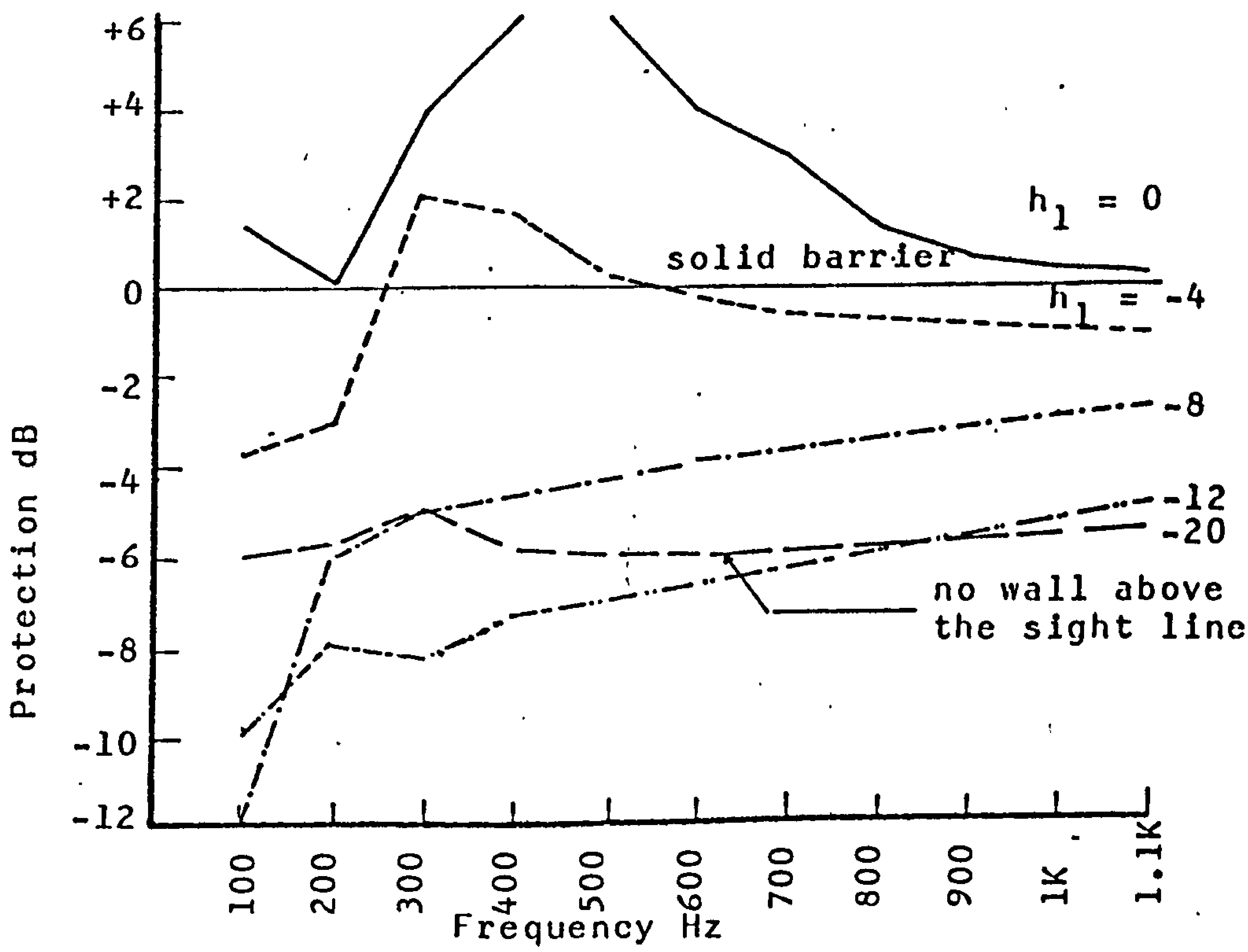
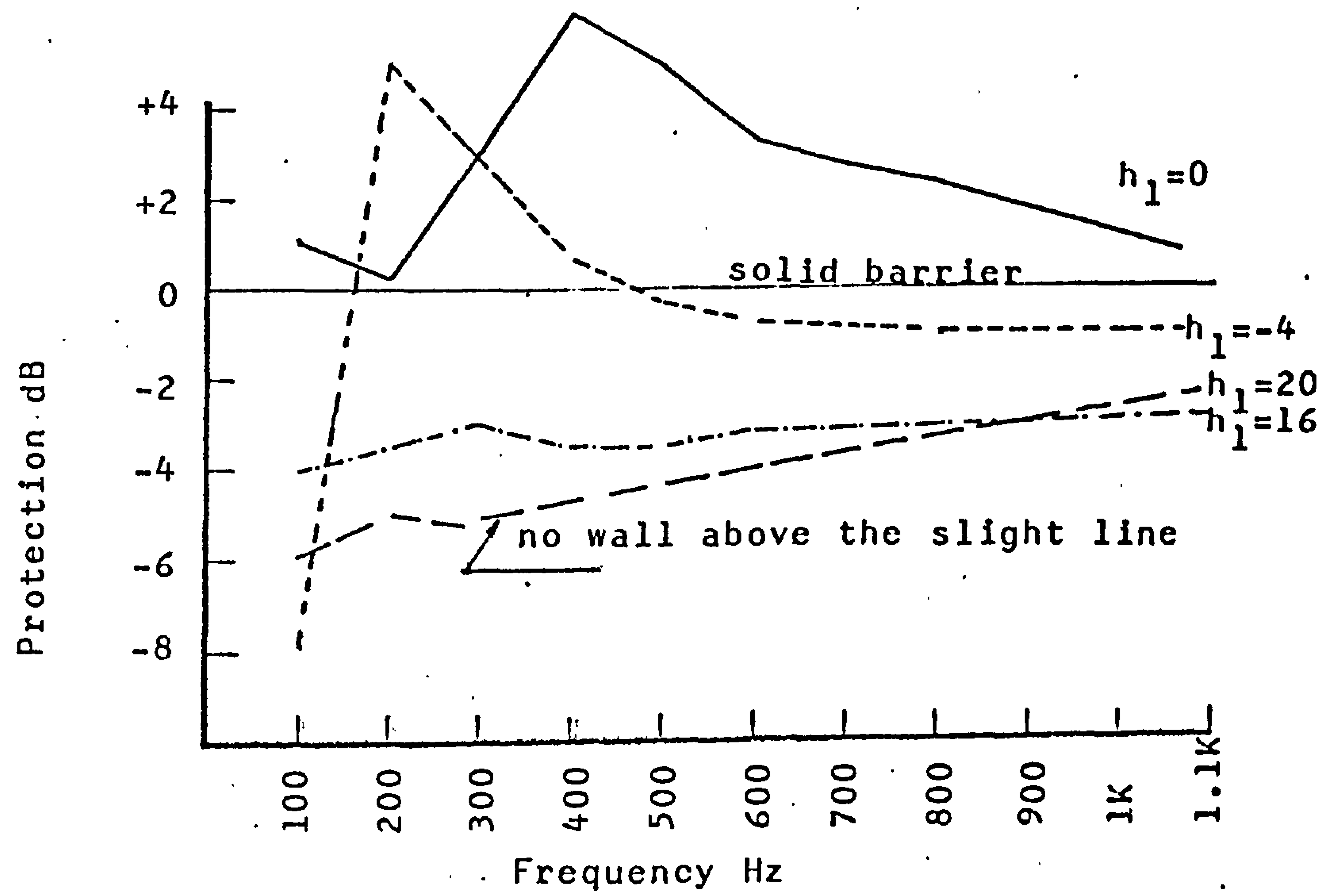


Fig. 5.22



As above with 25% perforation

Fig. 5.23



As before with 12.5% perforation

Fig. 5.24

Thnadner barrier
Effect of percentage perforation
200Hz

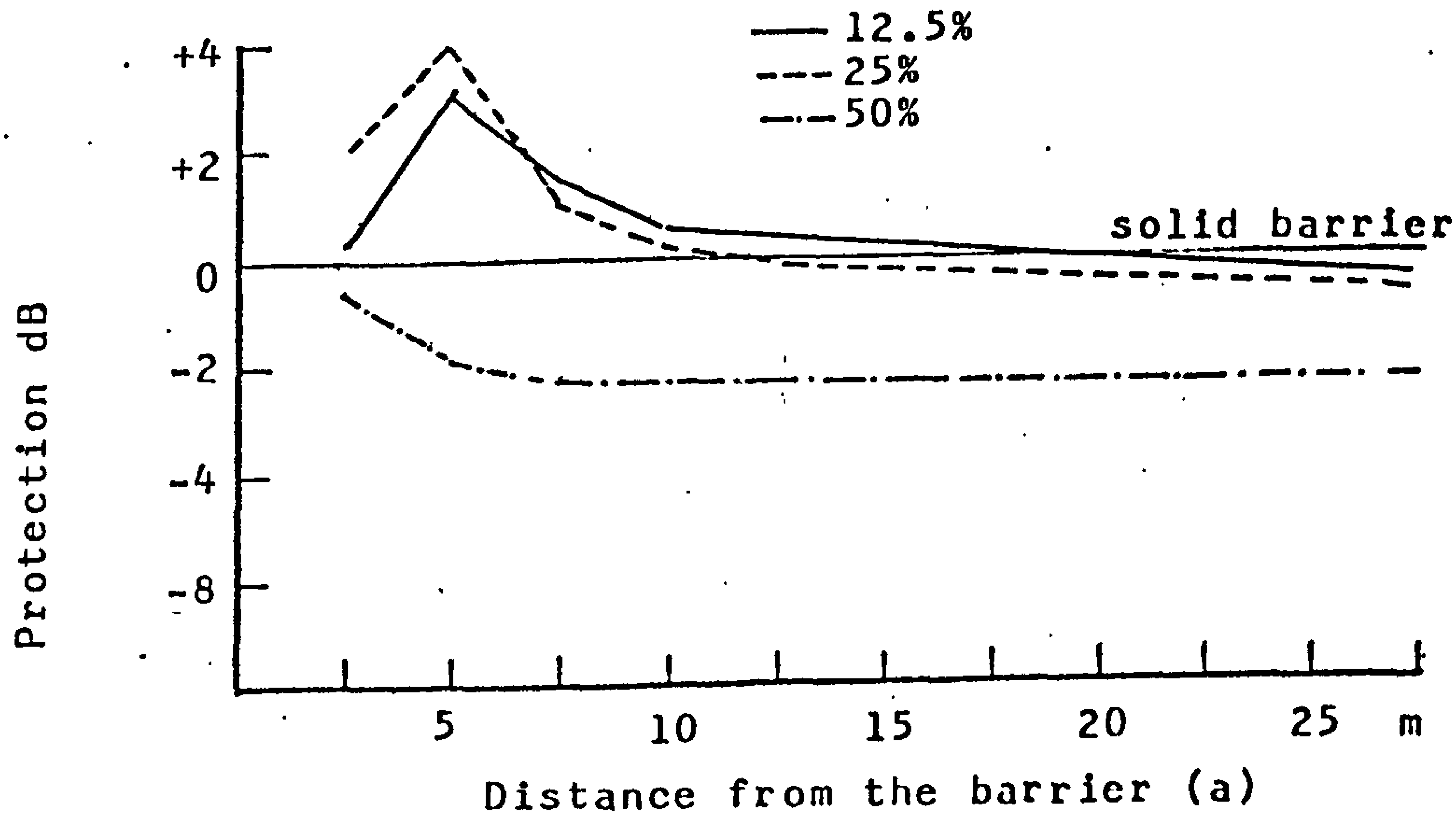


Fig. 5.25

Effect of percentage perforation
400Hz

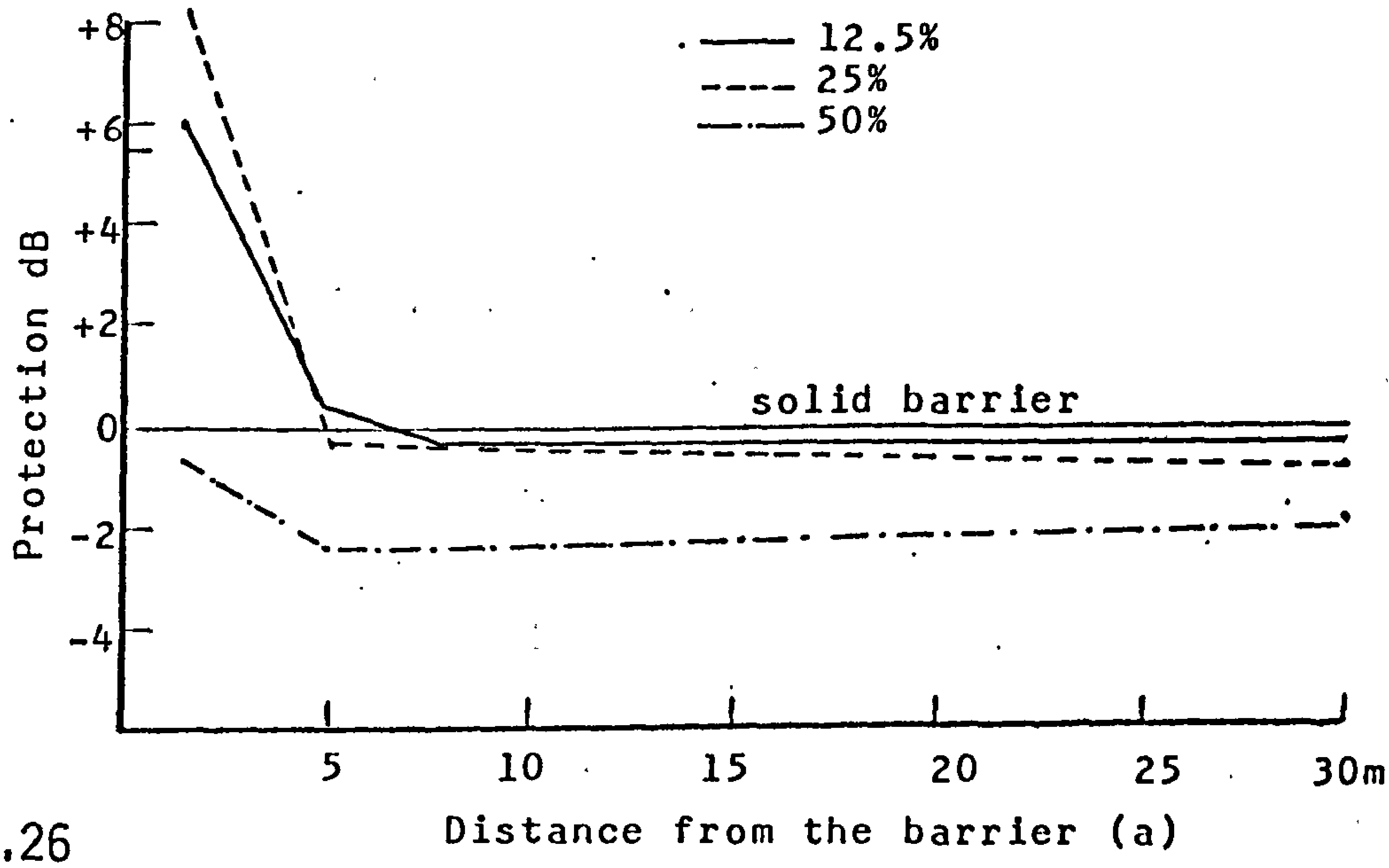
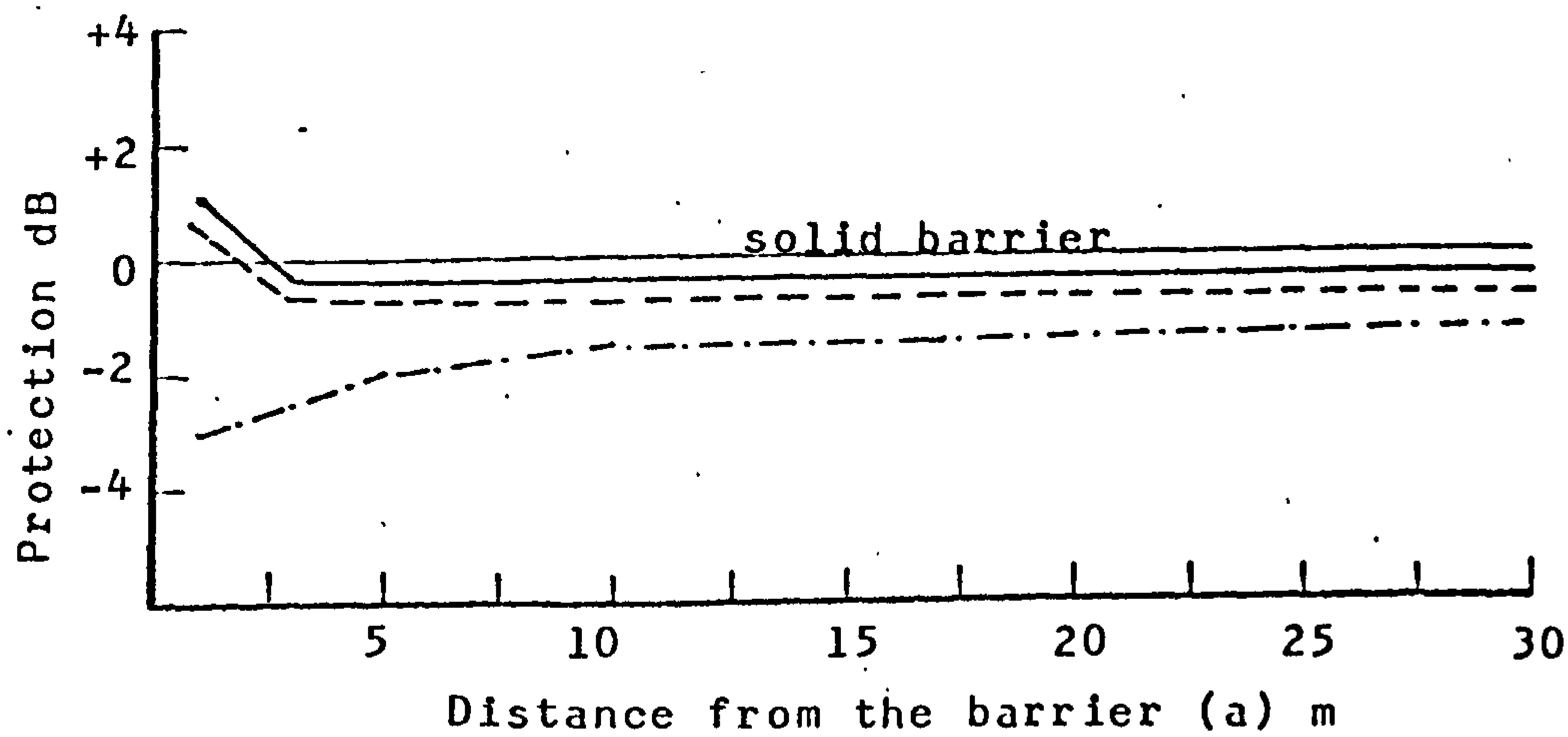


Fig. 5.26



As above for 1KHz

Fig. 5.27

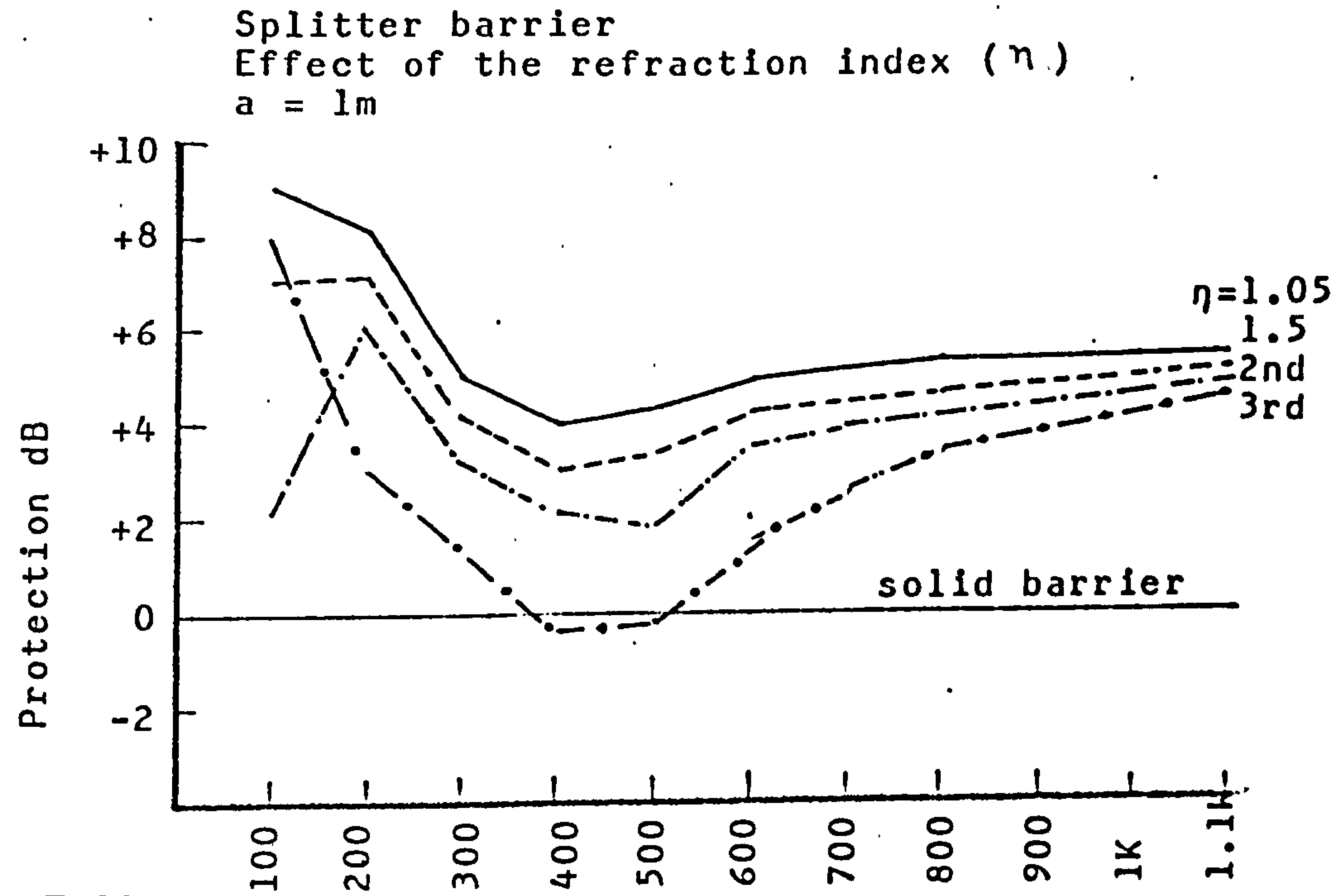


Fig. 5.28

As above with a = 31m

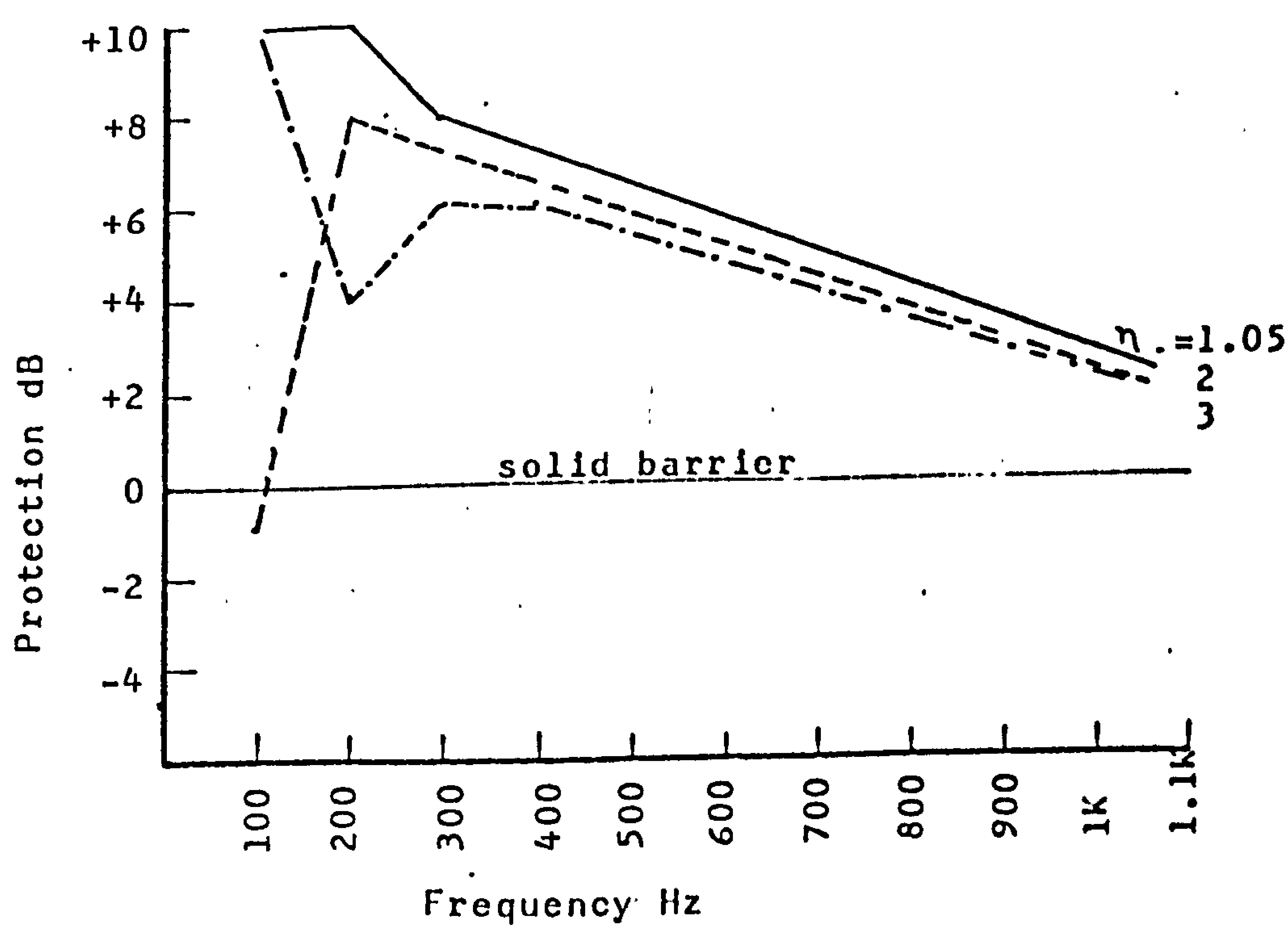


Fig. 5.29

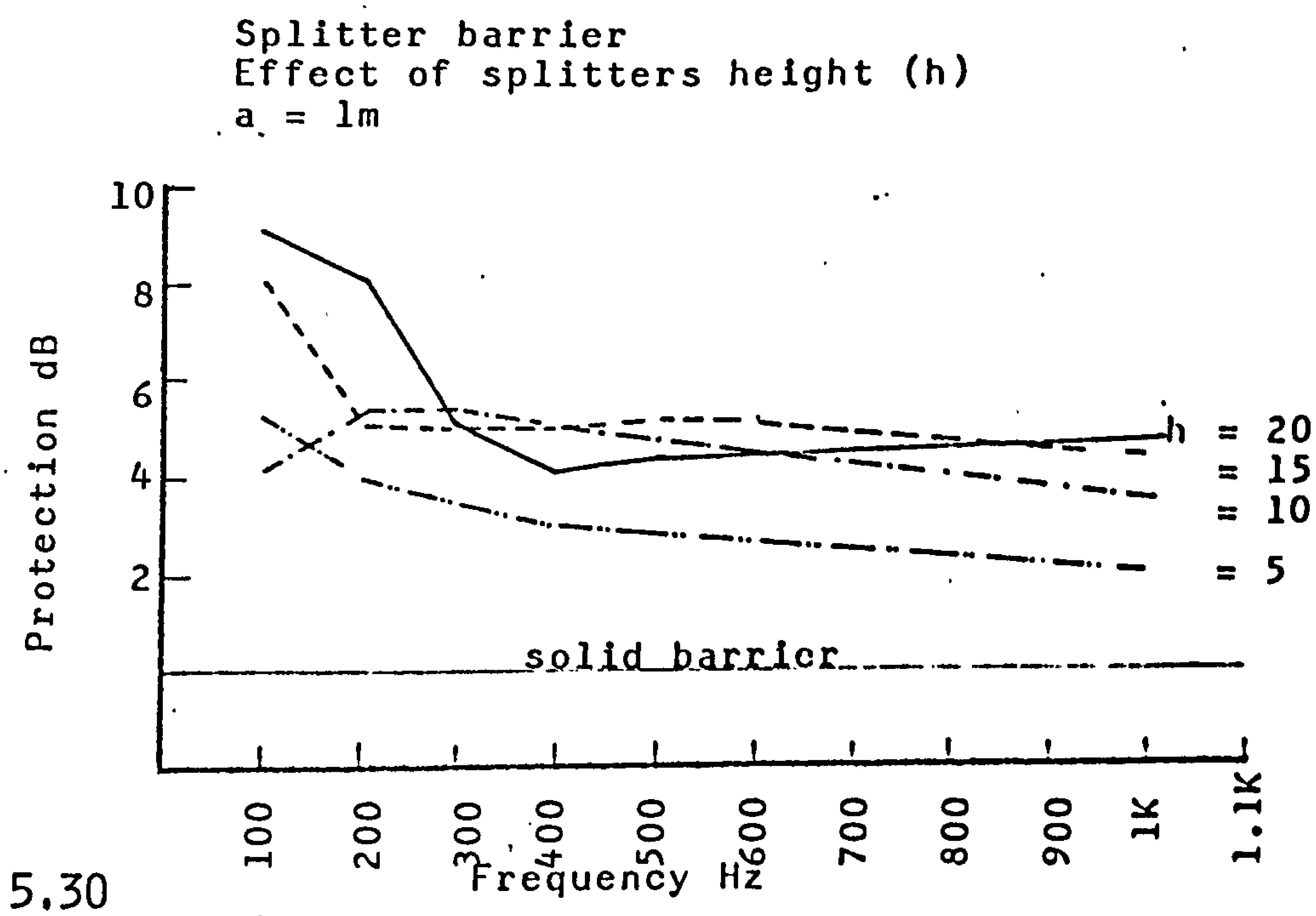
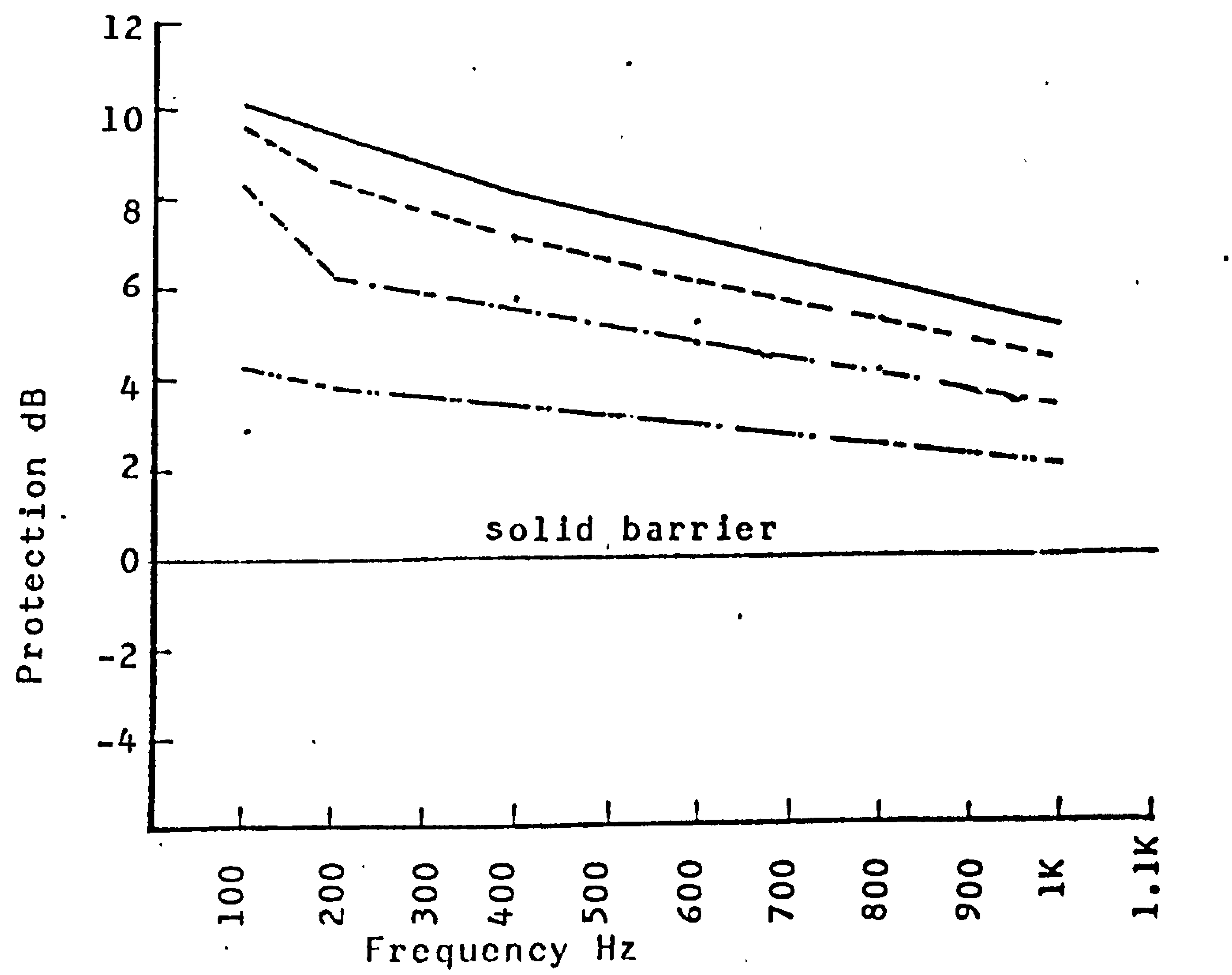
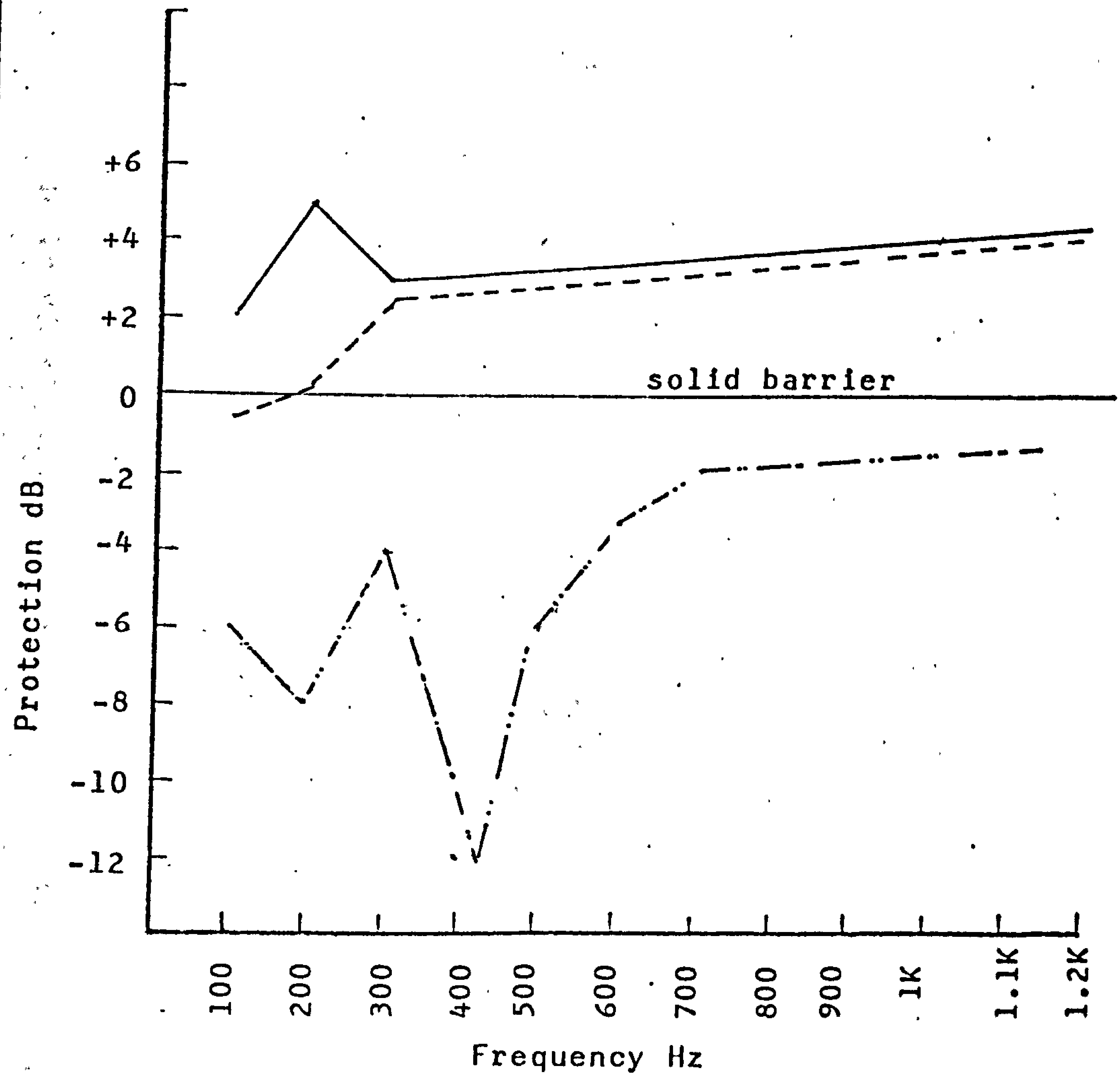


Fig. 5.30



As above with a = 31m

Fig. 5.31



Splitter barrier
Effect of receiver height

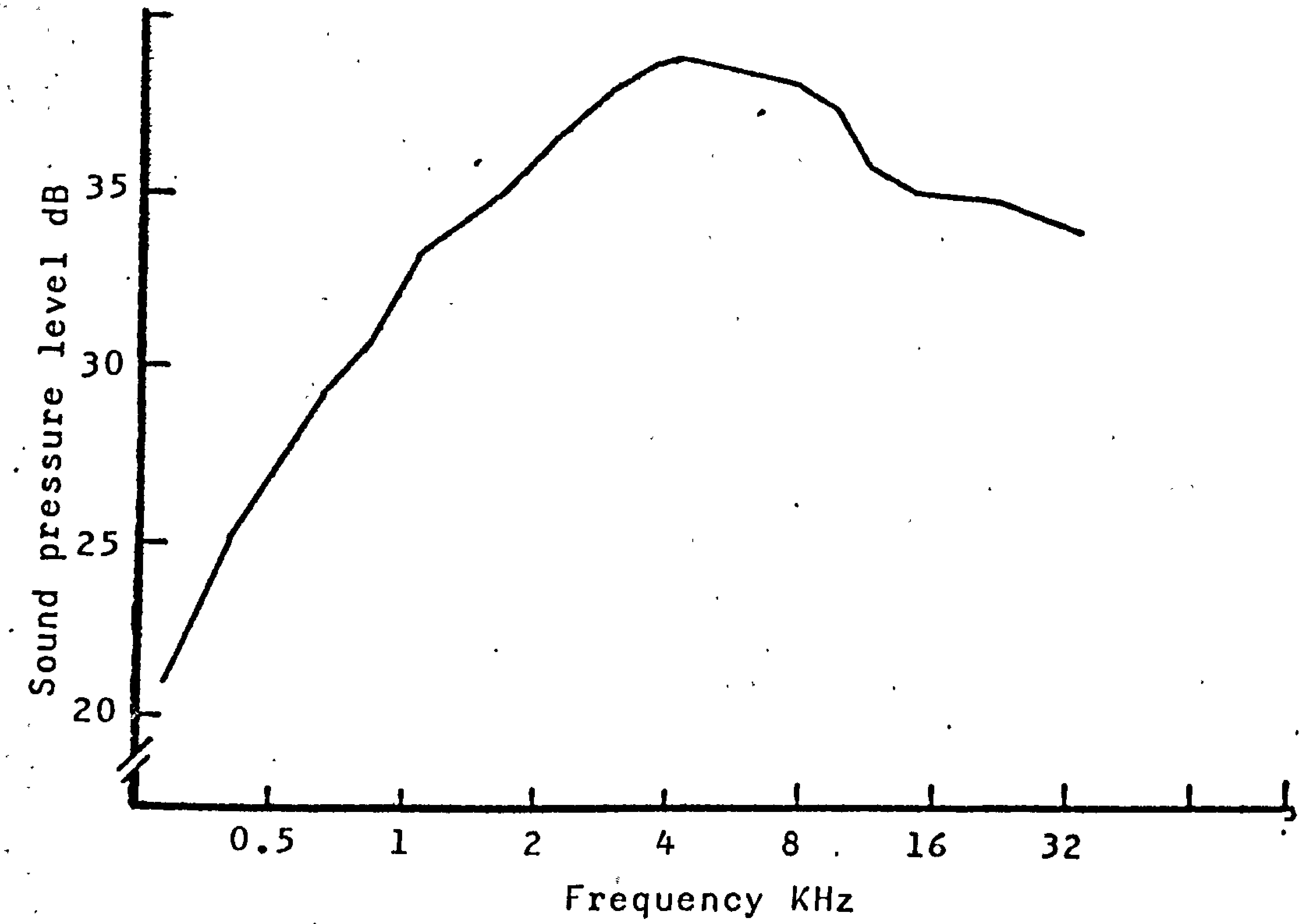
—— h_1 = -4

- - - h_1 = -8

—·— h_1 = -20 (no barrier above the sight line)

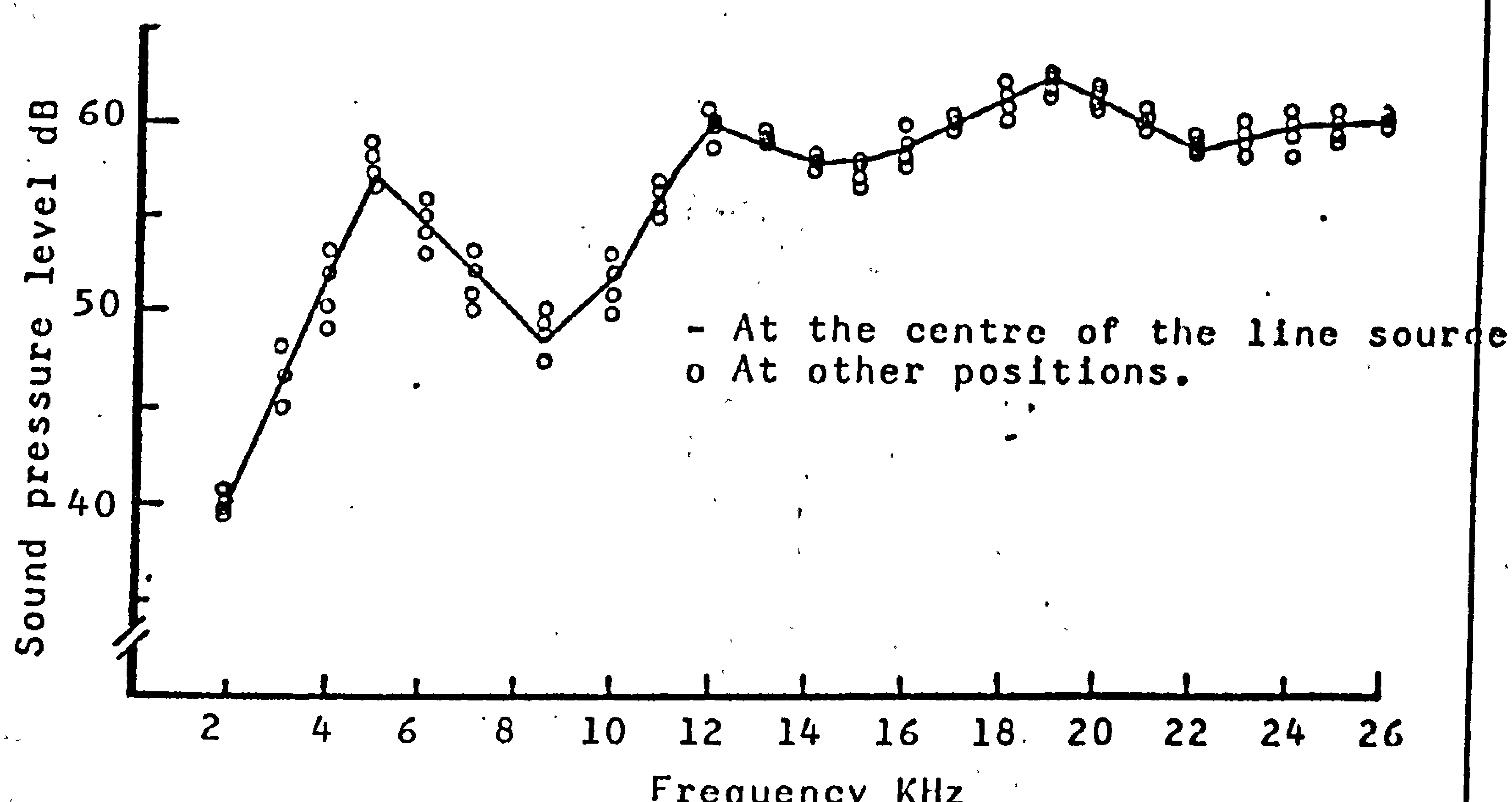
a = 1m

Fig. 5.32



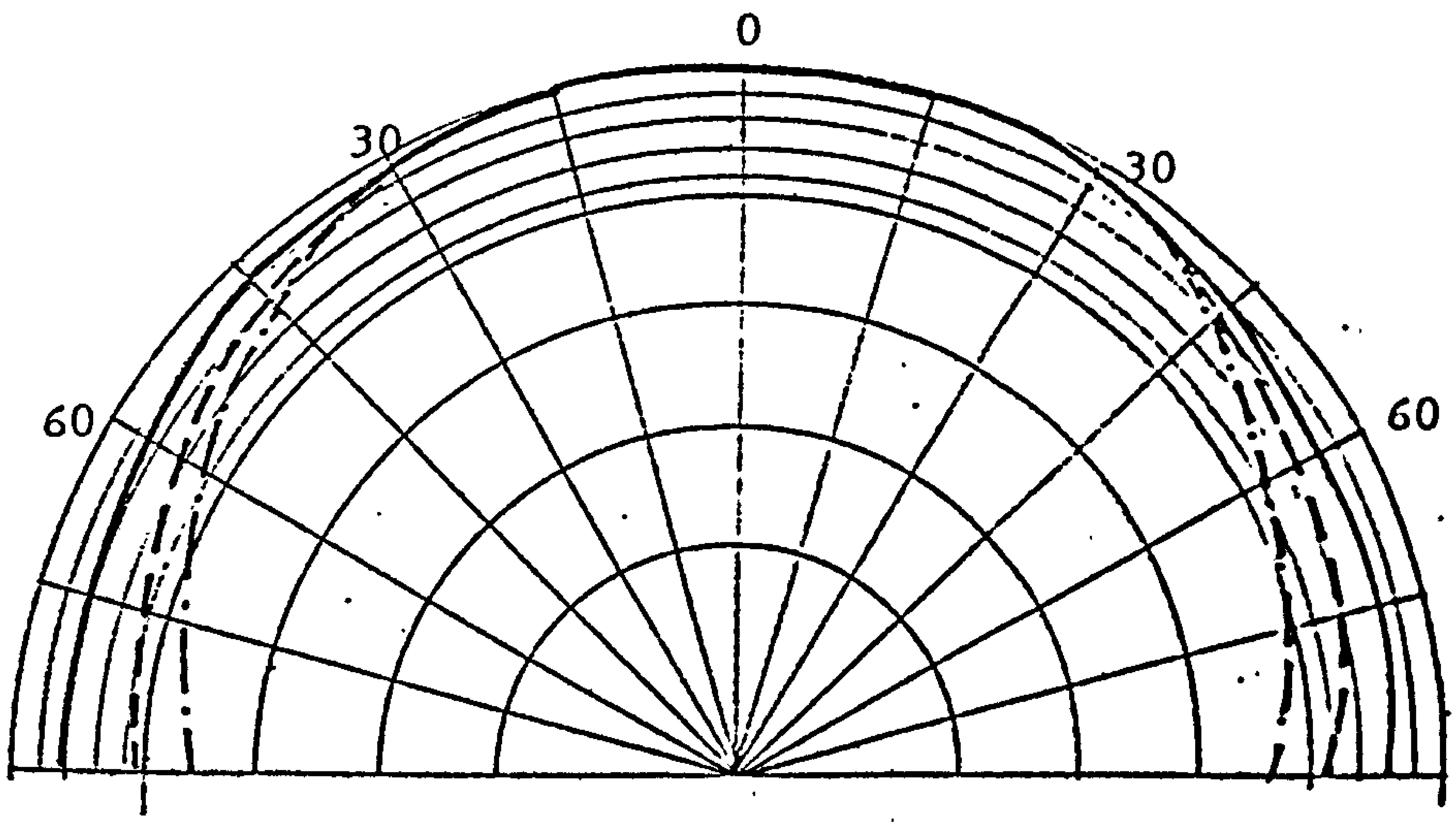
Frequency spectrum of Porada Line Source.

Fig. 6.1



Frequency spectrum of the author line source

Fig. 6.2

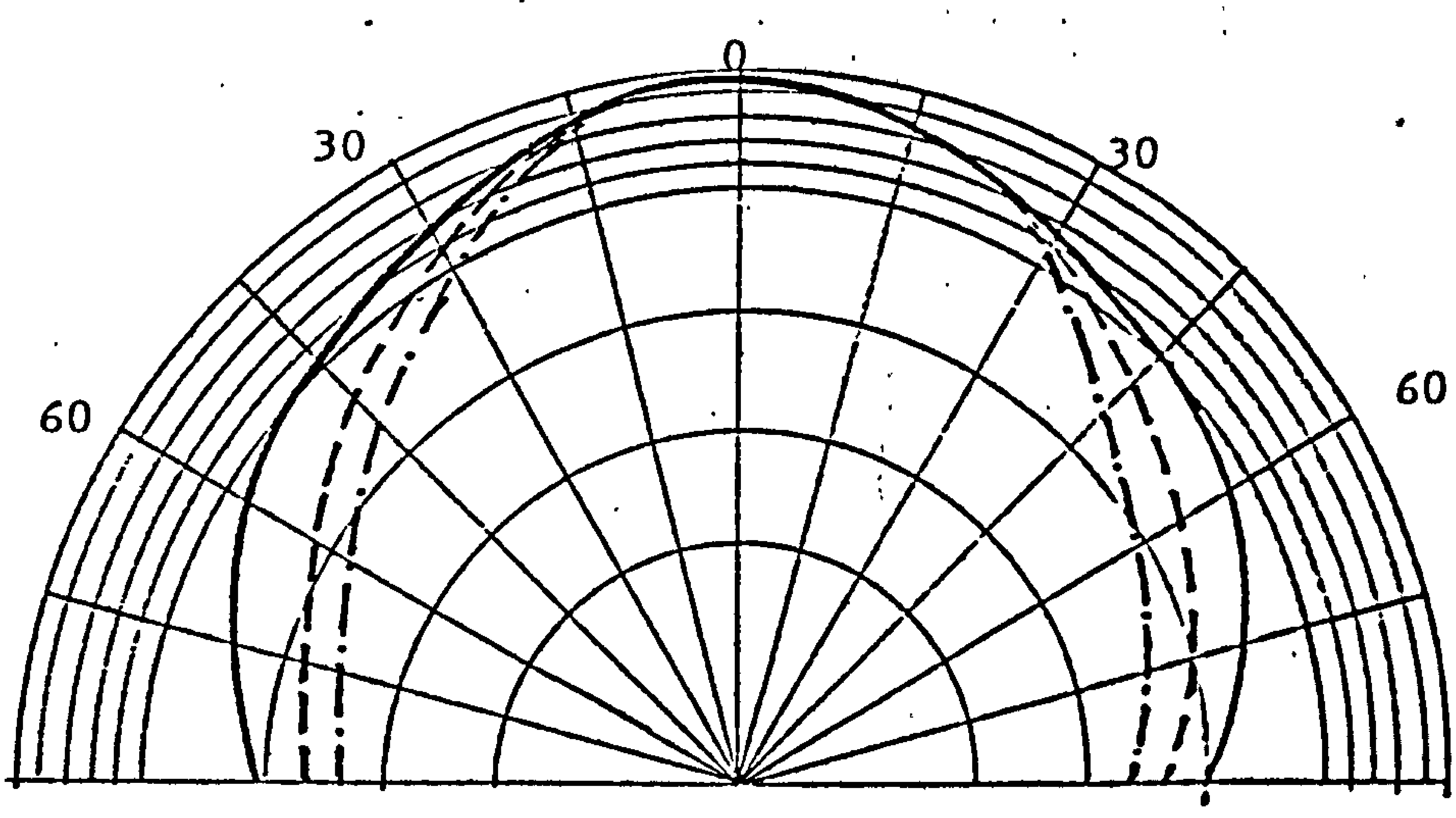


—— 2 KHz

- - - 4 KHz

—·— 6 KHz

The Directional Characteristic of the Line Source



—— 10 KHz

- - - 12 KHz

—·— 25 KHz

Fig. 6.3

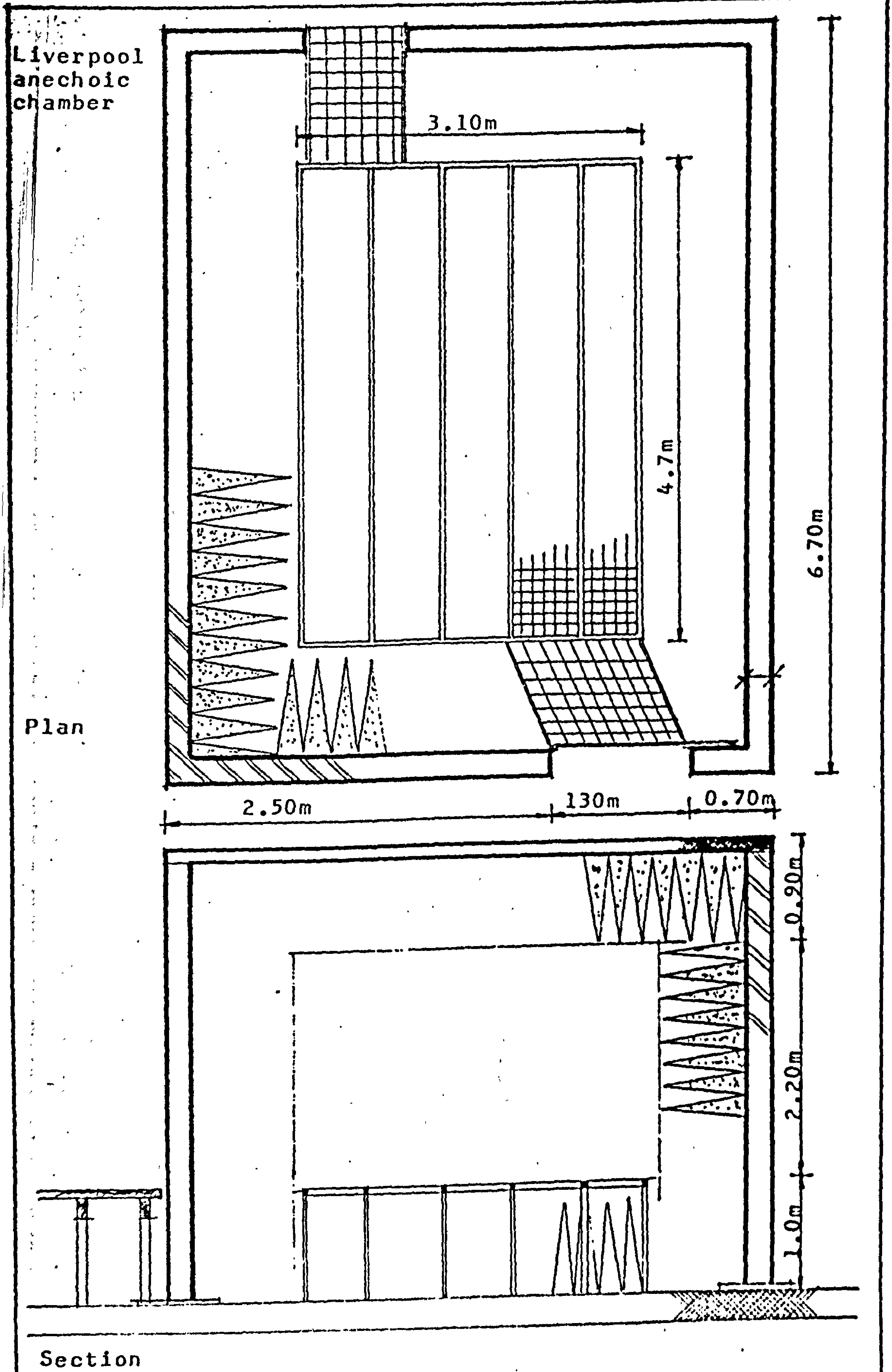
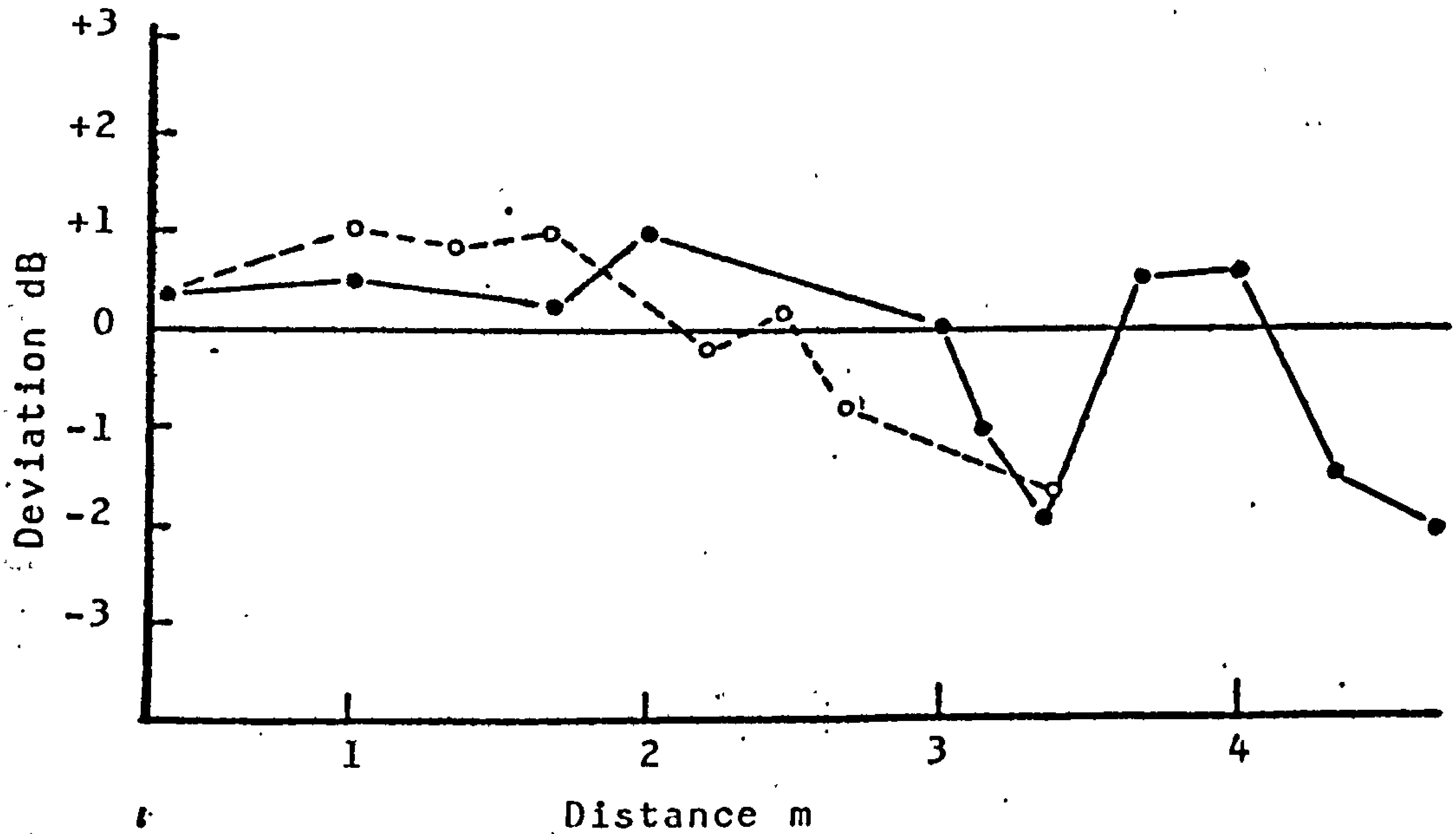
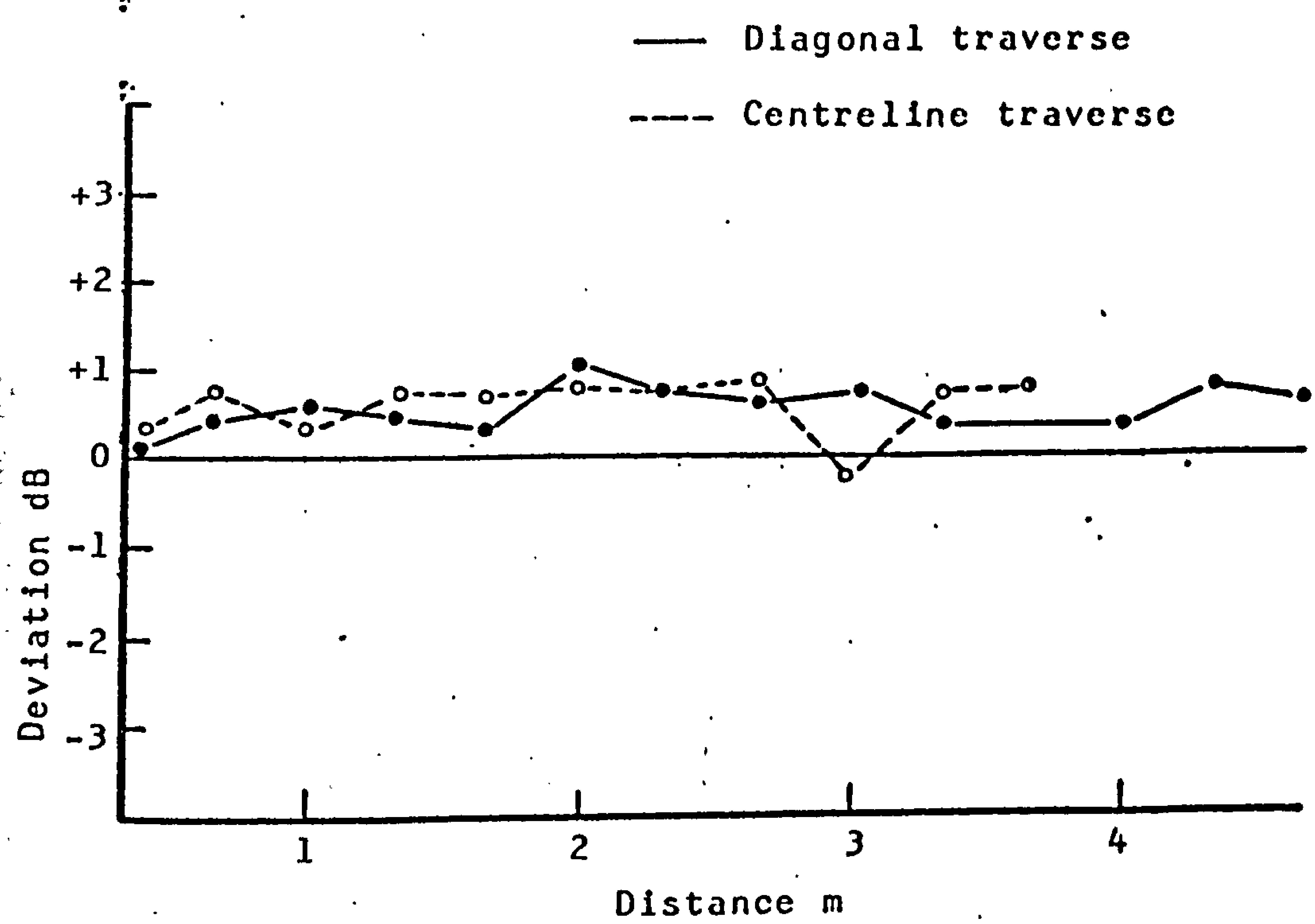

Liverpool
anechoic
chamber
3.10m
4.7m
6.70m
Plan
2.50m
130m
0.70m
0.90m
2.20m
1.0m
Section

Fig. 6.4

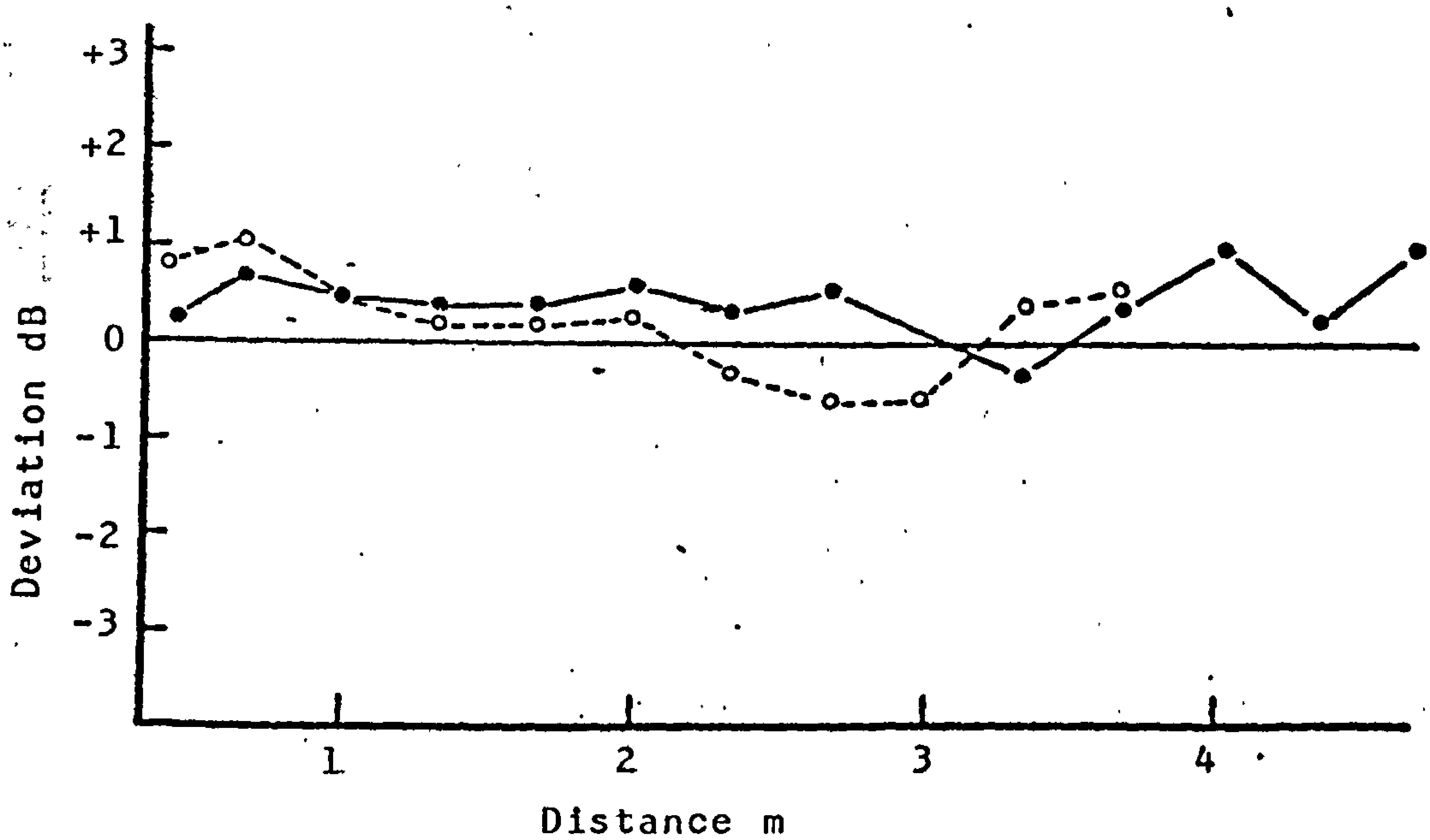
The deviation from the inverse - square law at 100Hz.



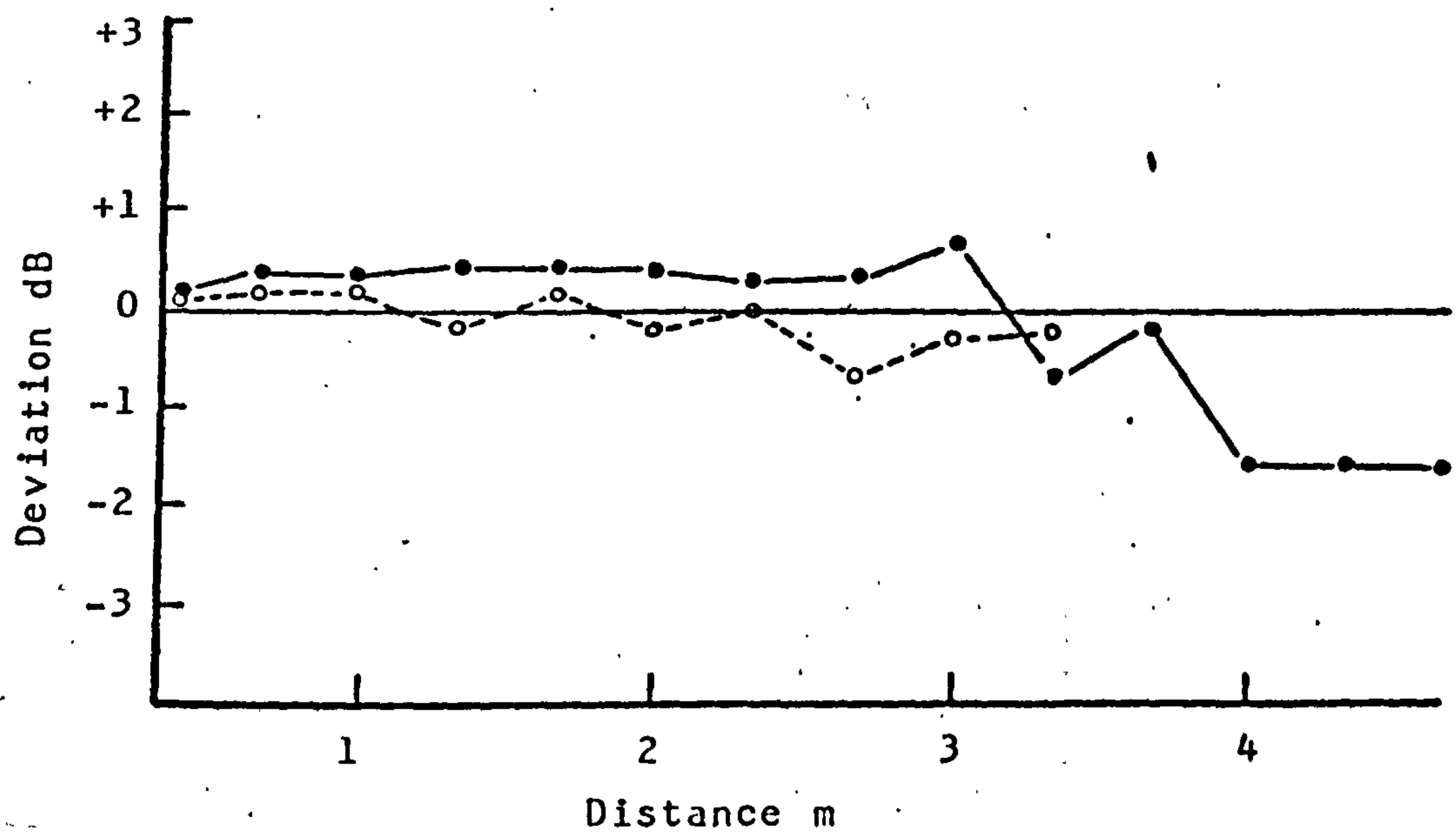


As above, at 250Hz.

Fig. 6.5

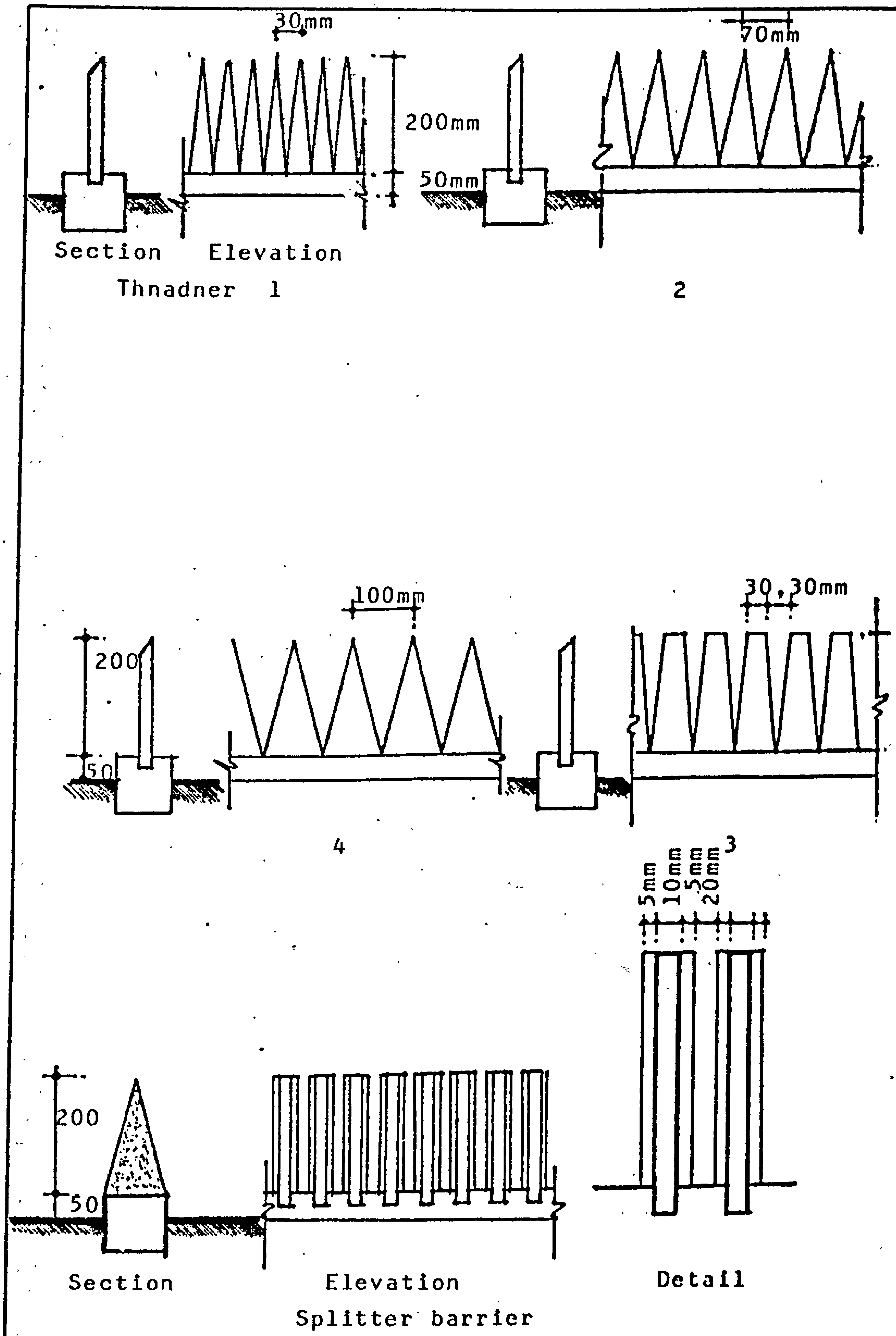


As before at 500Hz.



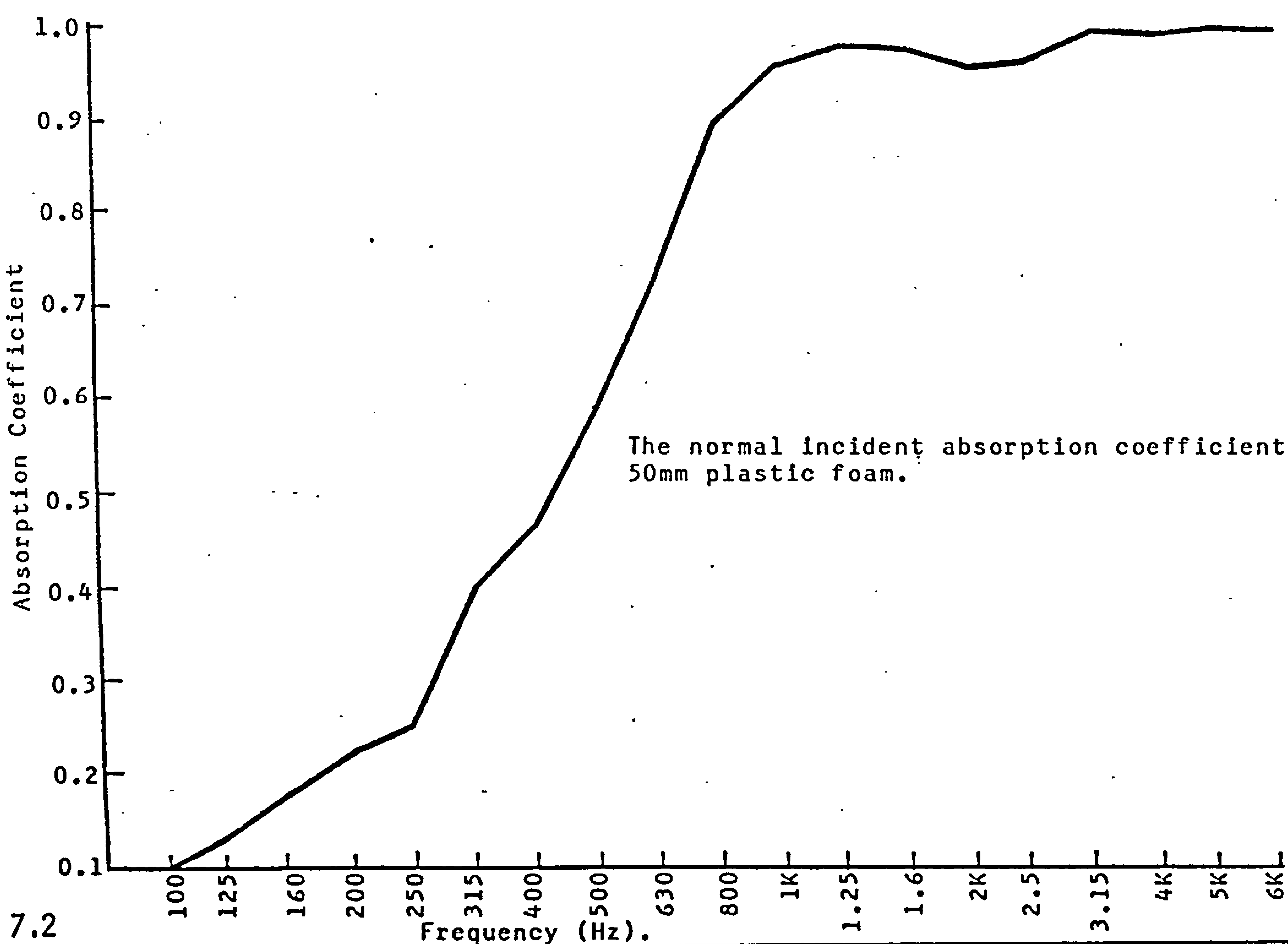
As before at 8KHz.

Fig. 6.6



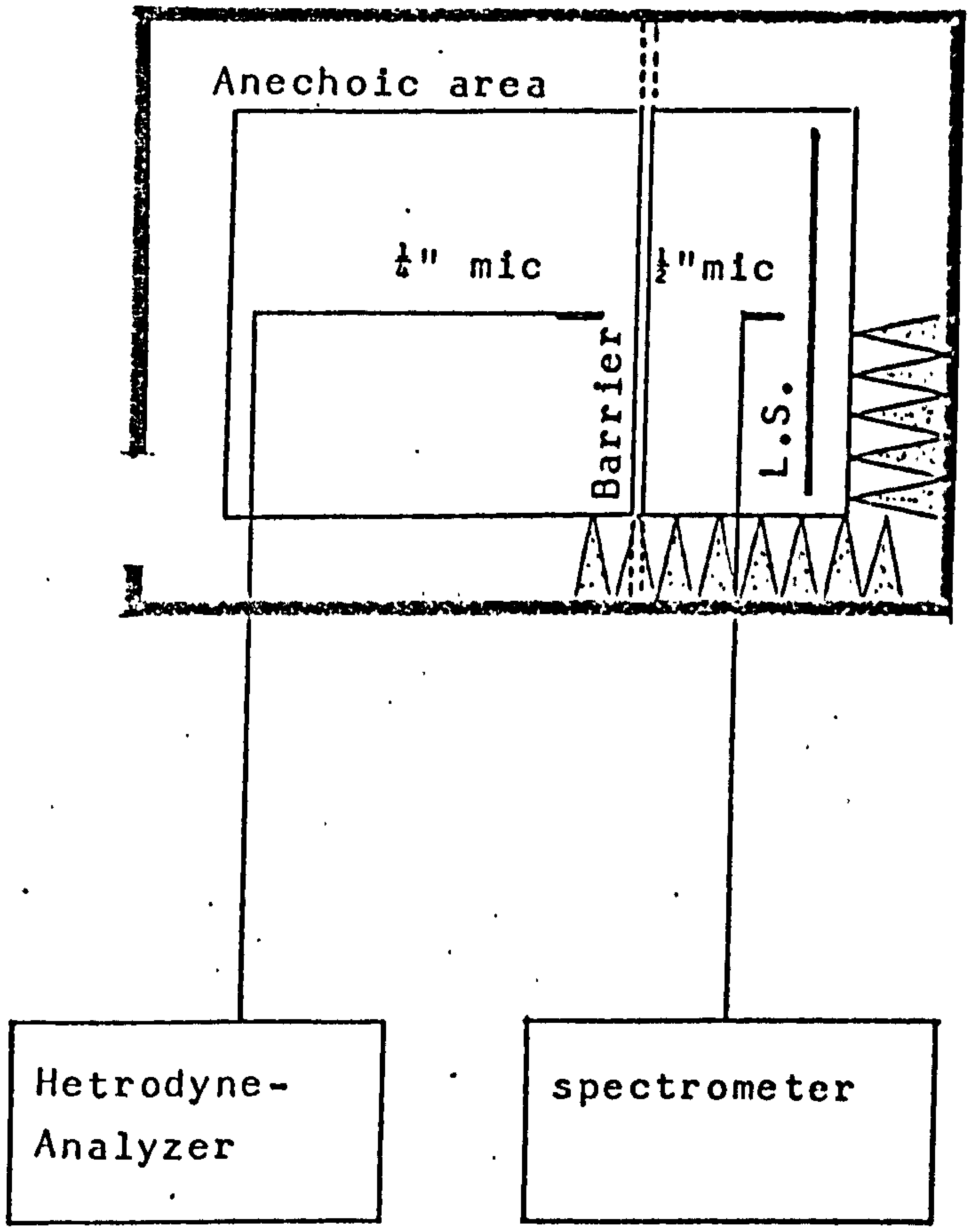
Dimensions of model barriers.

Fig. 7.1



The normal incident absorption coefficient of 50mm plastic foam.

Fig. 7.2



Model measurement of free standing barrier.
The experimental layout.

Fig. 7.3

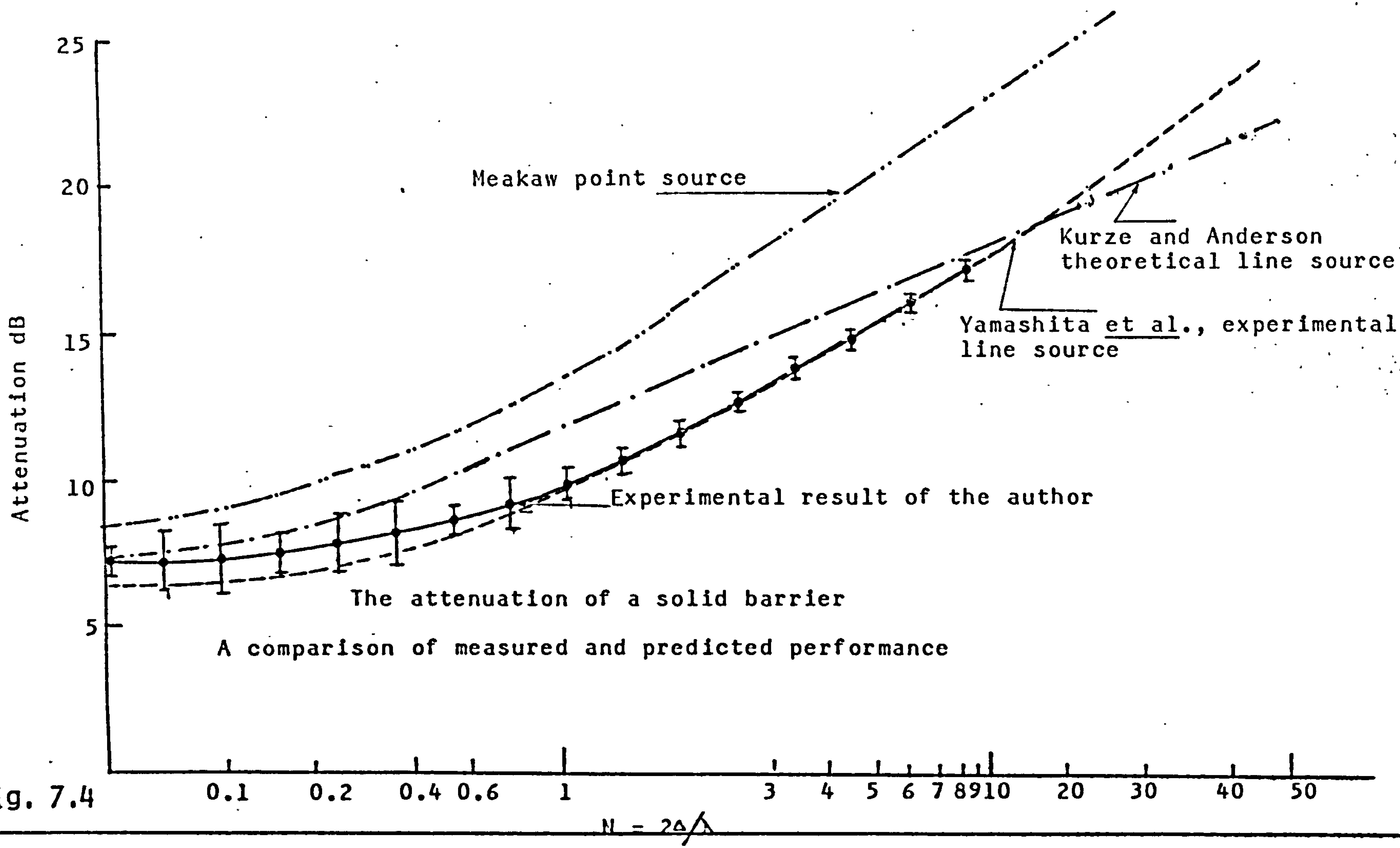
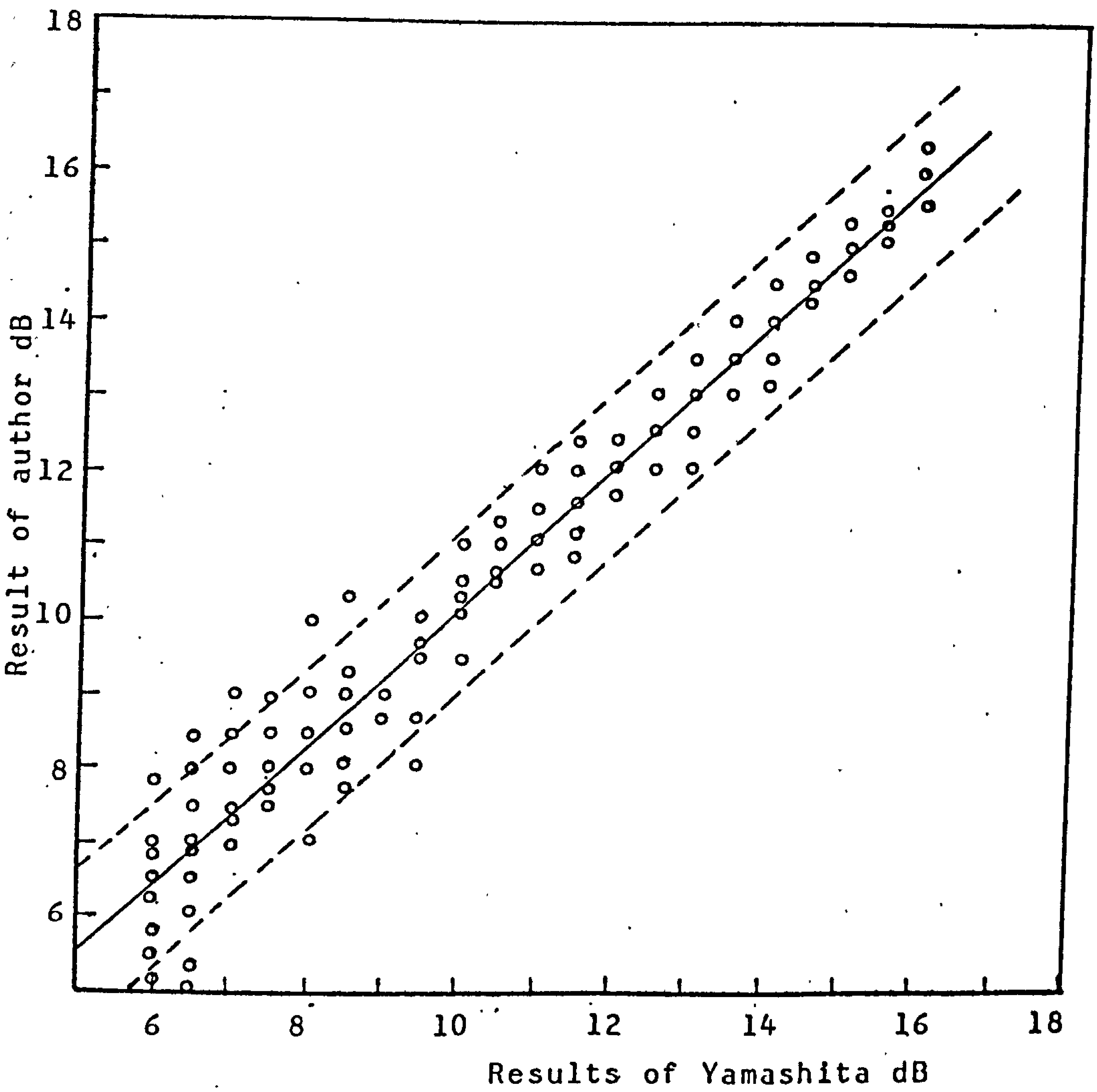


Fig. 7.4 The attenuation of a solid barrier

A comparison of measured and predicted performance



Comparison of the protection of a solid barrier measured by Yamashita et al., with that of the author. Also shown is the 95% confidence limits where the correlation coefficient is calculated to be 0.95.

Fig. 7.5

Measured relative protection of thnadner

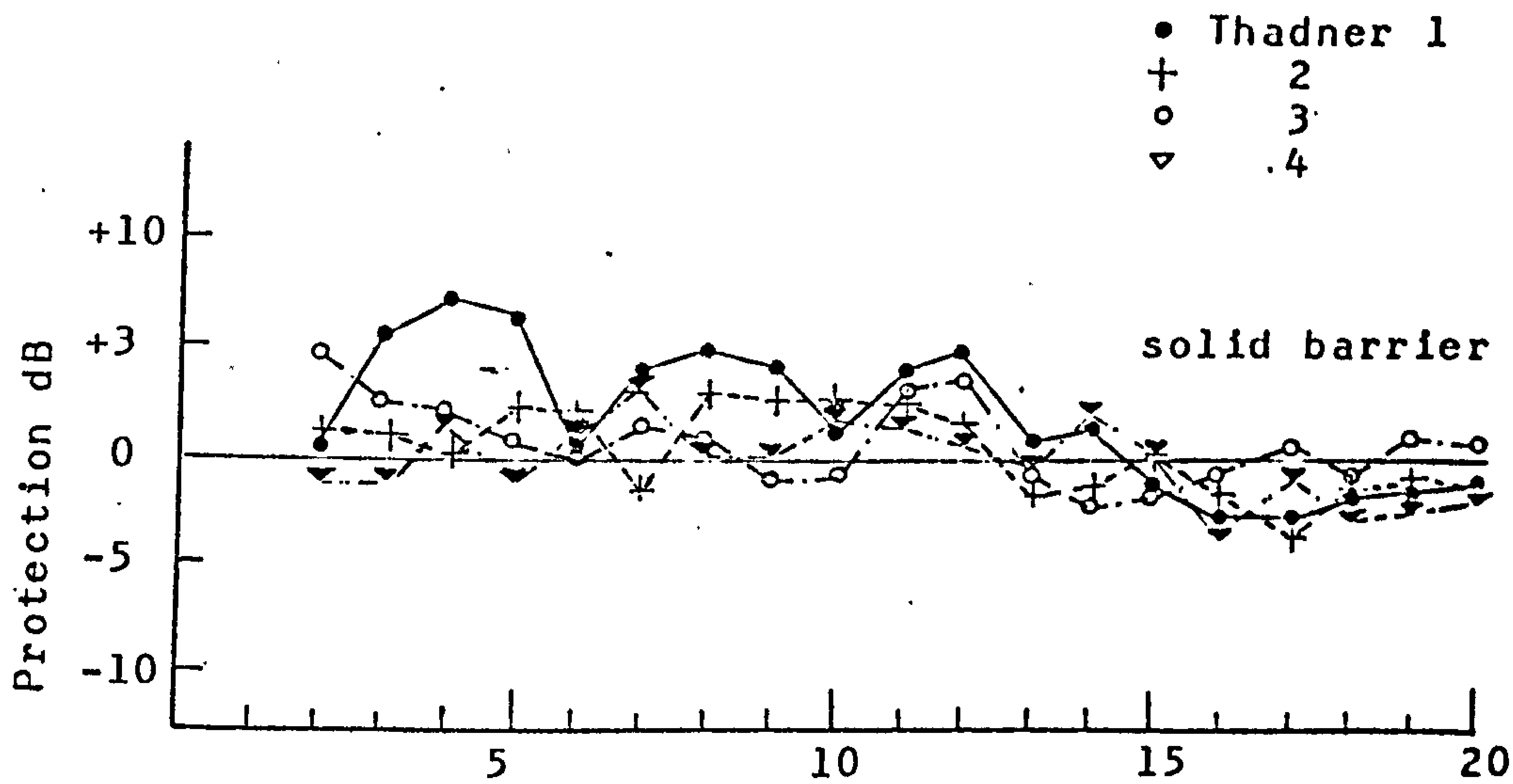
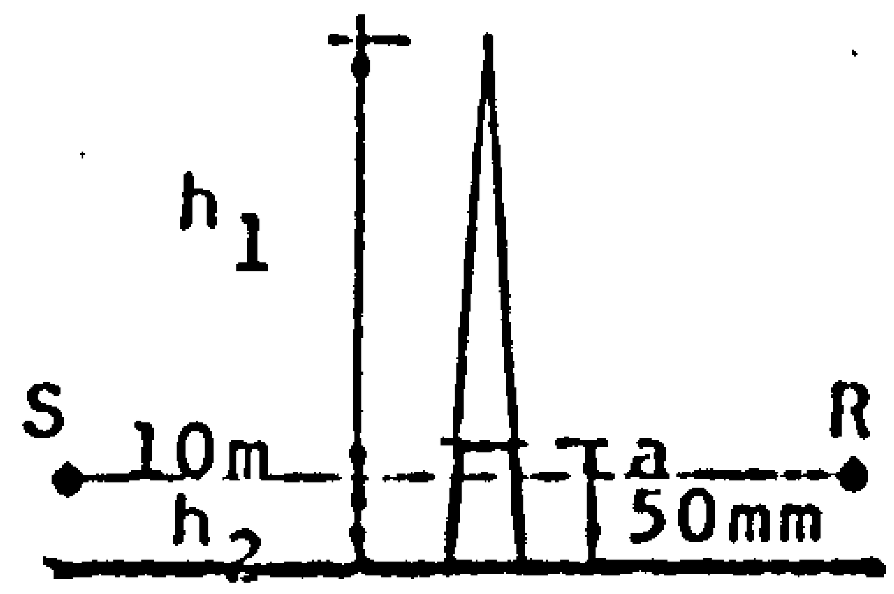


Fig. 7.6 Frequency KHz

receiver height (h_2) = 35mm; receiver barrier distance (a) = 50mm;



As above with a = 2m;

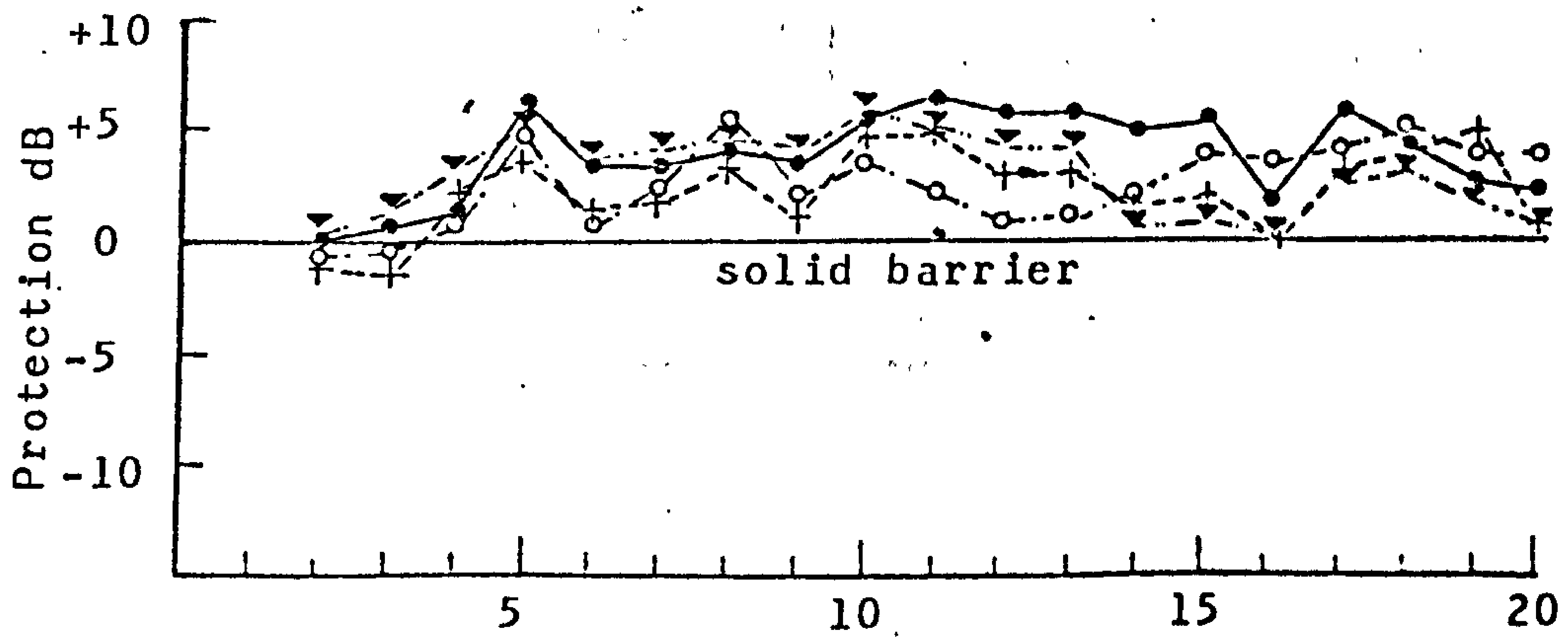


Fig. 7.7 Frequency KHz

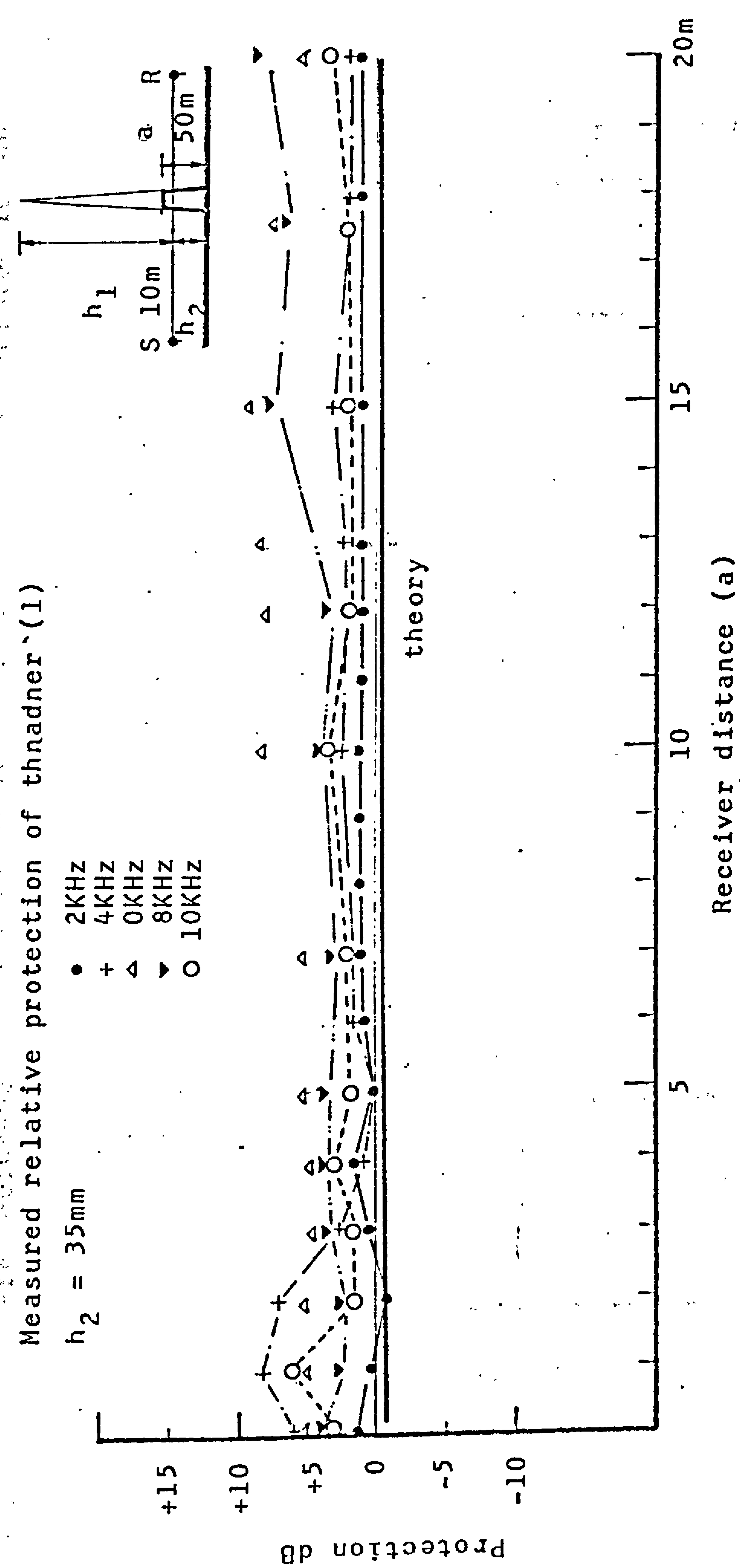
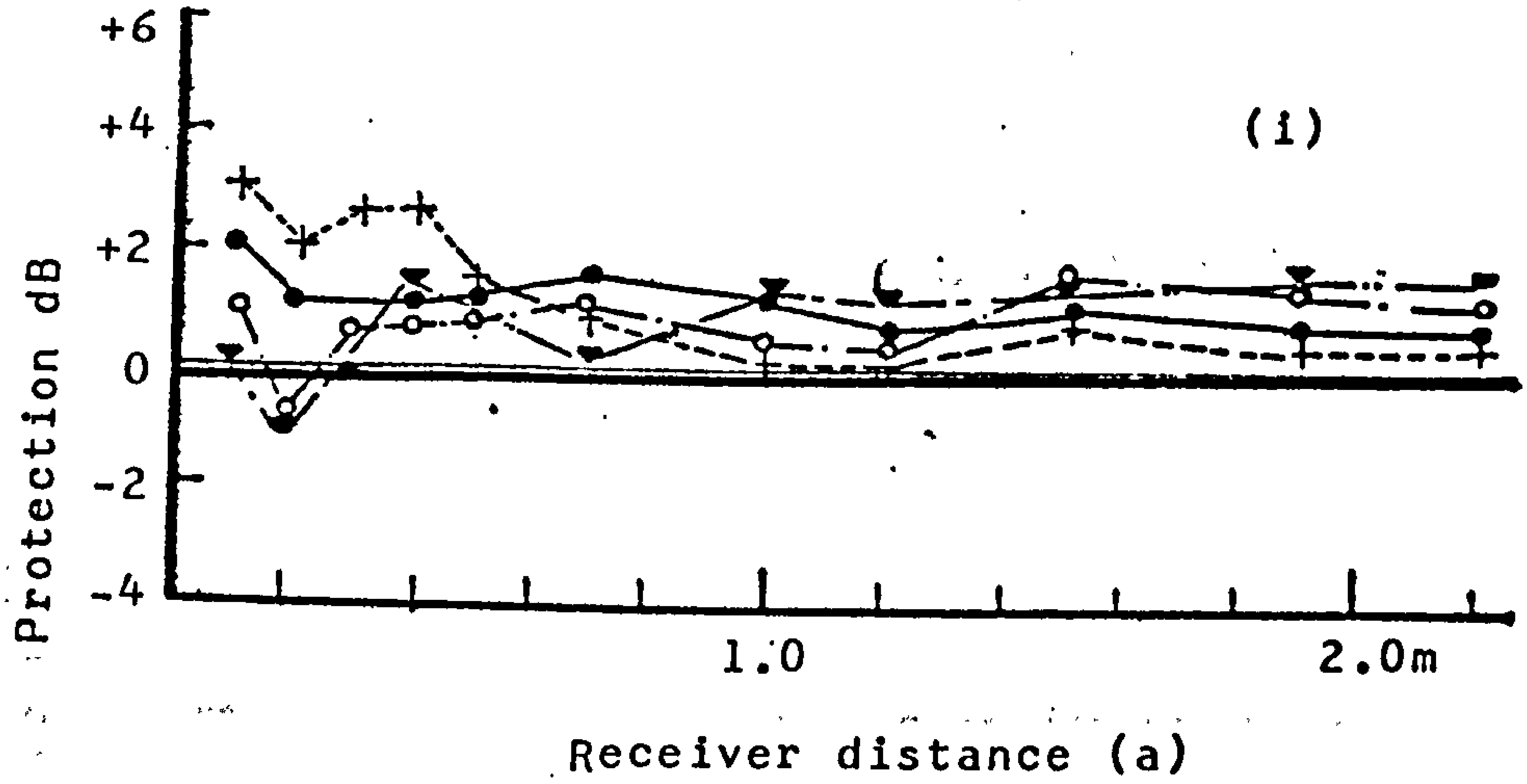
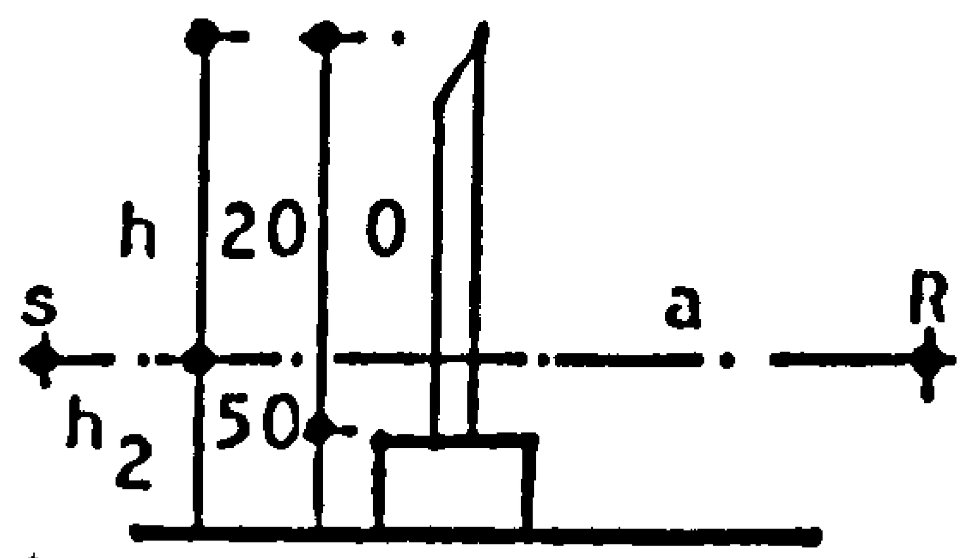

Measured relative protection of thnadner`(1)
h2 = 35mm
● 2KHz
+ 4KHz
△ 0KHz
▼ 8KHz
○ 10KHz
h1
S 10m
h2
a
50m
R
theory
Protection dB
+15
+10
+5
0
-5
-10
Receiver distance (a)
5
10
15
20m

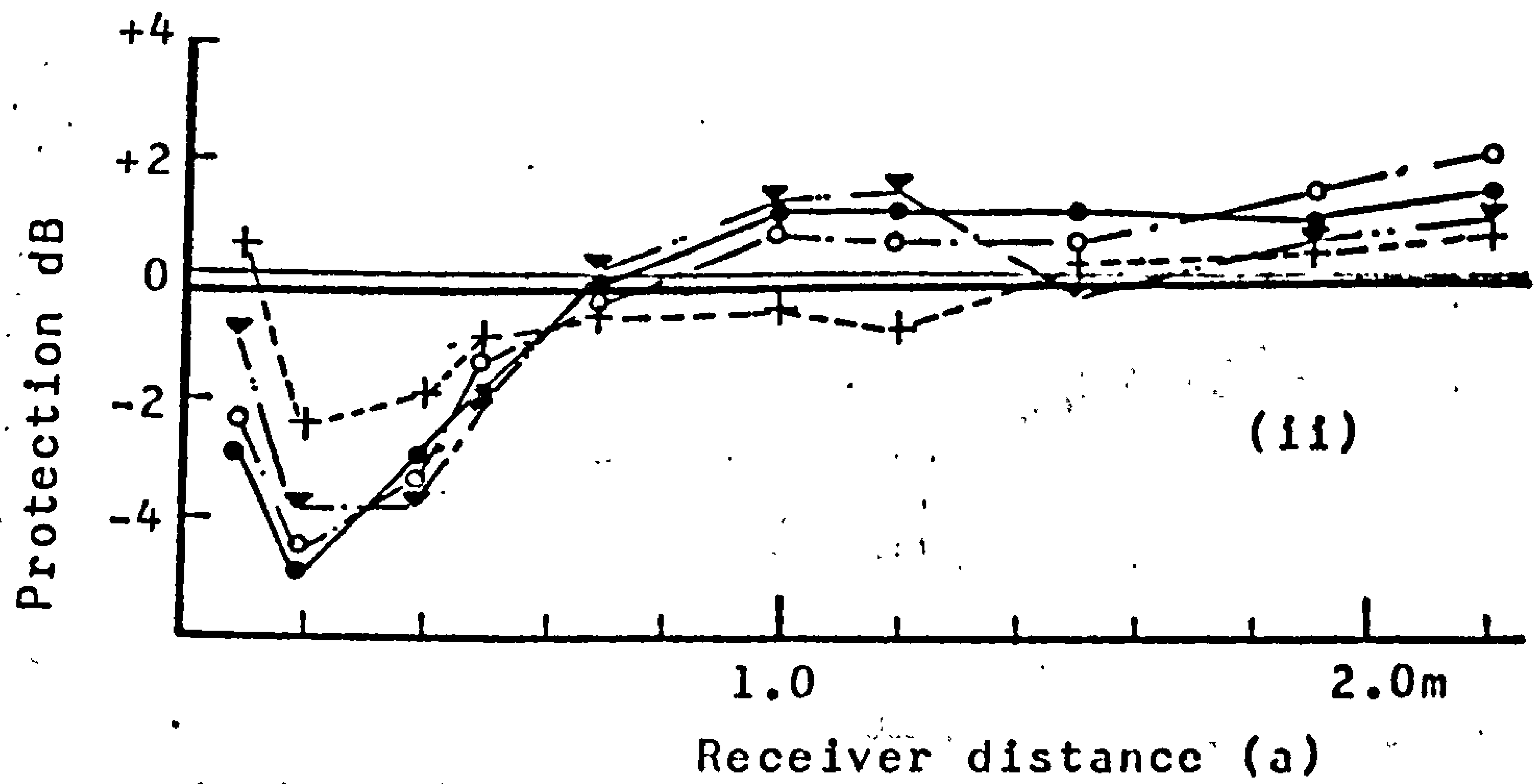
Fig. 7.8



(i) h_2 = 35mm

— Solid barrier
— Thnadner Theory
• Thnadner 1
o 2
+ 3
▼ 4

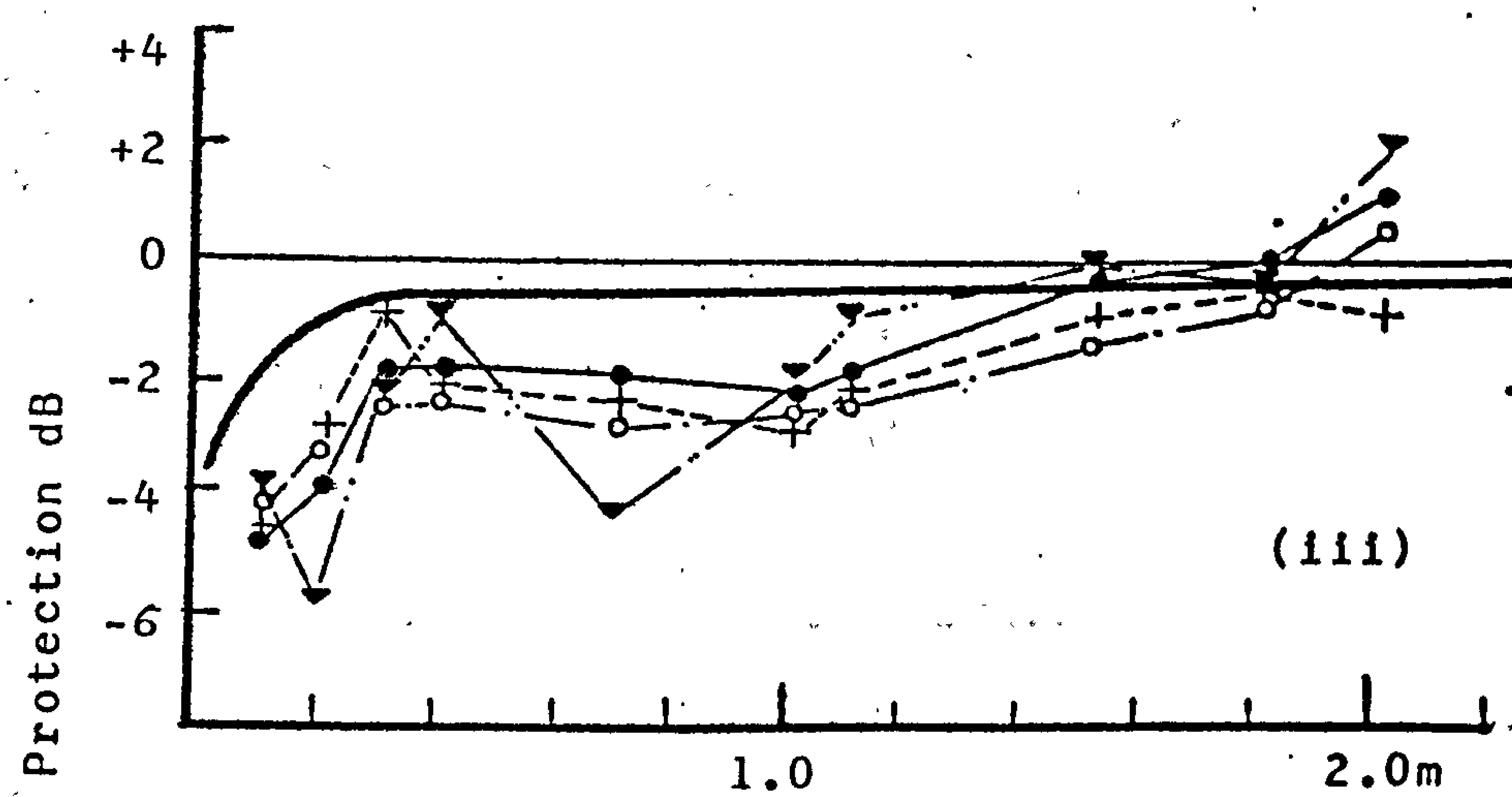




(ii) as (i) with h_2 = 50mm

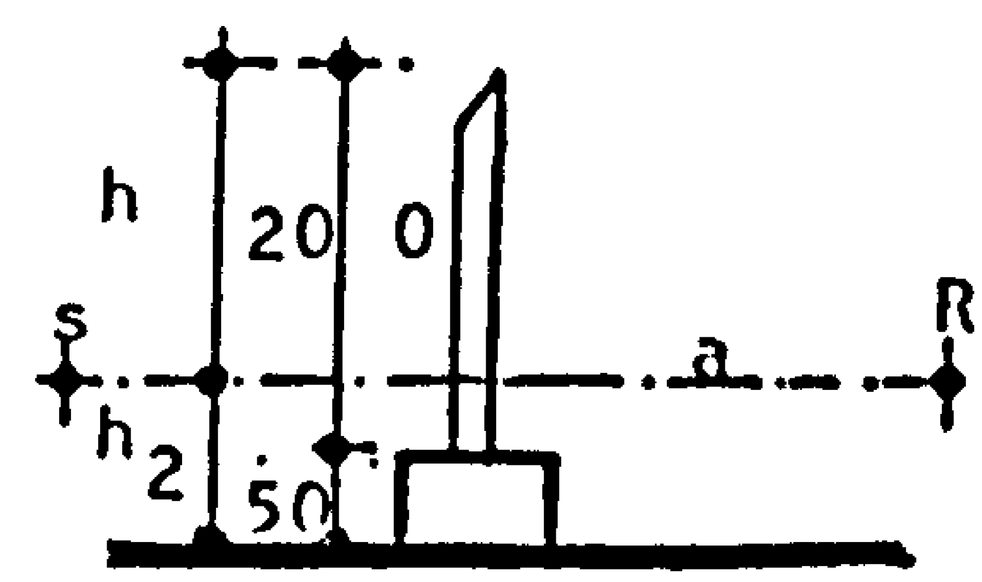
Measured and predicted thnadner barrier protection at 2 KHz.

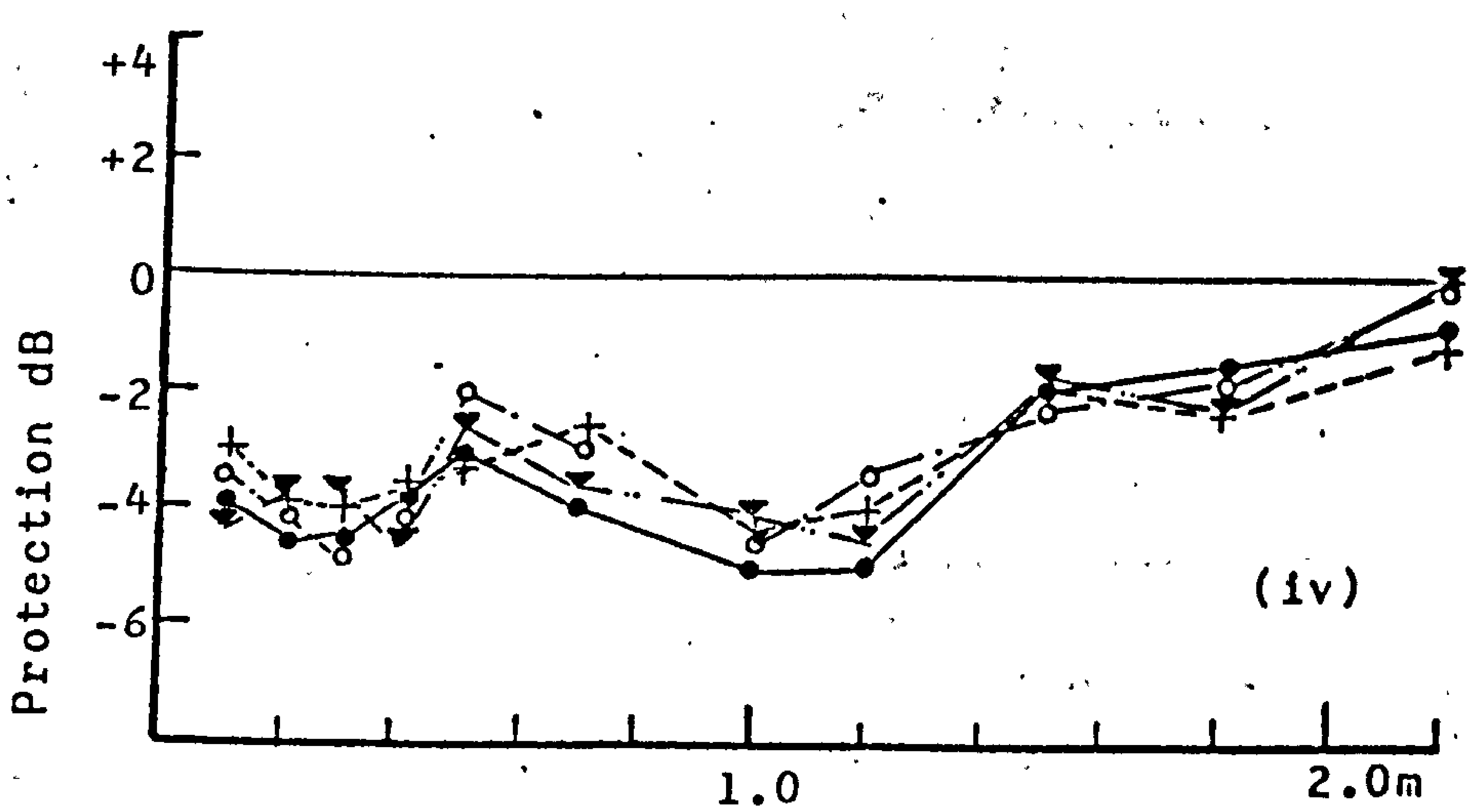
Fig. 7.9



(iii) Receiver distance (a)

As (i) with h_2 = 150mm



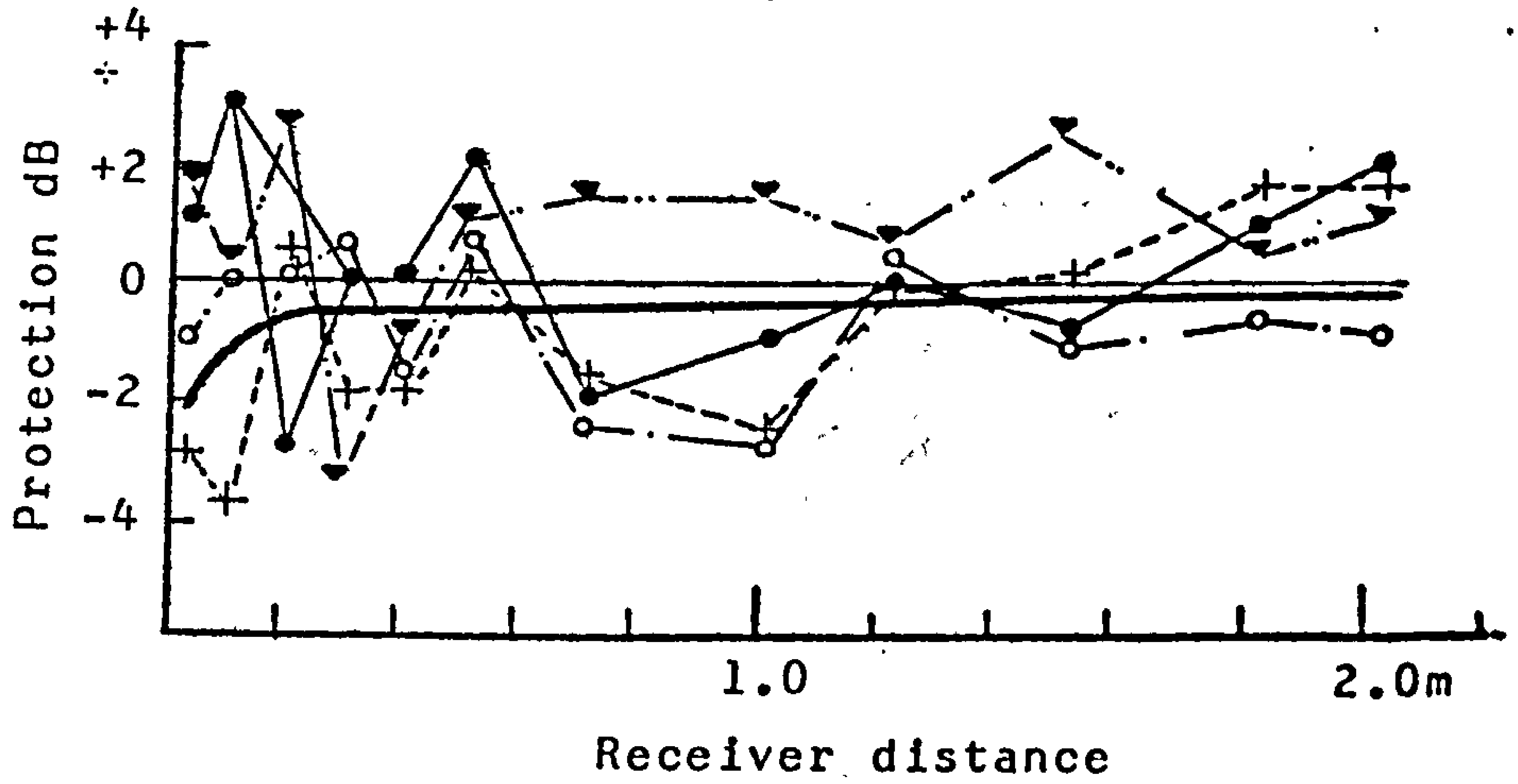


Receiver distance (a)

(iv)

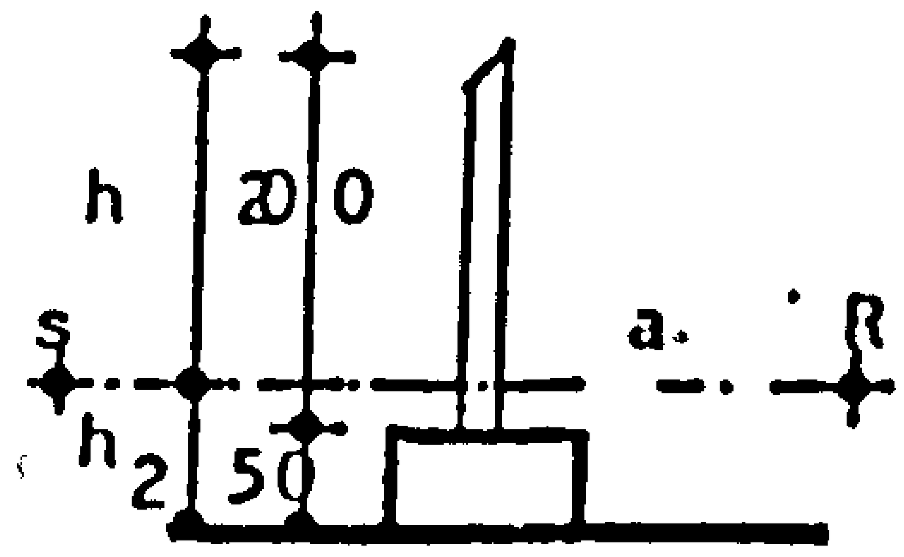
As (i) with h_2 = 250mm

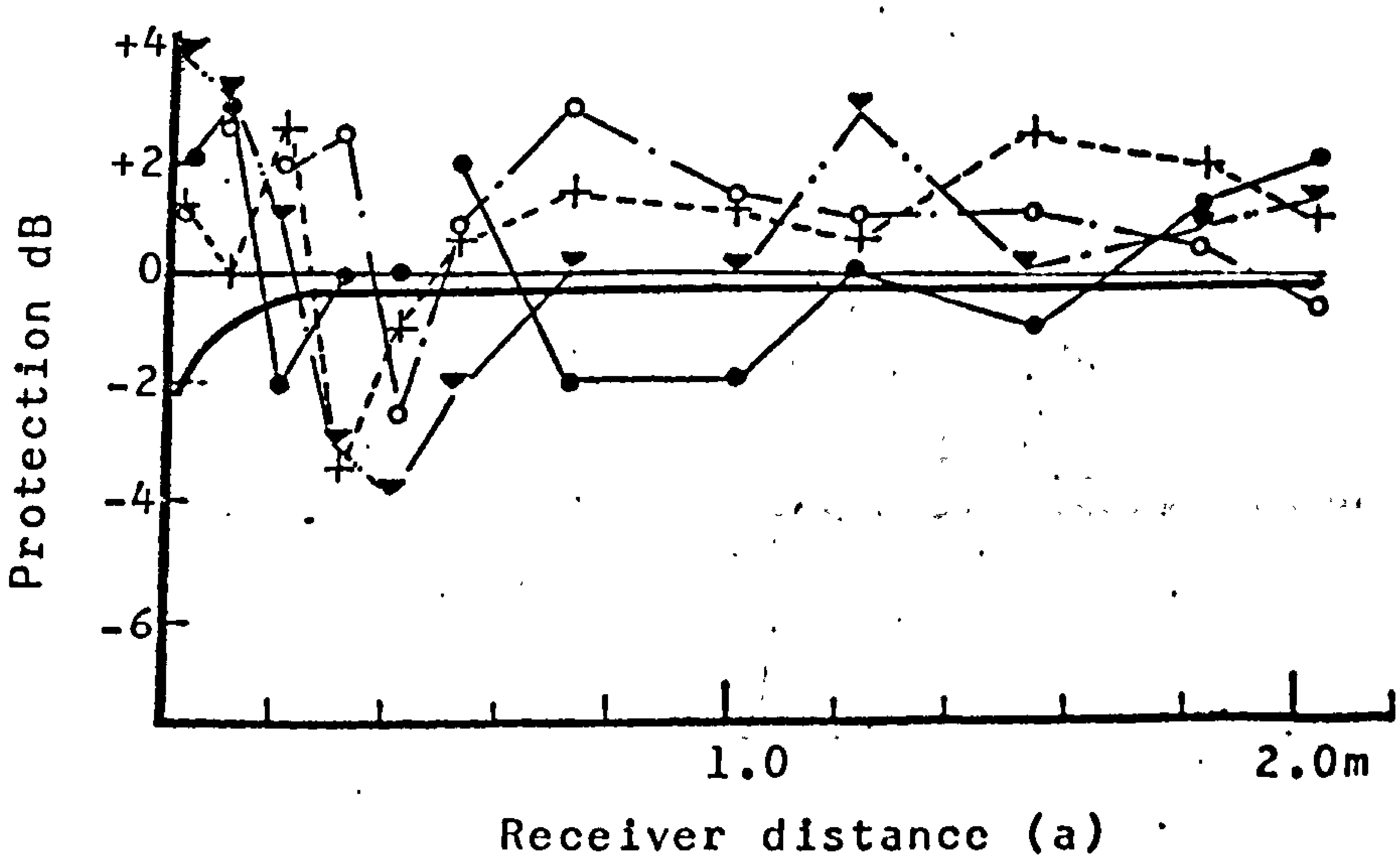
Fig. 7.9



(i) h_2 = 150m

— solid barrier
— Thnadner Theory
• Measured Thnadner 1
o 2
+ 3
▼ 4

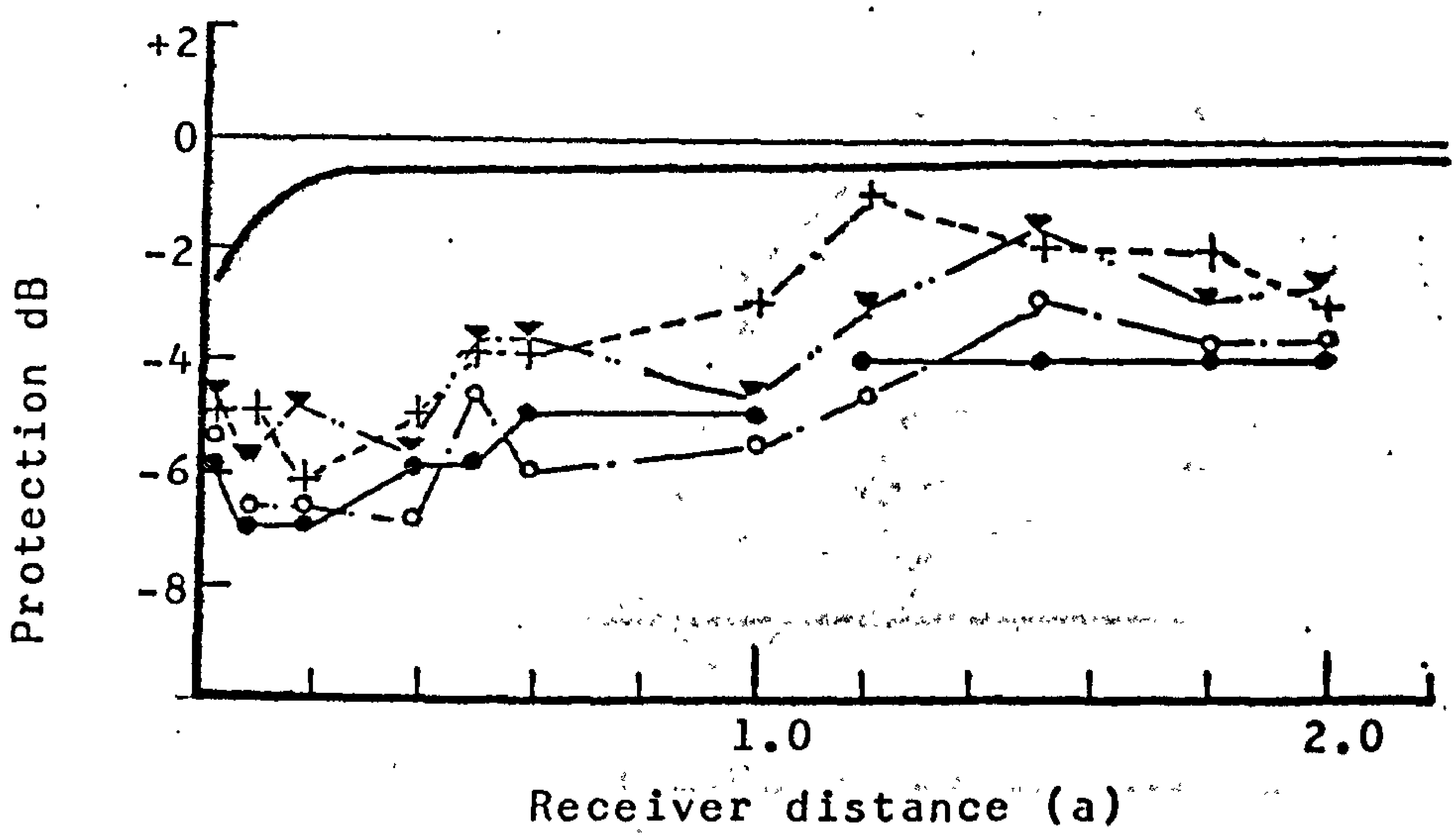




(ii) As (i) with h_2 = 50mm

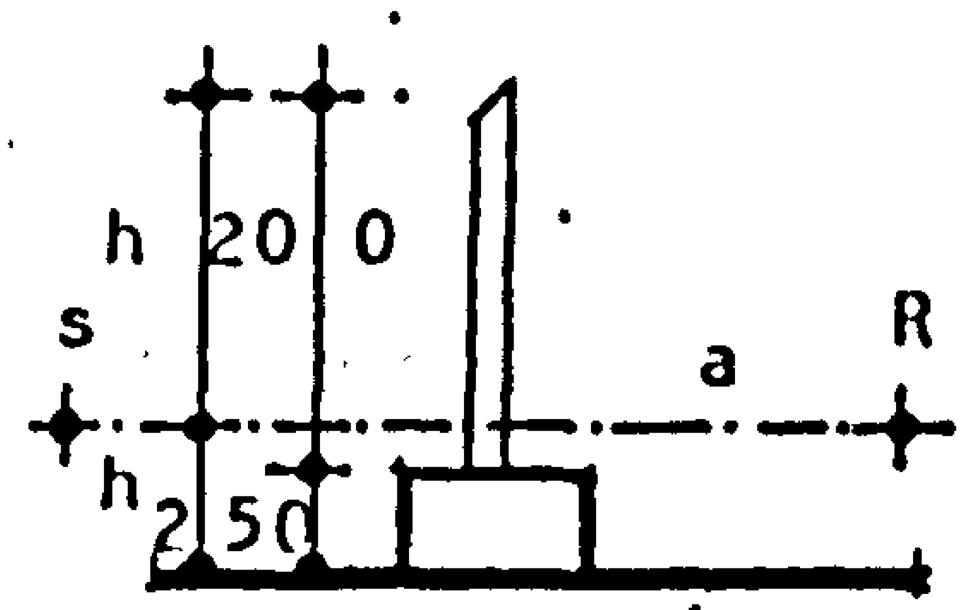
Measured and predicted thnadner barrier protection at 4KHz.

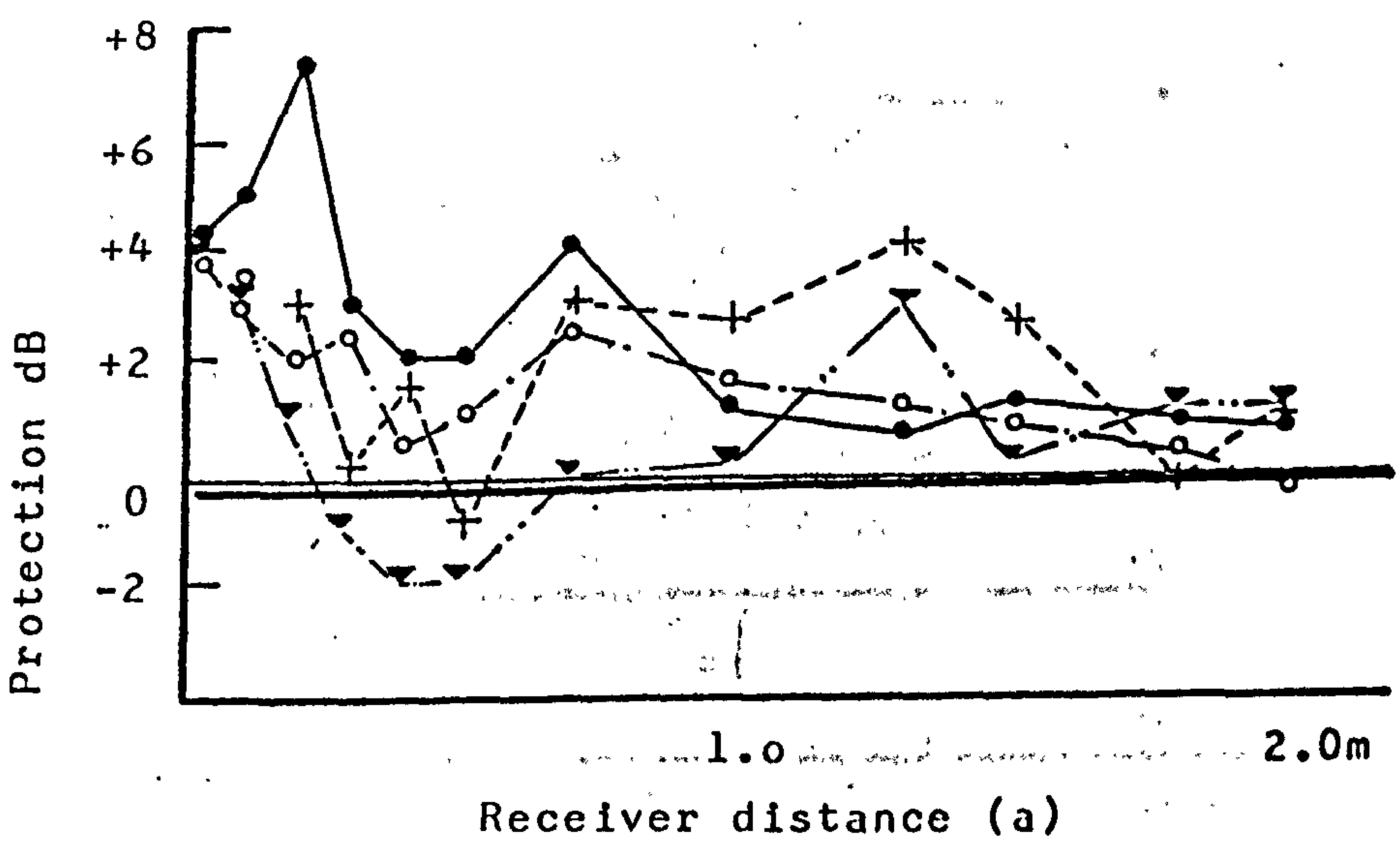
Fig. 7.10



(iii)

as (i) with h_2 = 250mm

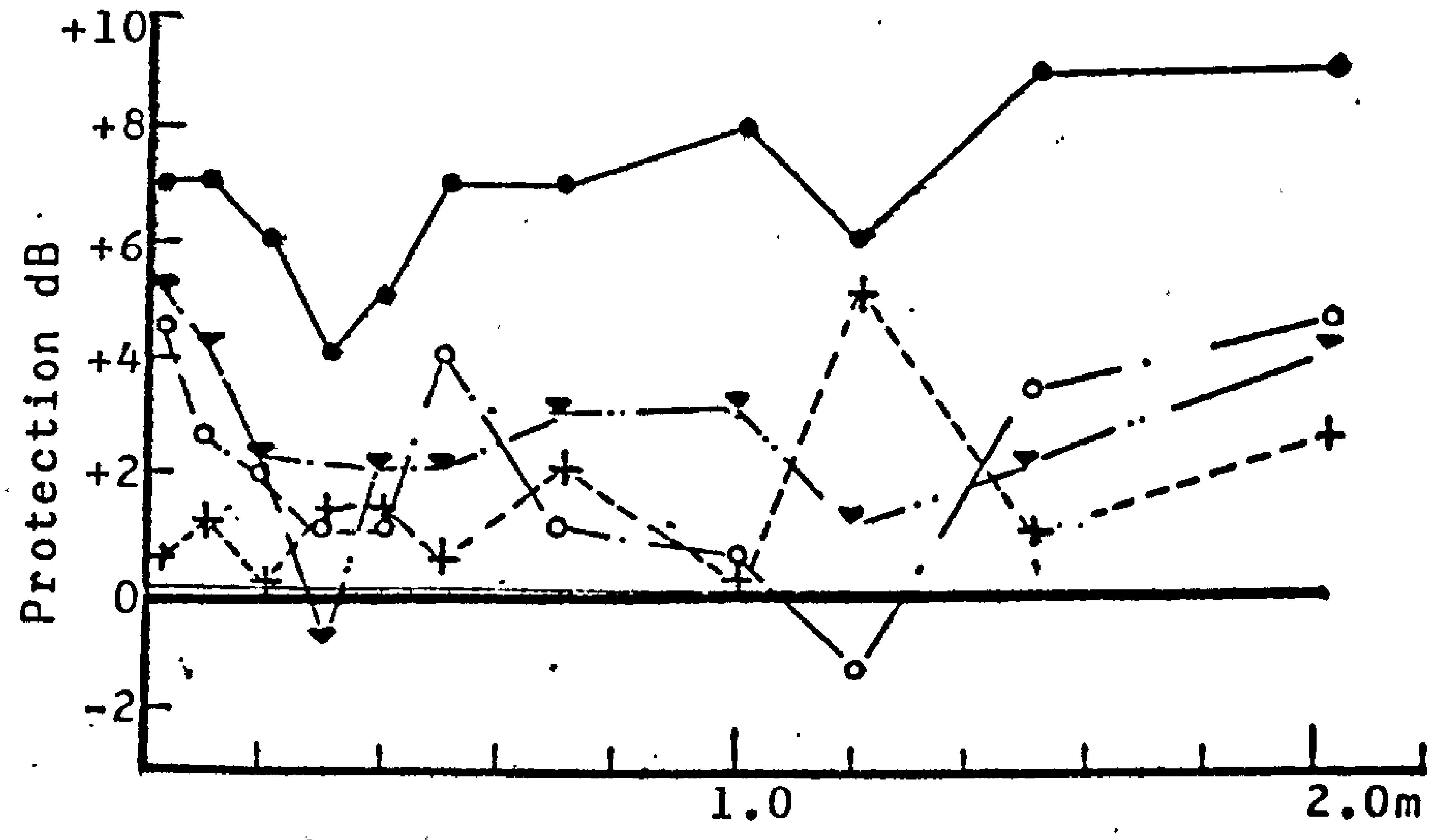




(iv)

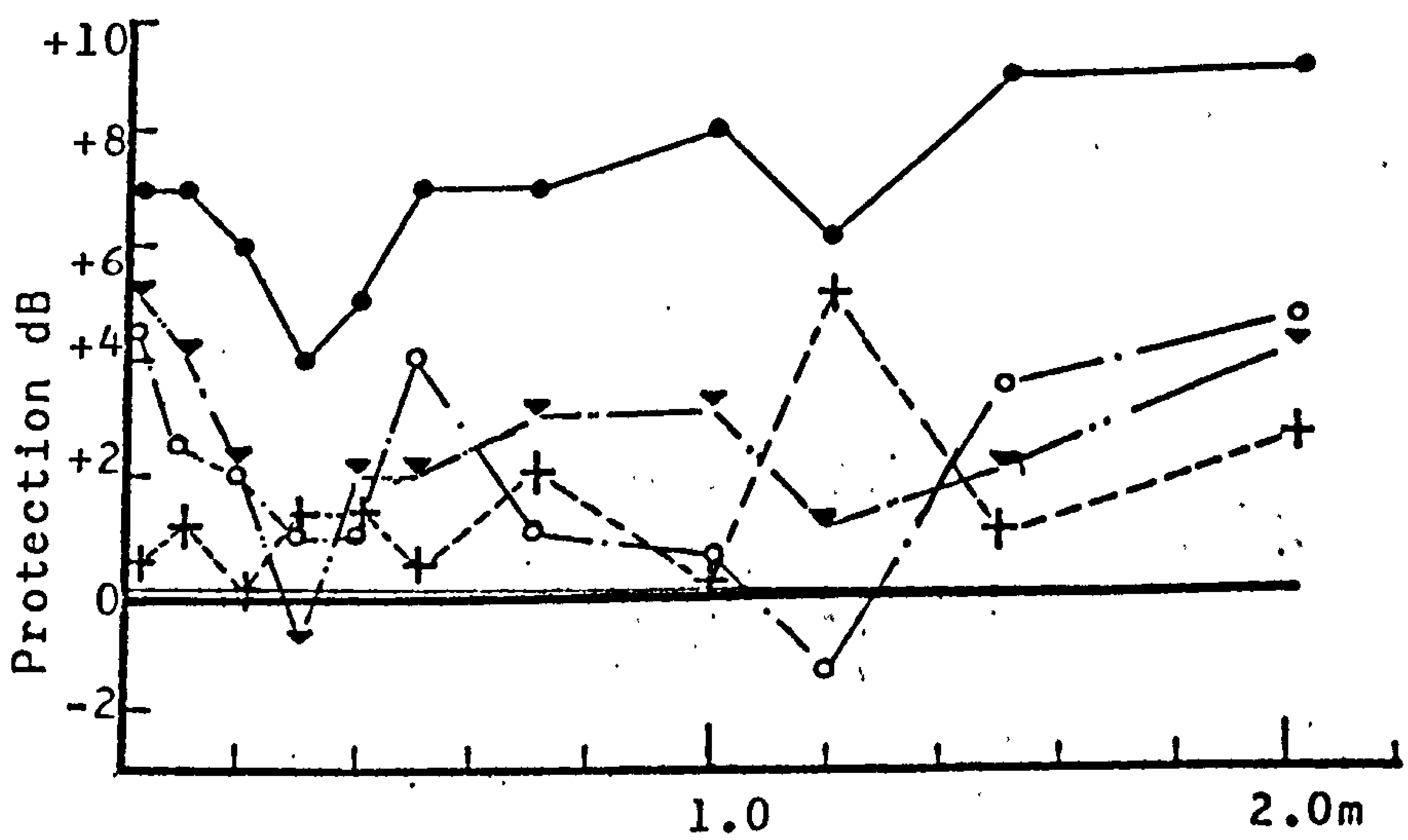
as (i) with h_2 = 35mm

Fig. 7.10



(i) h_2 = 35mm

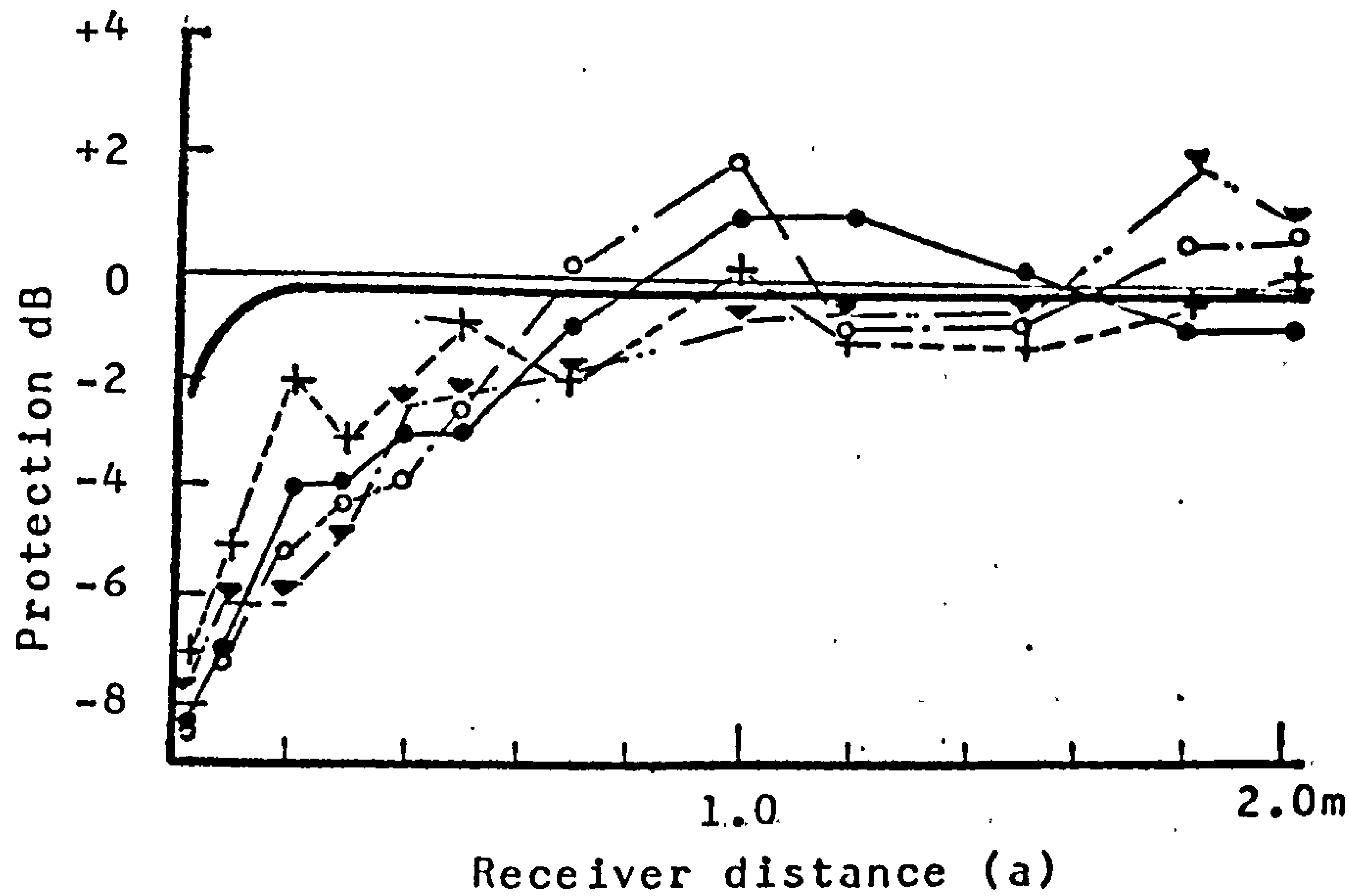
— Solid barrier
— Thnadner theory
• Measured Thnadner 1; o TH 2; +TH 3; ▾ Th 4;



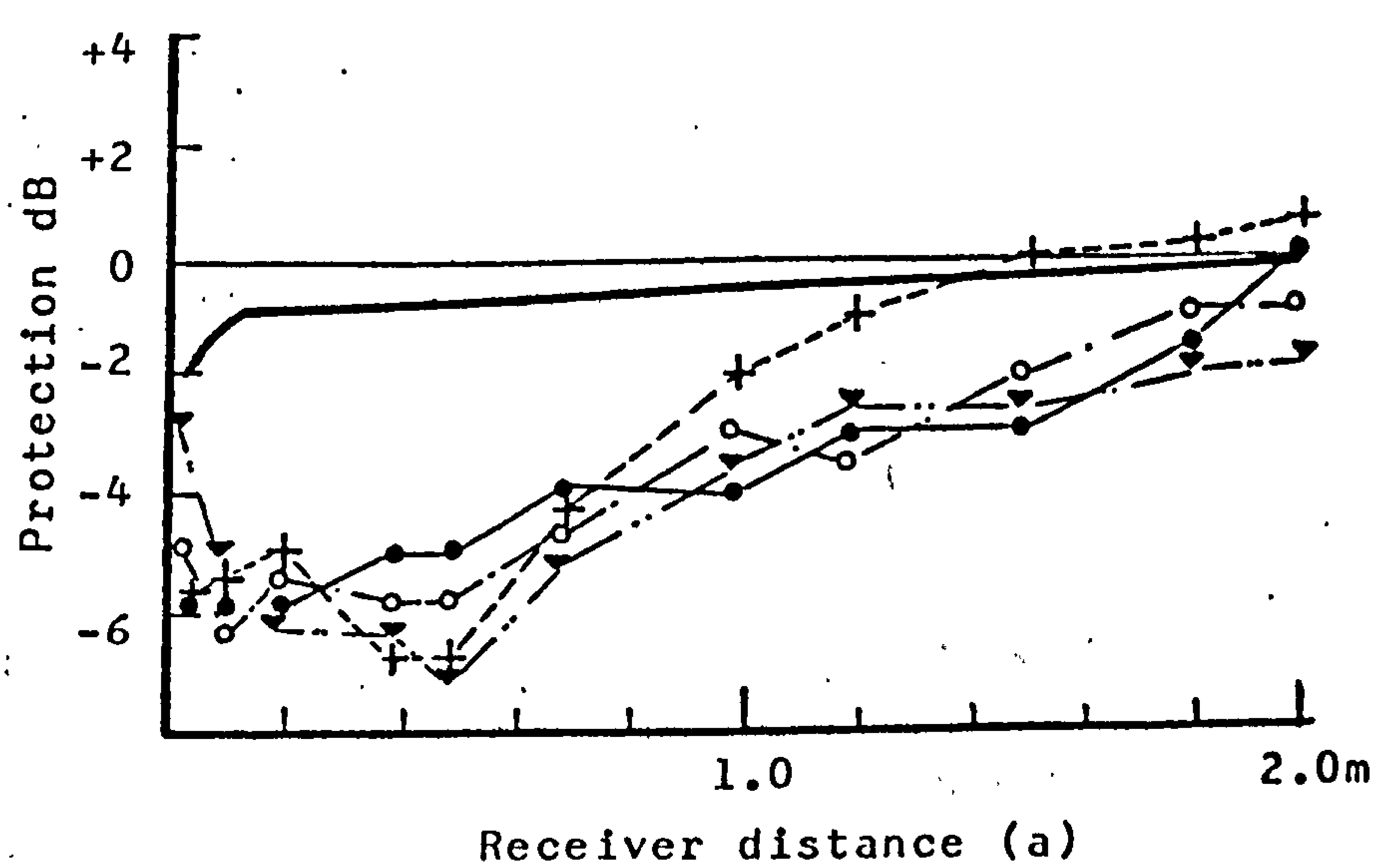
(ii) As (i) with h_2 = 50mm

Measured and predicted thnadner barrier protection at 6 KHz.

Fig. 7.11



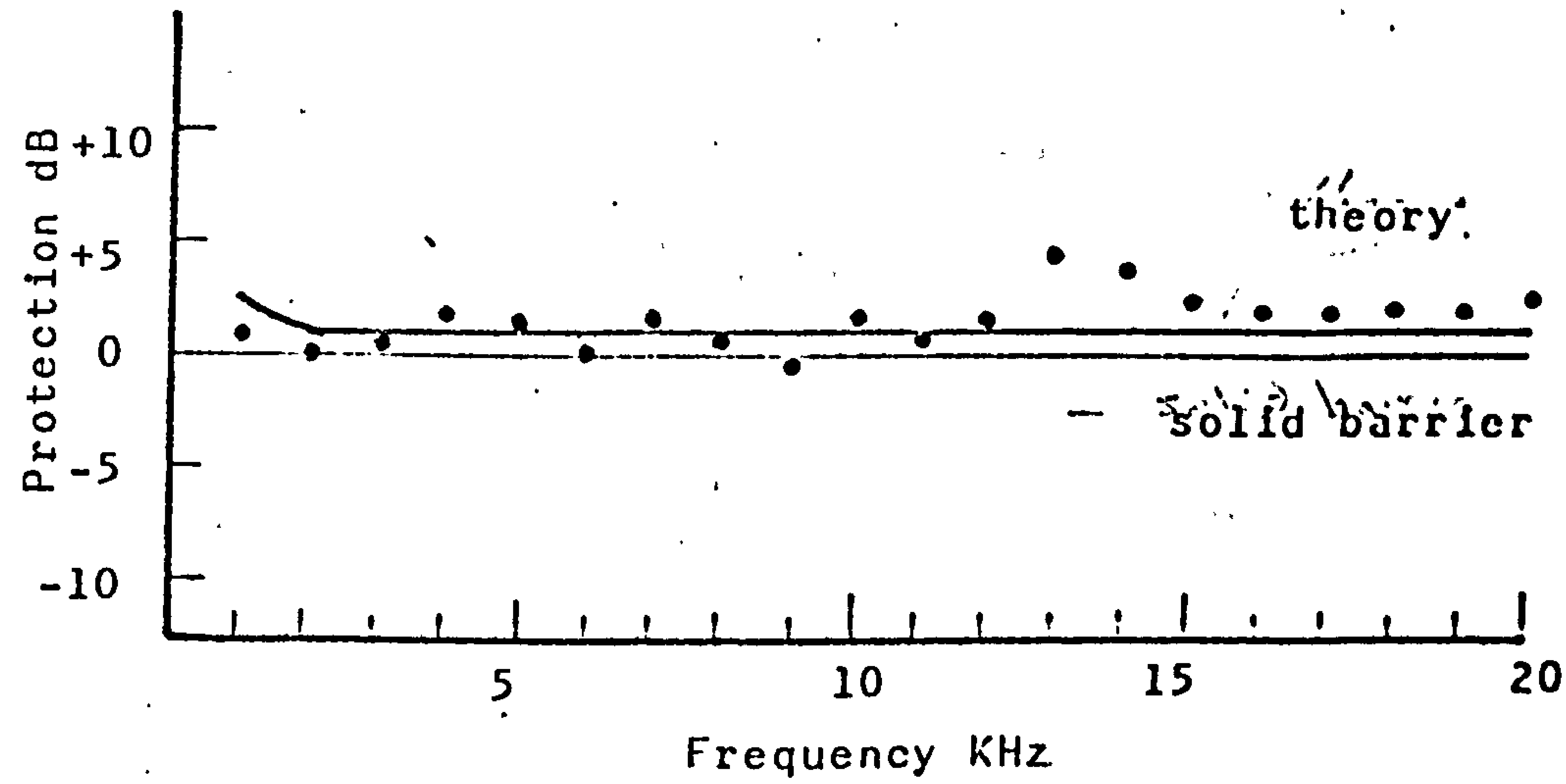
(iii) As (i) with h_2 = 150mm



(iv) As (i) with h_2 = 250mm

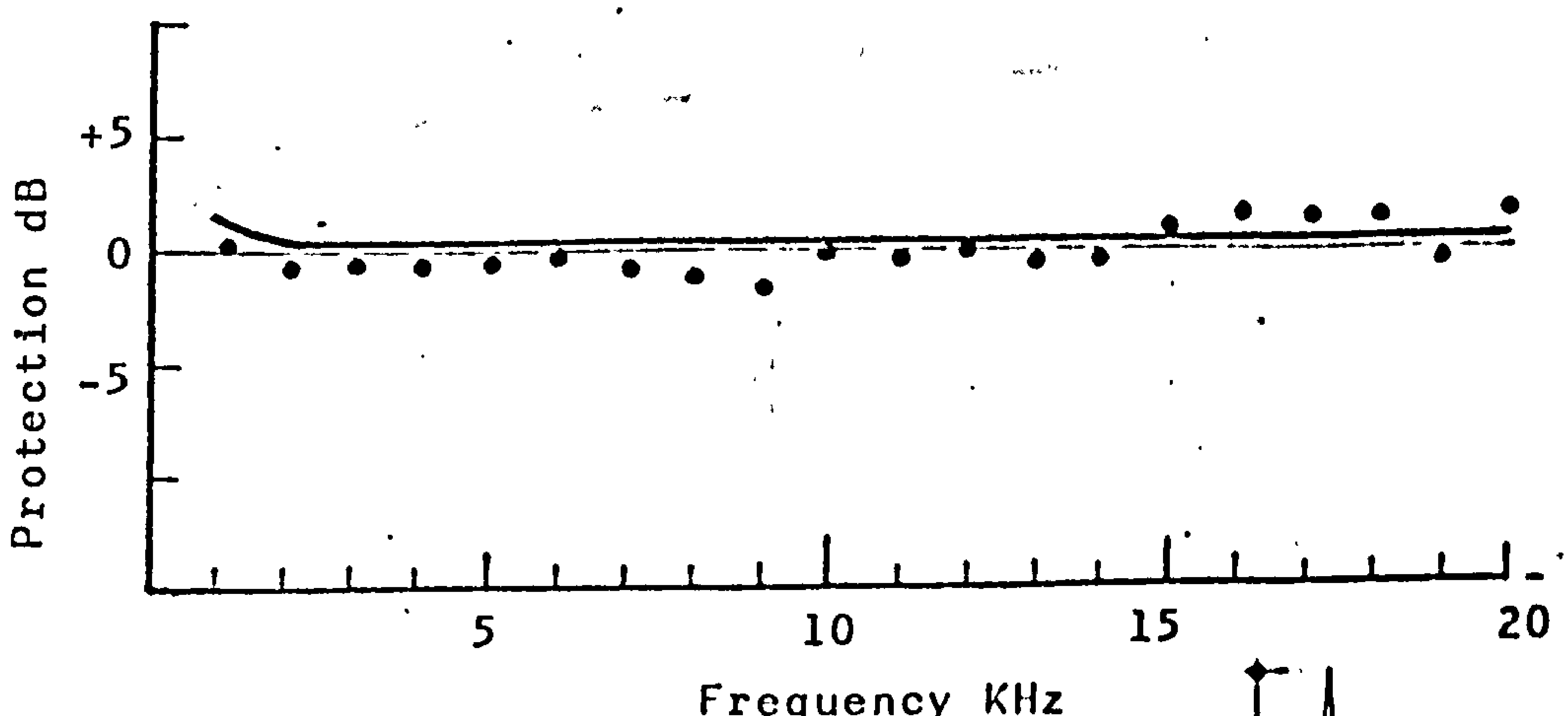
Fig. 7.11

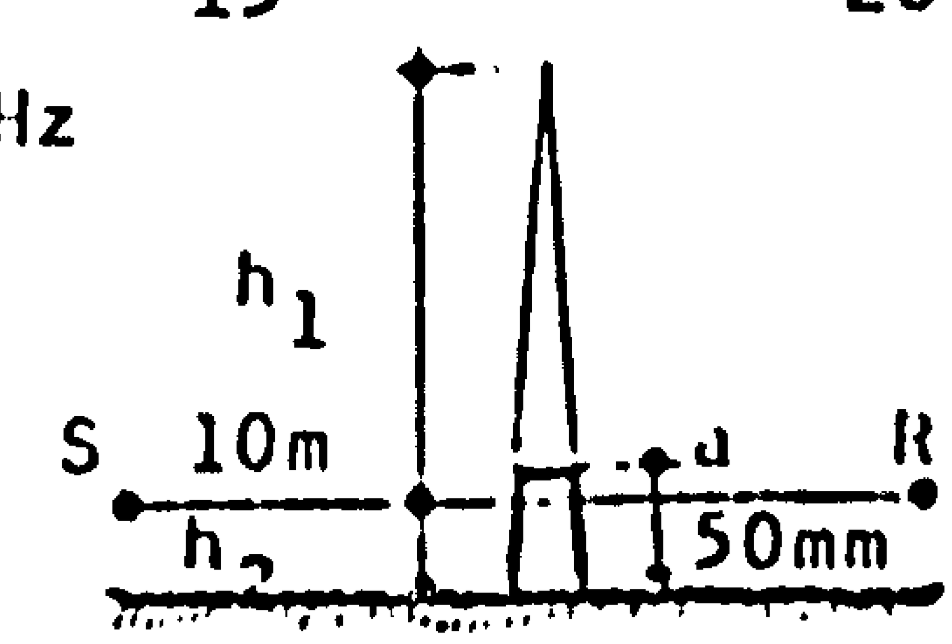
Measured and predicted relative protection of splitter barrier



h_2 = 35mm
a = 50mm

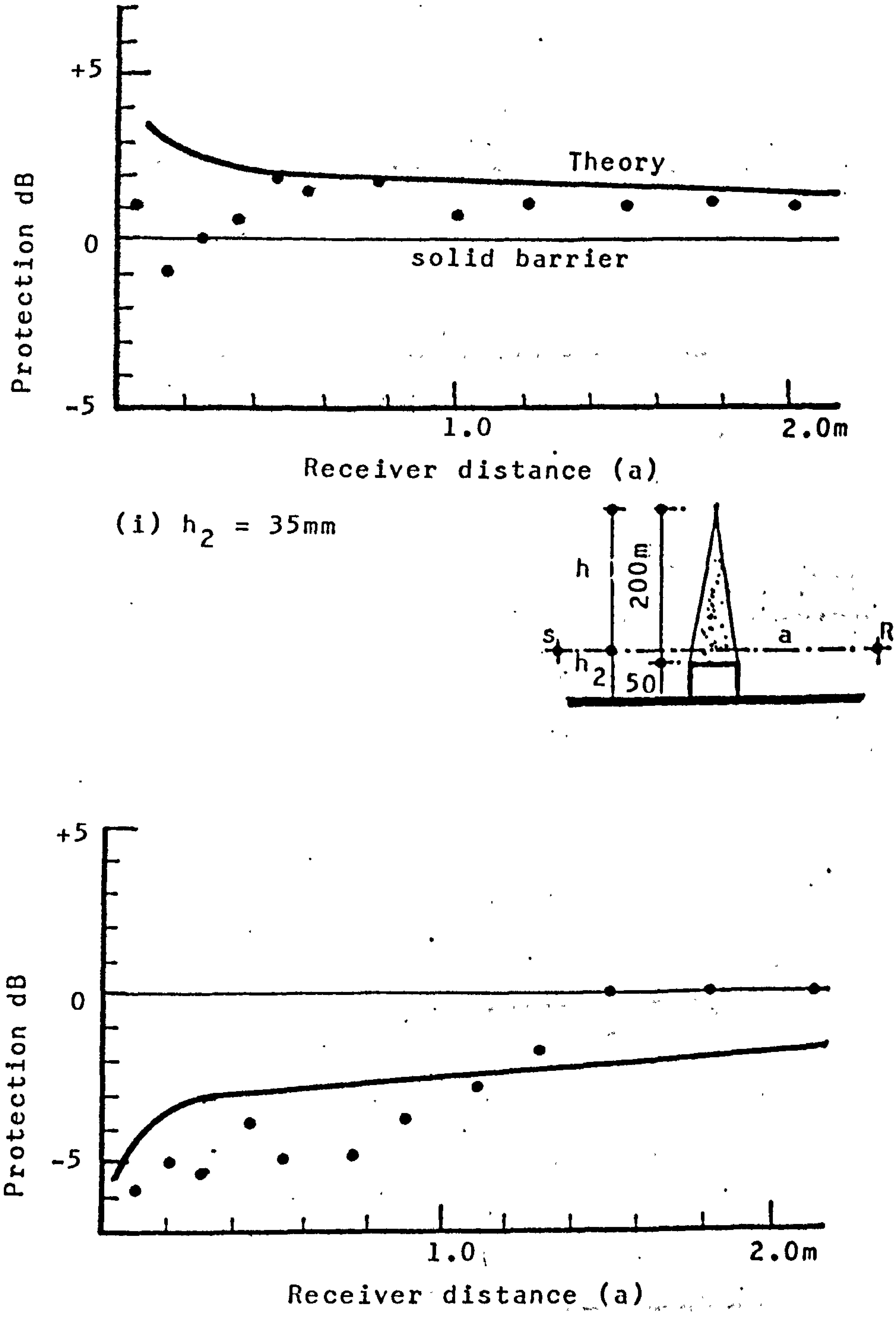
Fig. 7.12





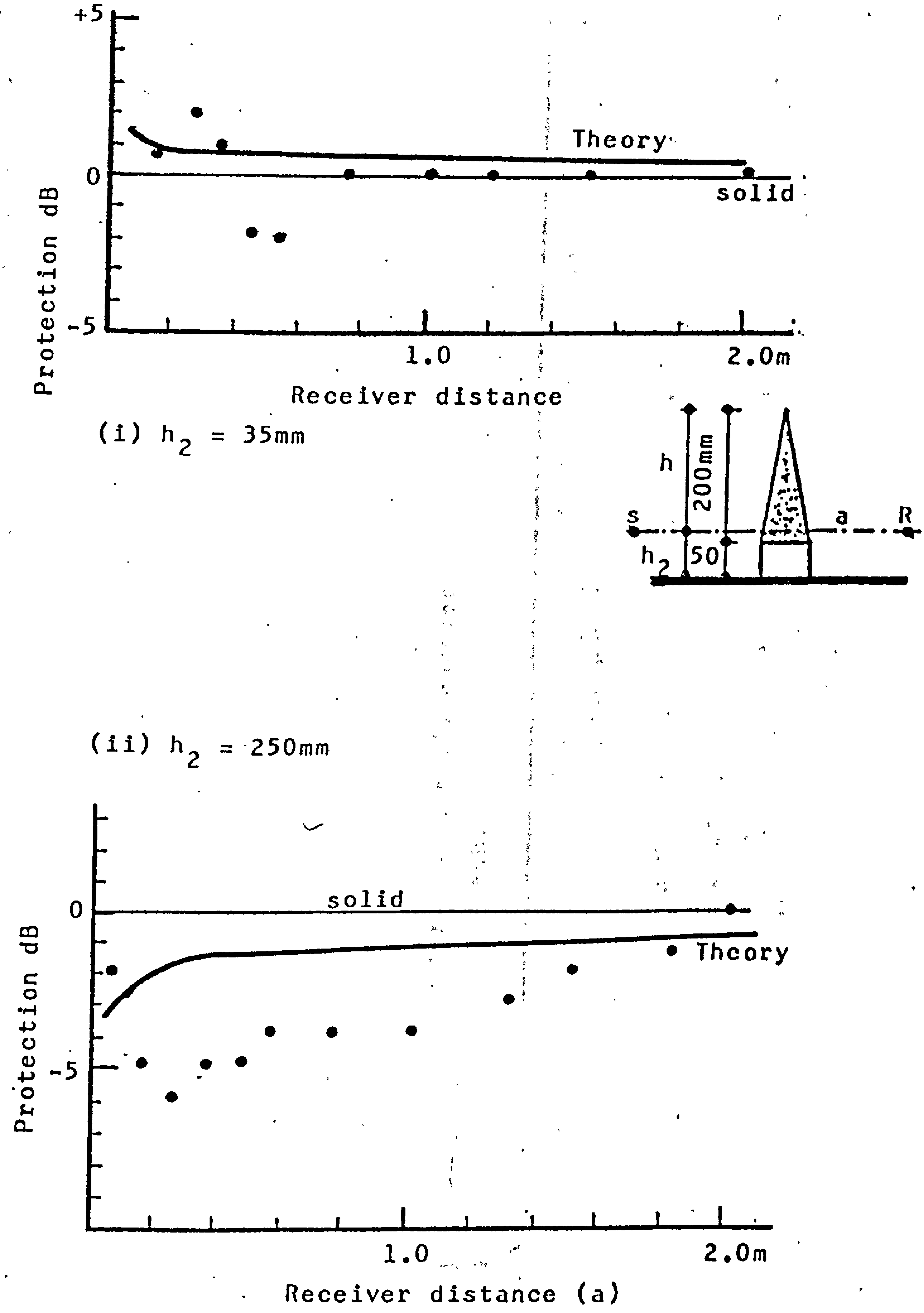
As above with h_2 = 35mm;
a = 400mm

Fig. 7.13



Measured relative protection of splitter barrier at 4 KHz.

Fig. 7.14



Measured Relative Protection of splitter barriers at 4KHz.

Fig. 7.15

● greater than a solid barrier
o ± 1 dB
+ -2dB to - 4dB
△ -5 to -7dB
Shadow zone
worse than no barrier
above the sight line
-2dB to -4dB
equal to or better than a solid barrier
(-1dB to + 8dB)
Perforated
solid
2
4
6
8
10
12
14
16
18
20
Distance m
L.s
10
Distance m

Fig. 7.16

Absorption coefficient of the plywood

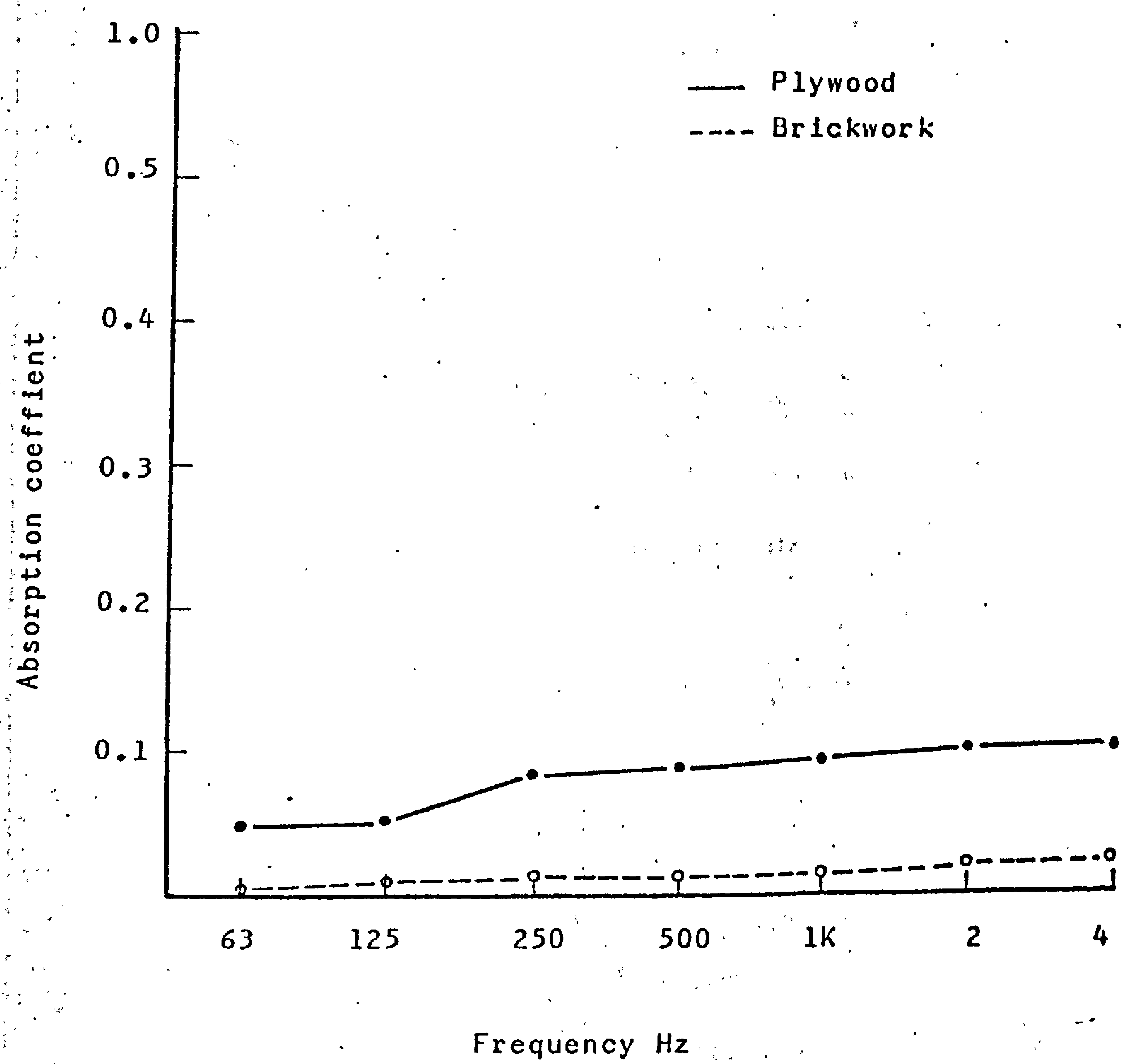


Fig. 8.1

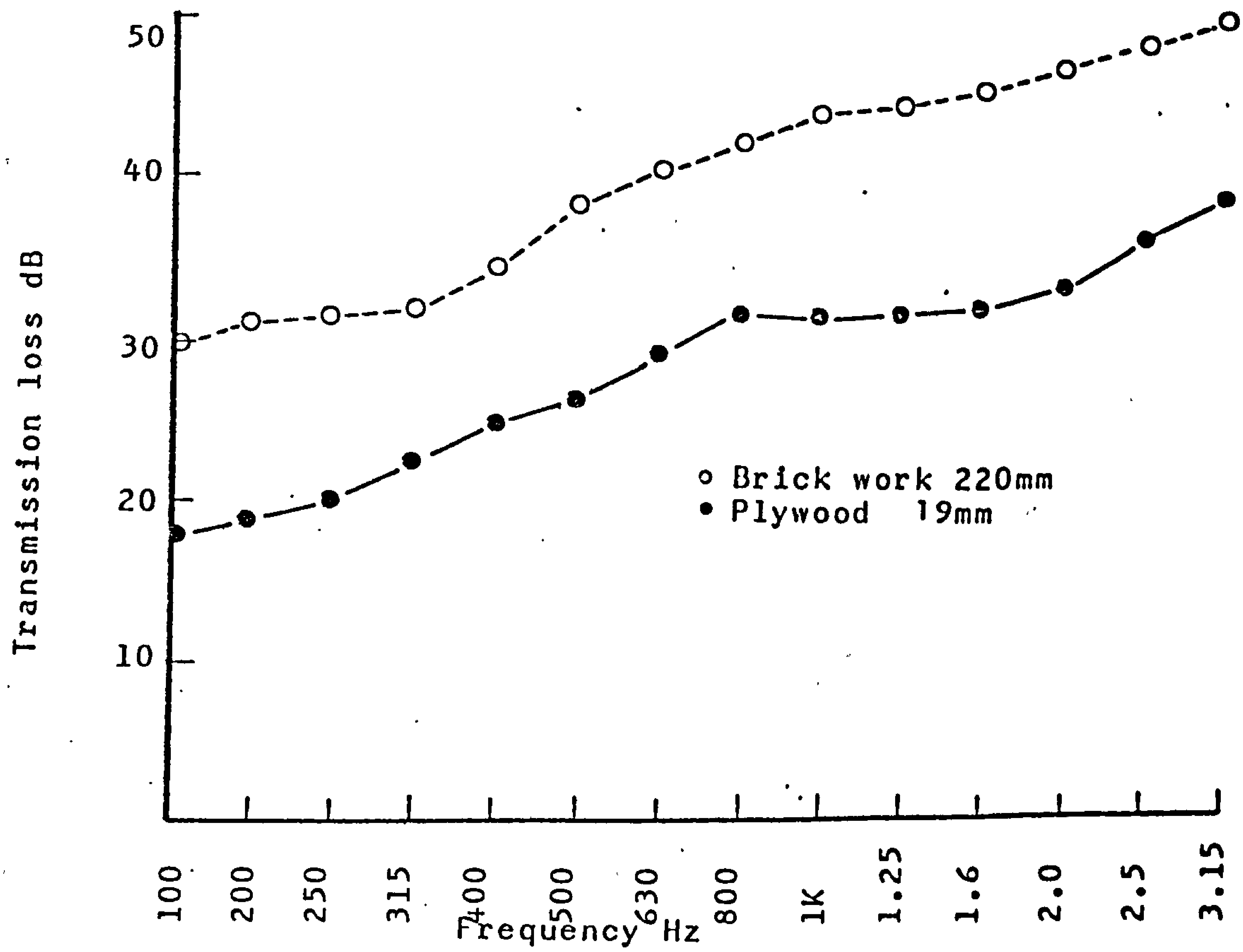


Fig.8.2 Transmission loss of plywood of thickness of 19mm

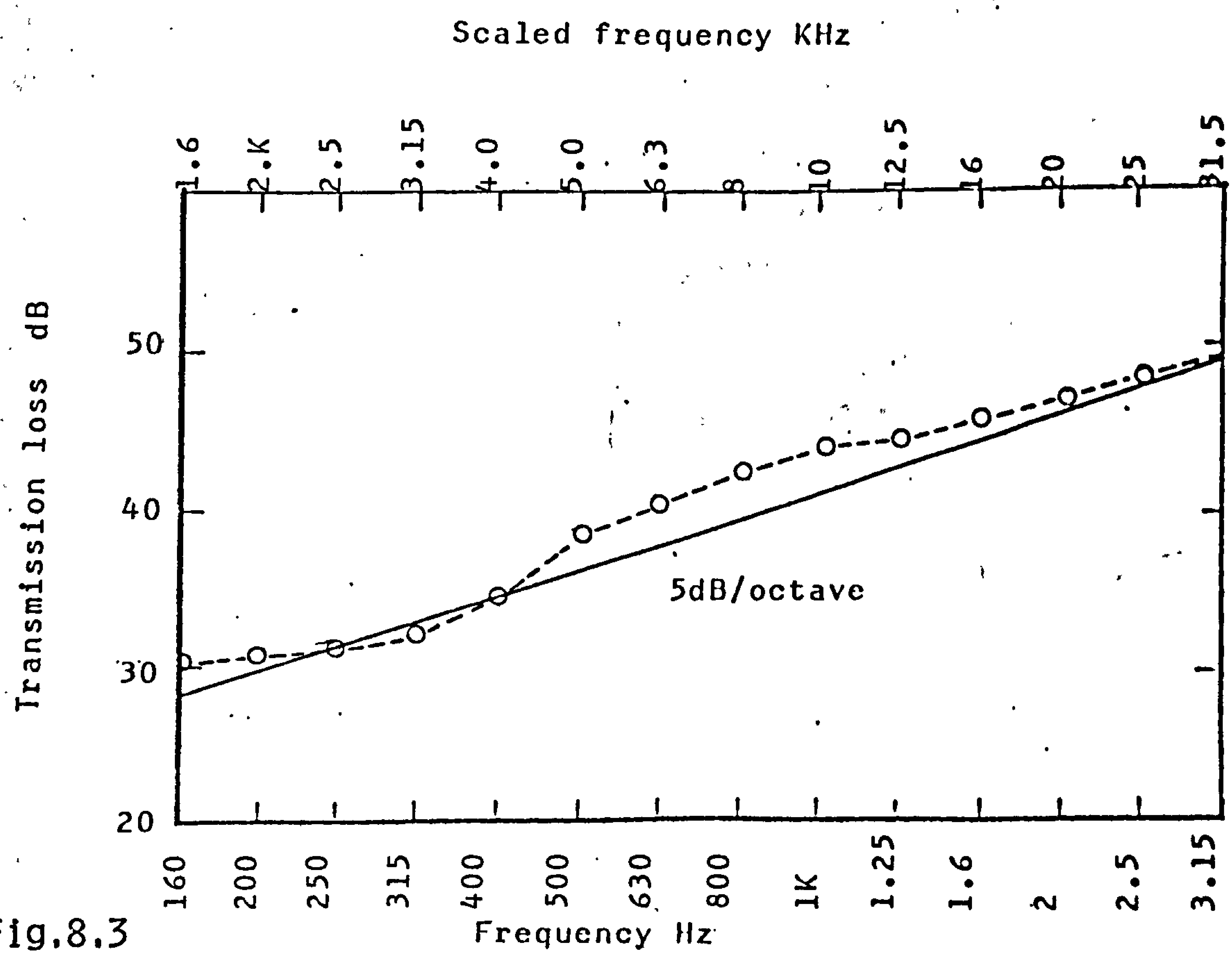
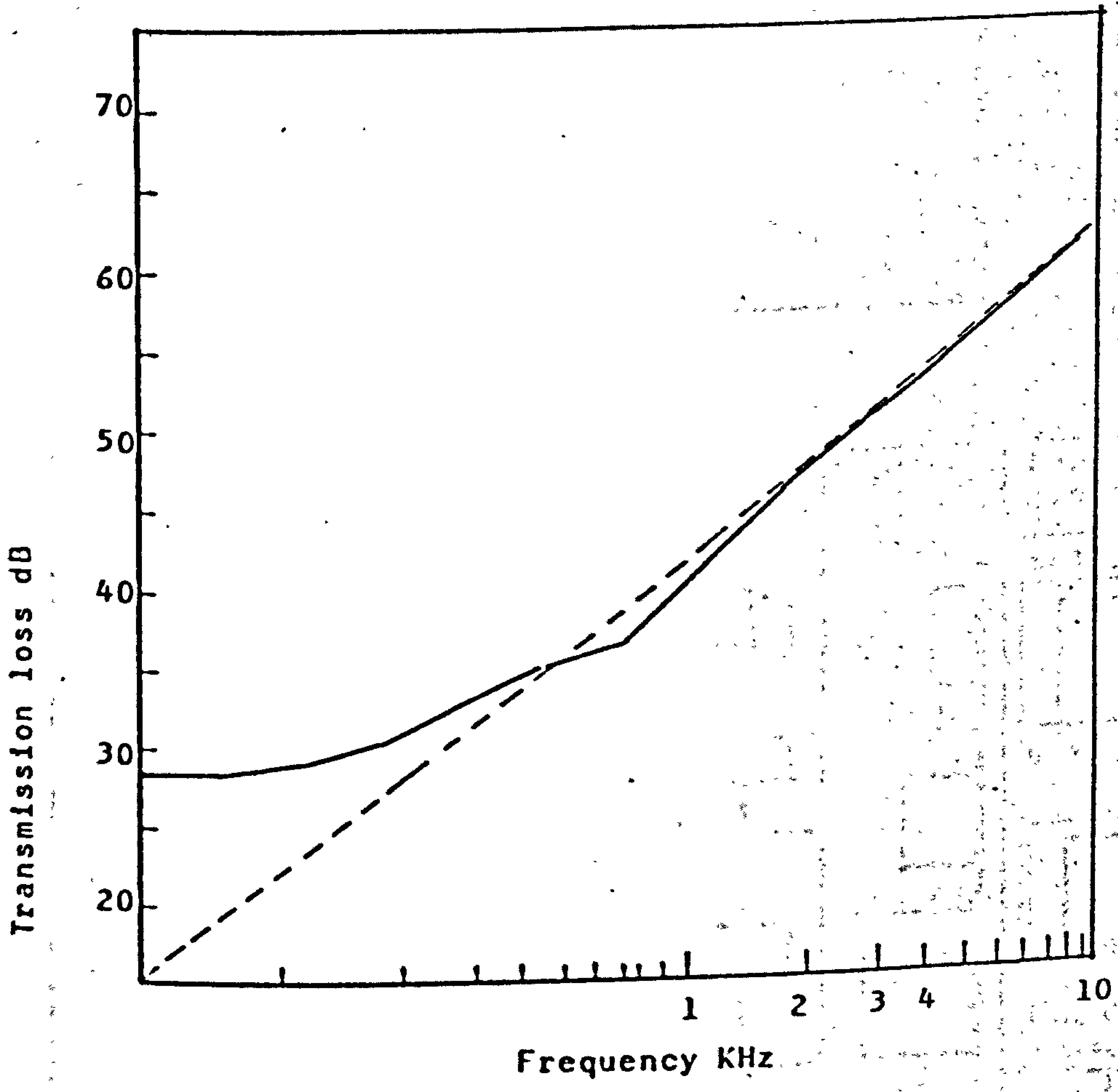


Fig.8.3



The transmission loss of perspex of thickness 13mm

Fig. 8.4

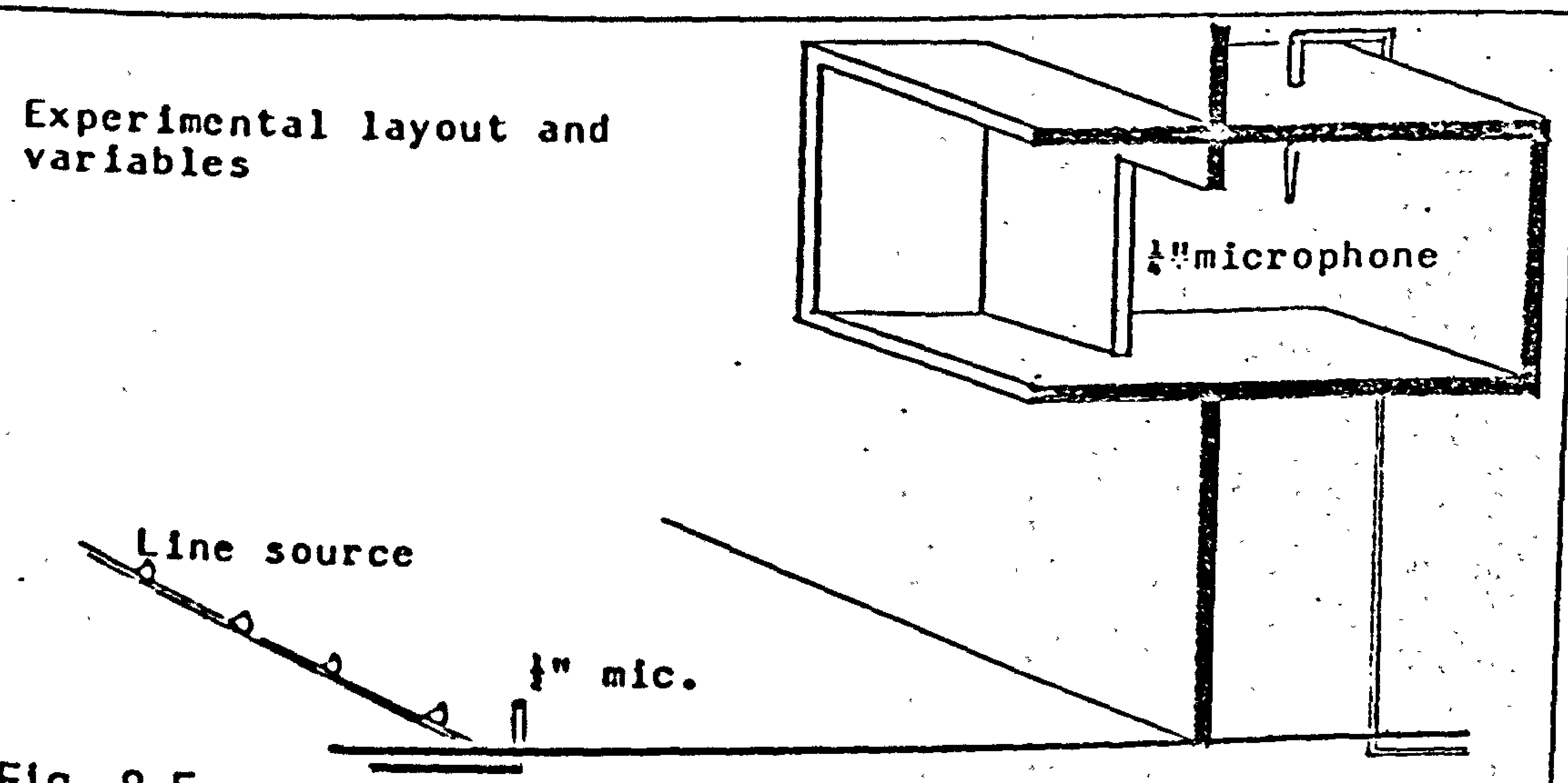
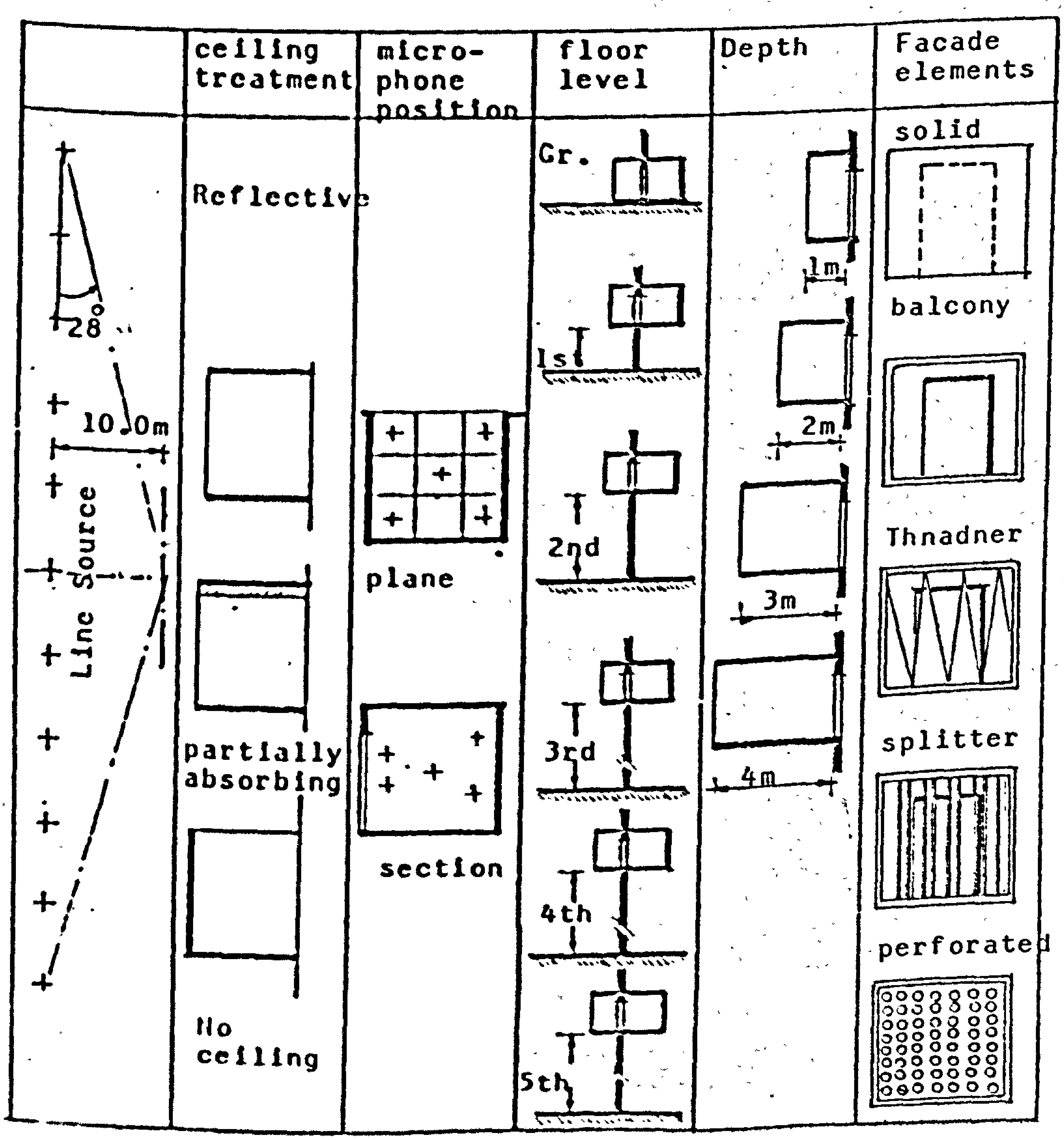
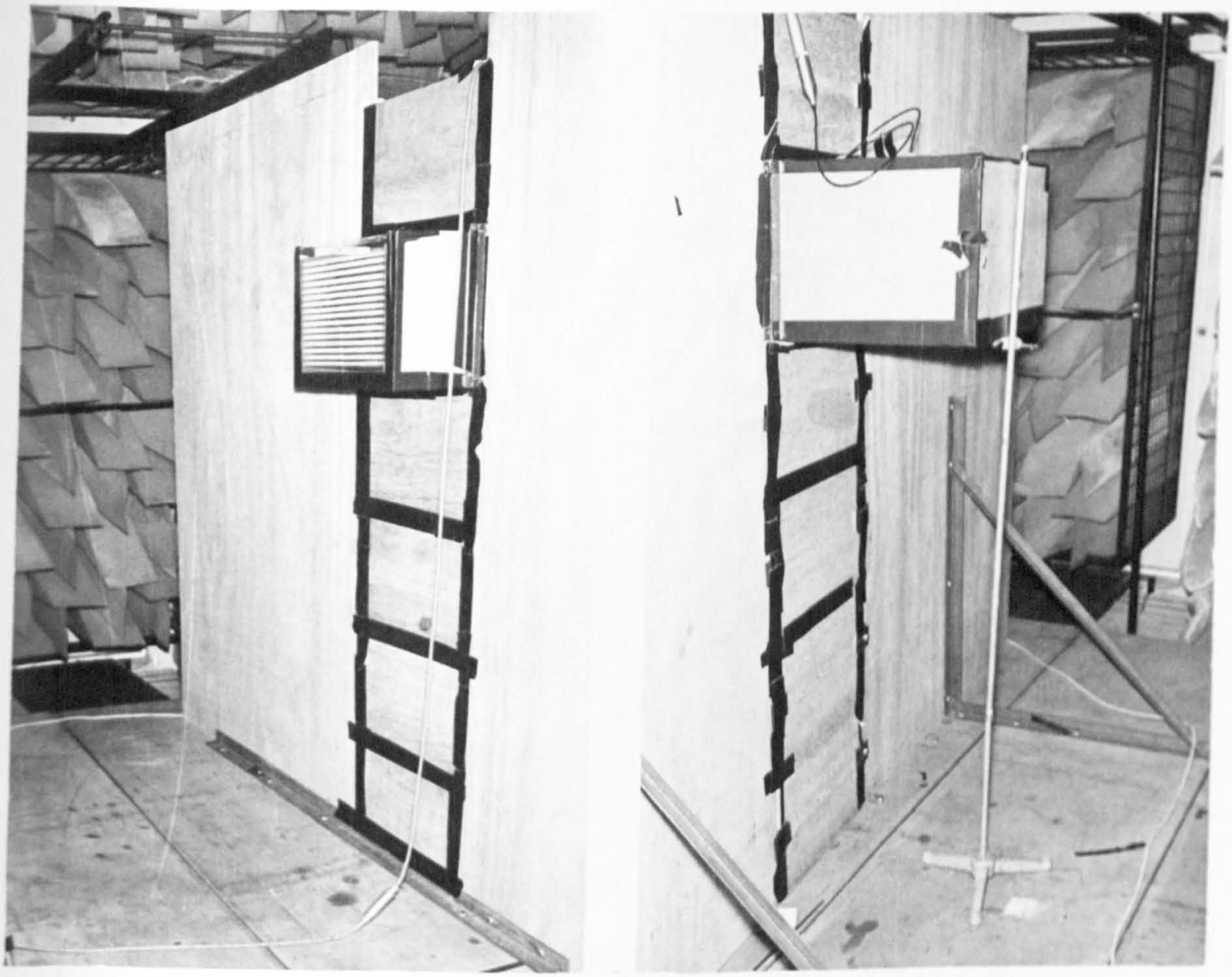
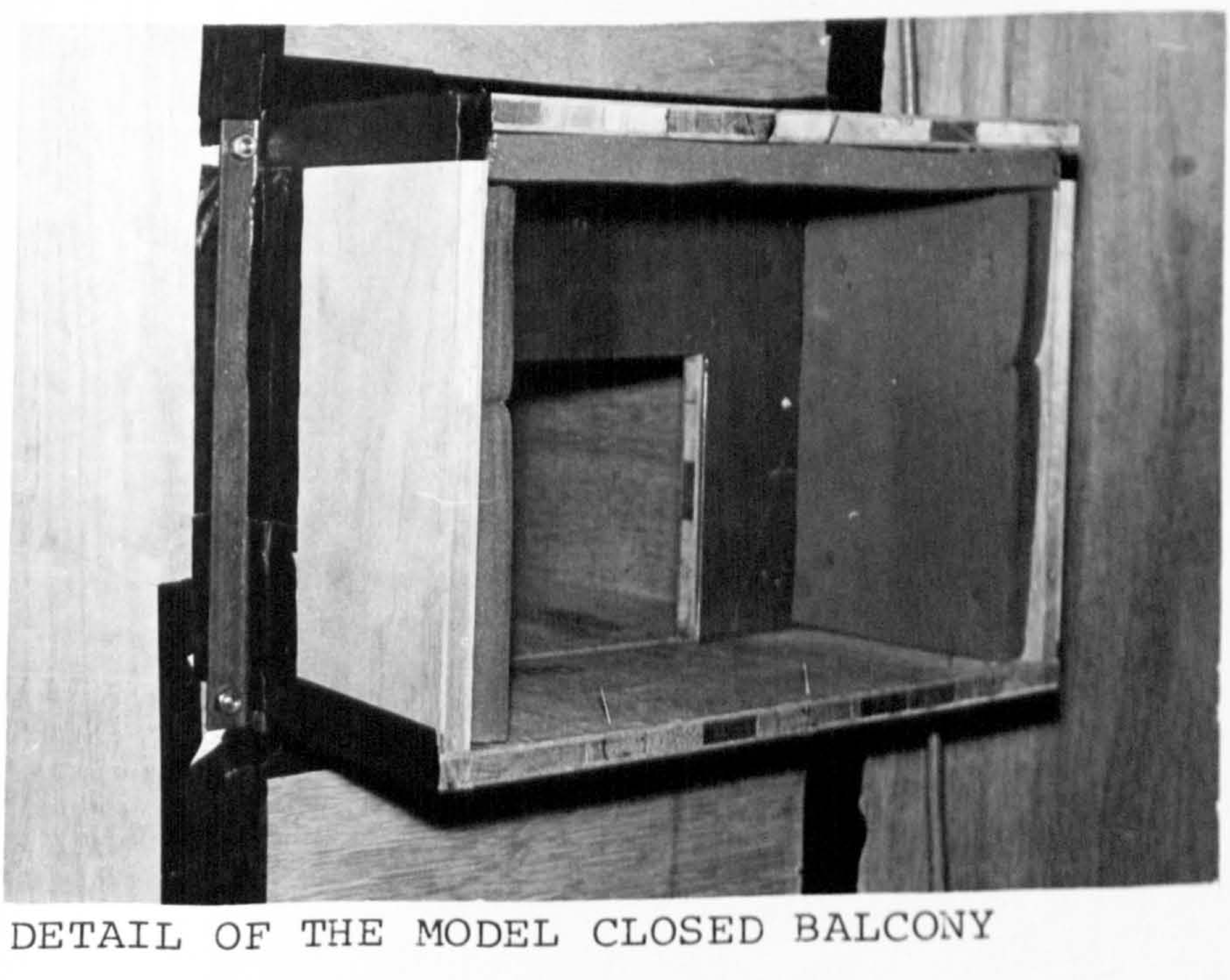

Experimental layout and variables
¼"microphone
Line source
¼" mic.

Fig. 8.5

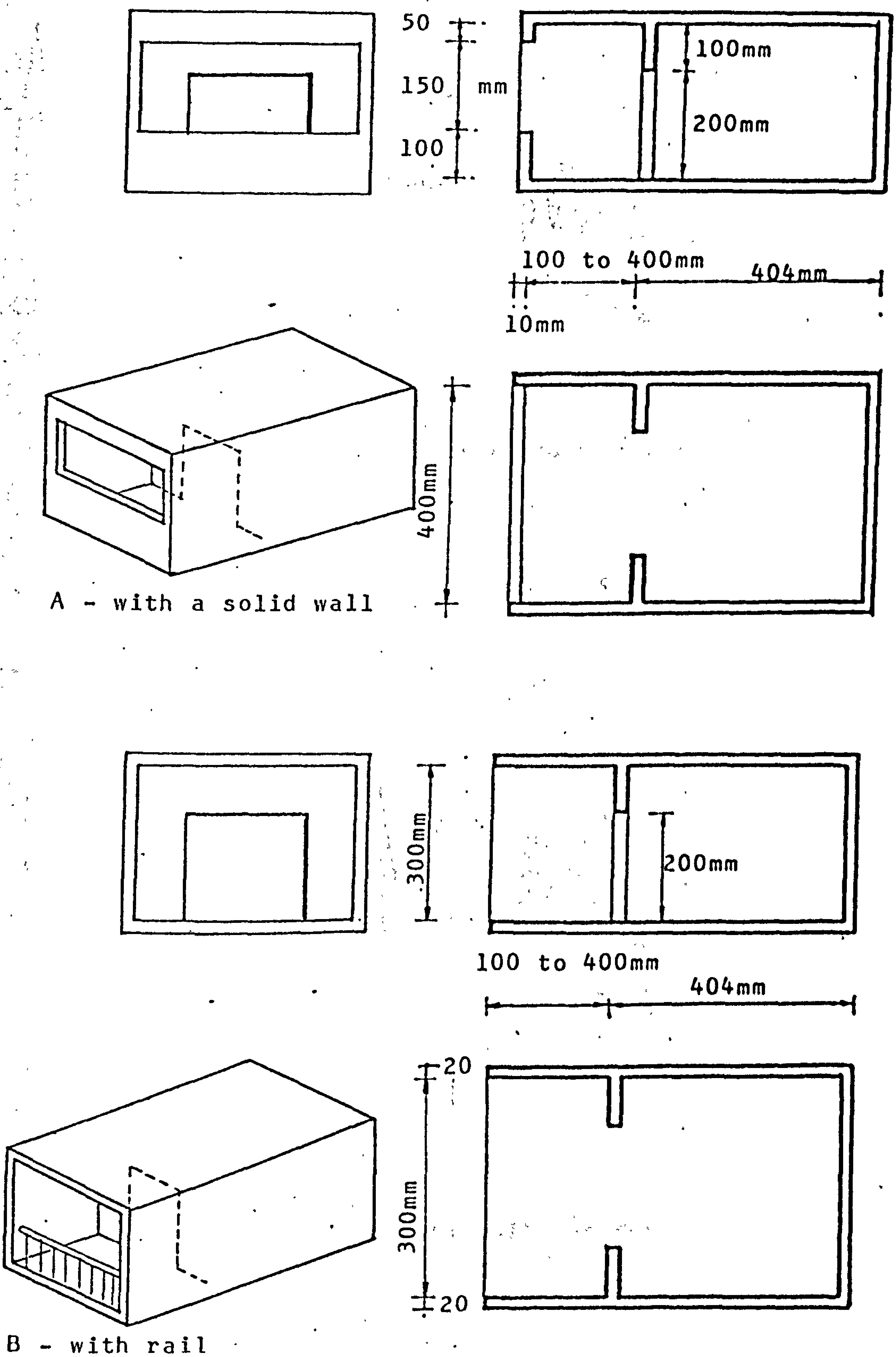

ceiling treatment
micro-phone position
floor level
Depth
Facade elements
28°
10.0m
Line Source
Reflective
partially absorbing
No ceiling
plane
section
Gr.
1st
2nd
3rd
4th
5th
1m
2m
3m
4m
solid
balcony
Thnadner
splitter
perforated



EXPERIMENTAL SET-UP OF THE MODEL ROOM AND FACADE SEEN FROM BOTH SIDES



DETAIL OF THE MODEL CLOSED BALCONY



Closed Balcony

Fig. 8.7

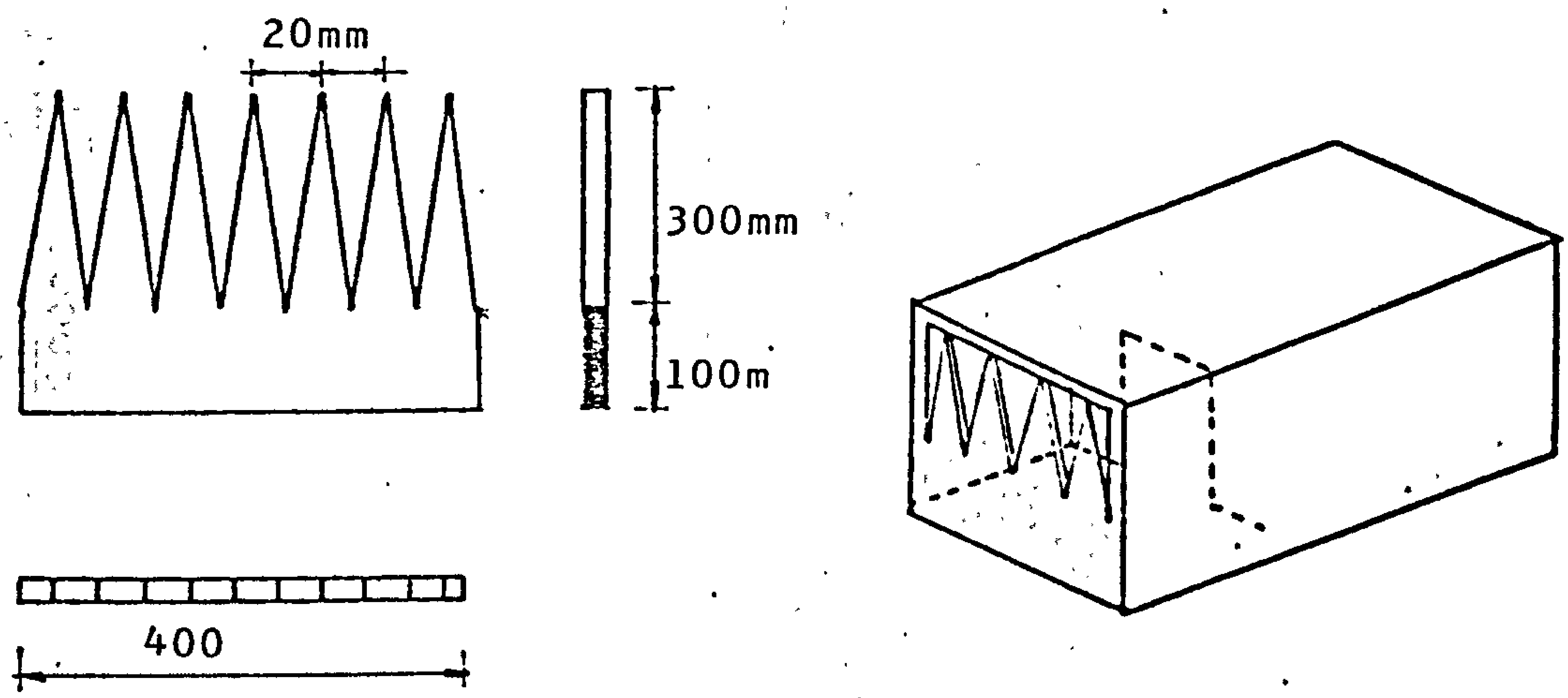


Fig. 8.8 Balcony with Thnadner screen

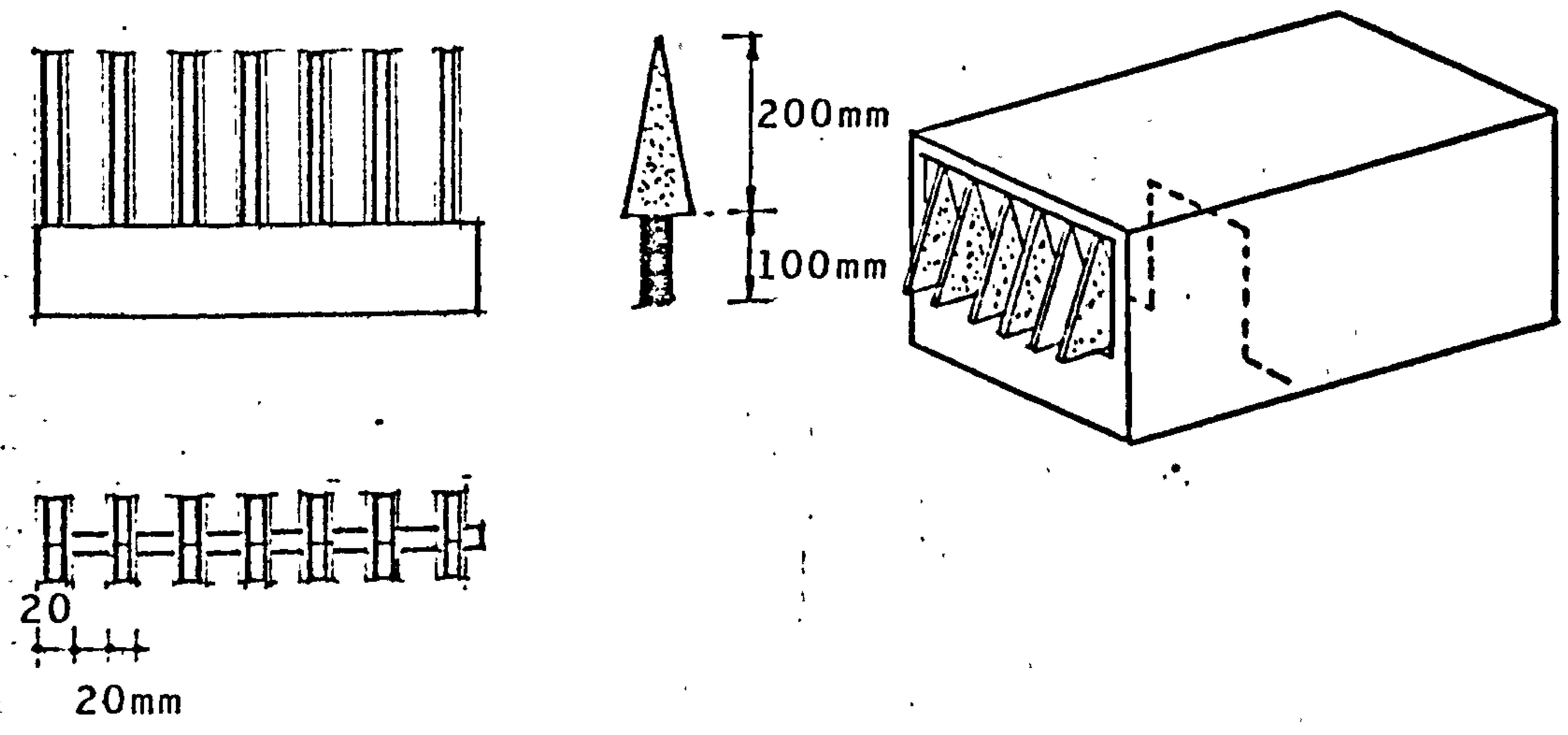


Fig. 8.9 Balcony with splitter screen

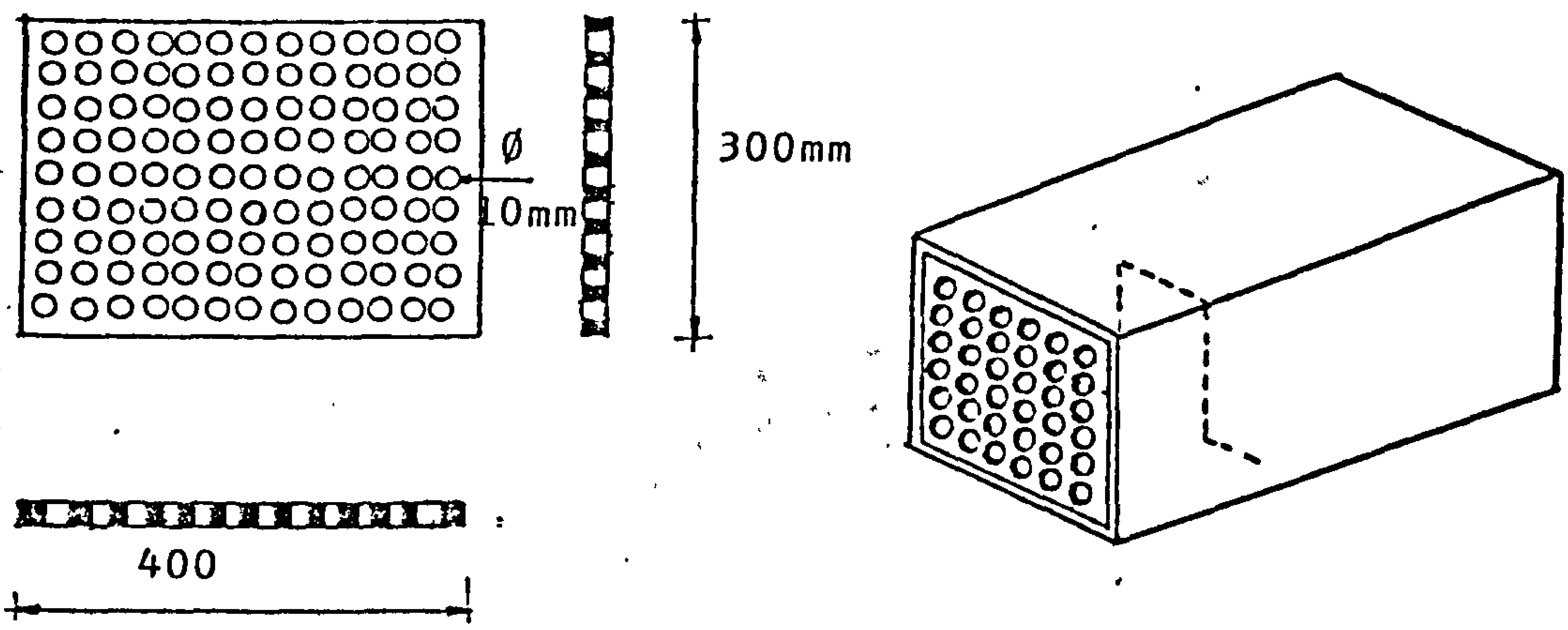


Fig. 8.10 Balcony with conventional perforation

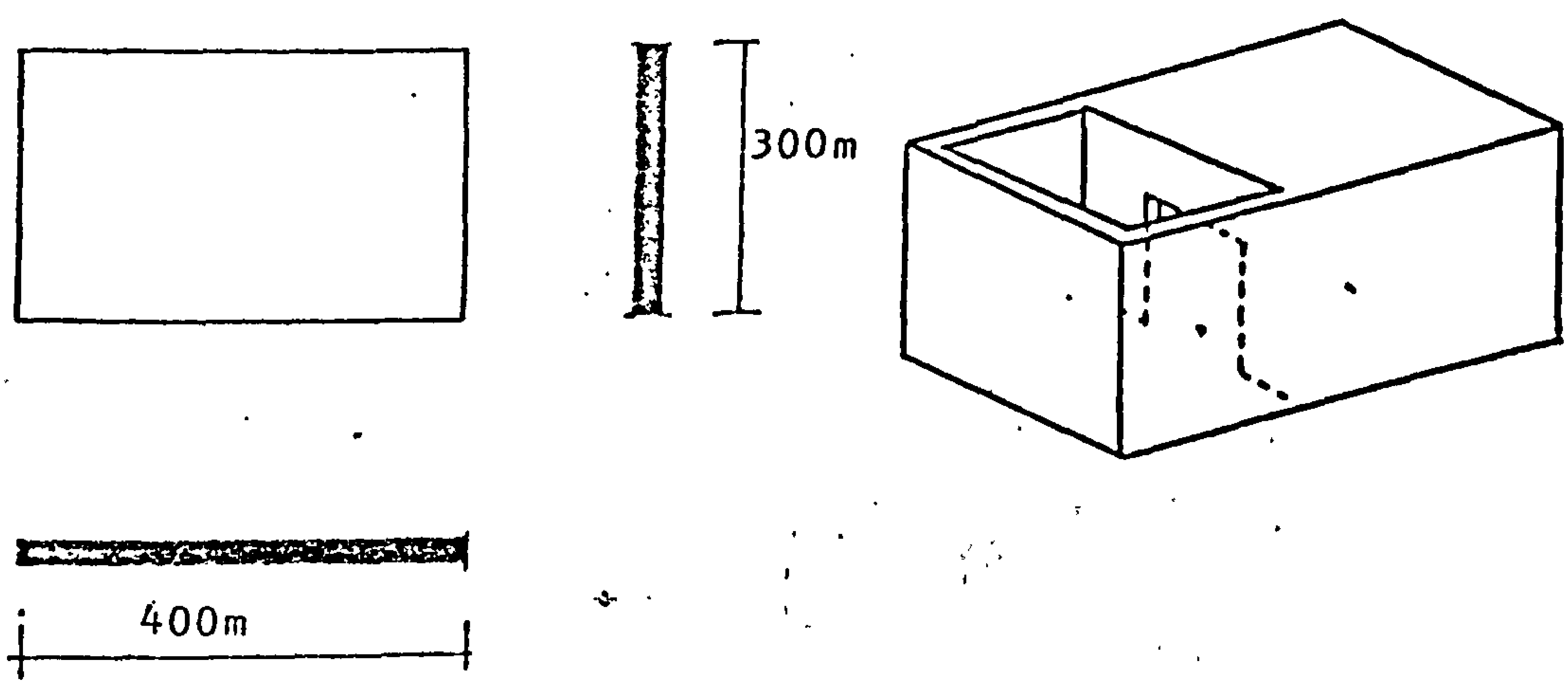


Fig. 8.11 Courtyard with a solid wall (reference wall).

Effect of ground reflection

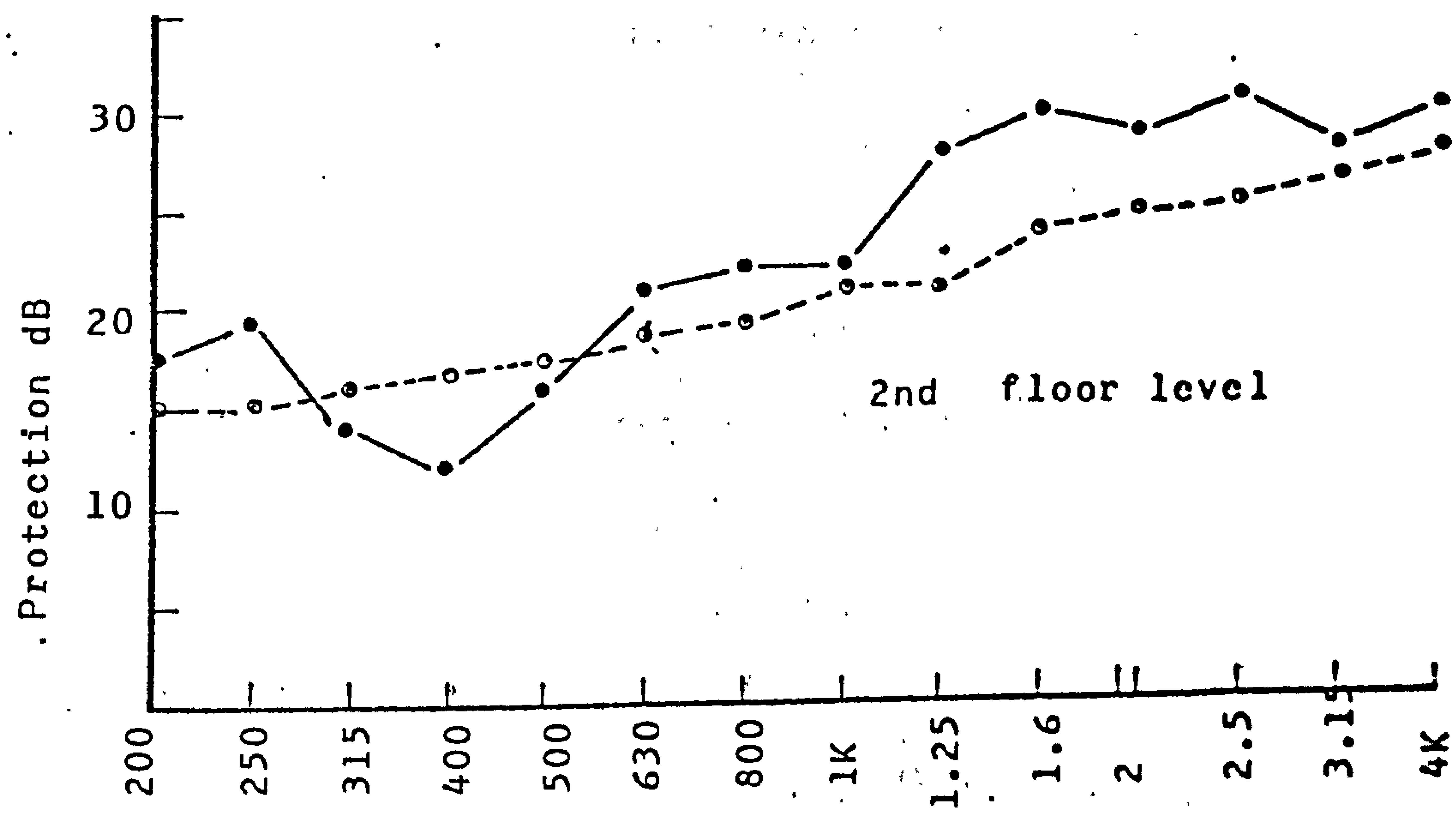


Fig. 8.12

• reflective ground
o absorptive ground

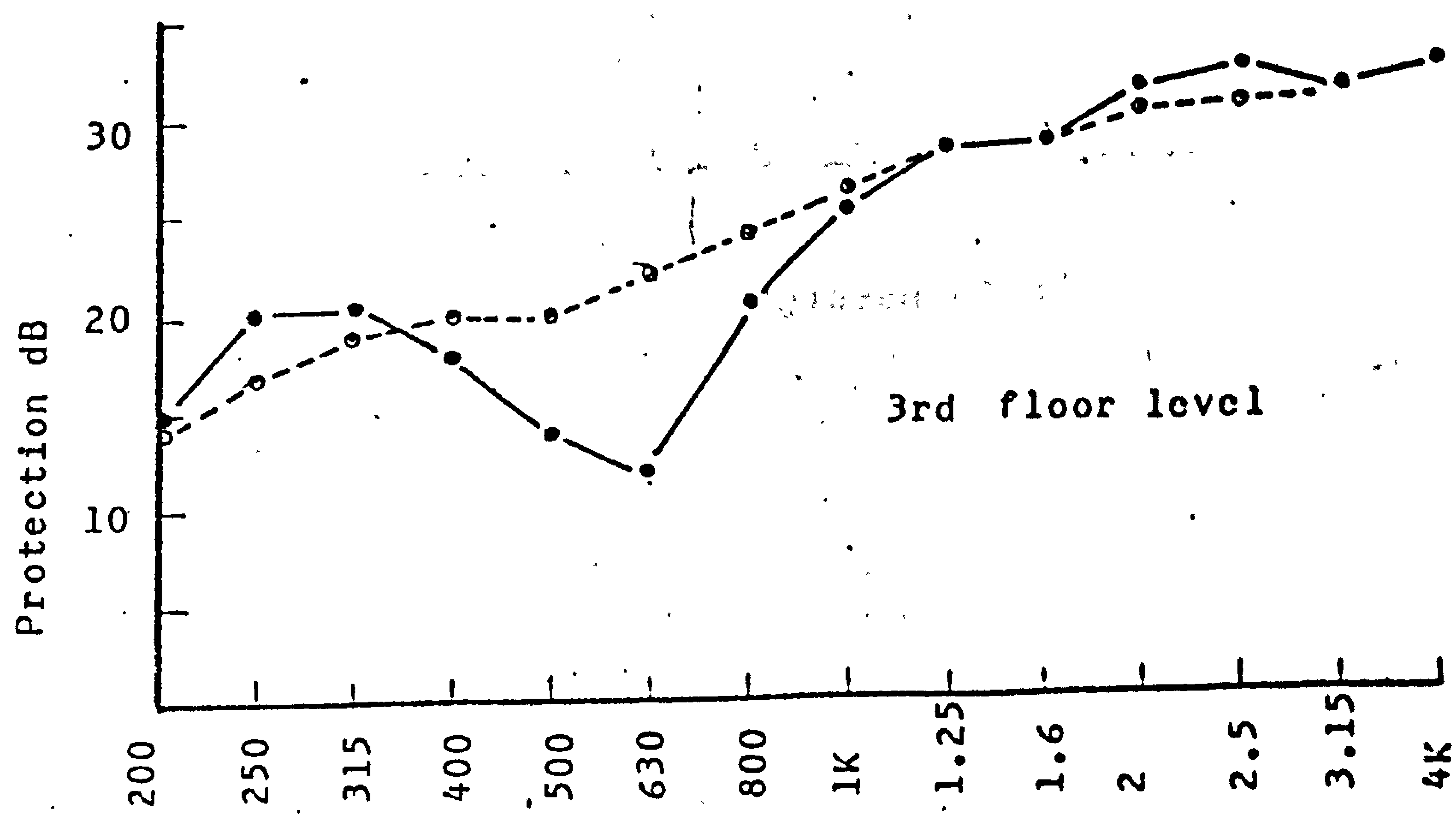
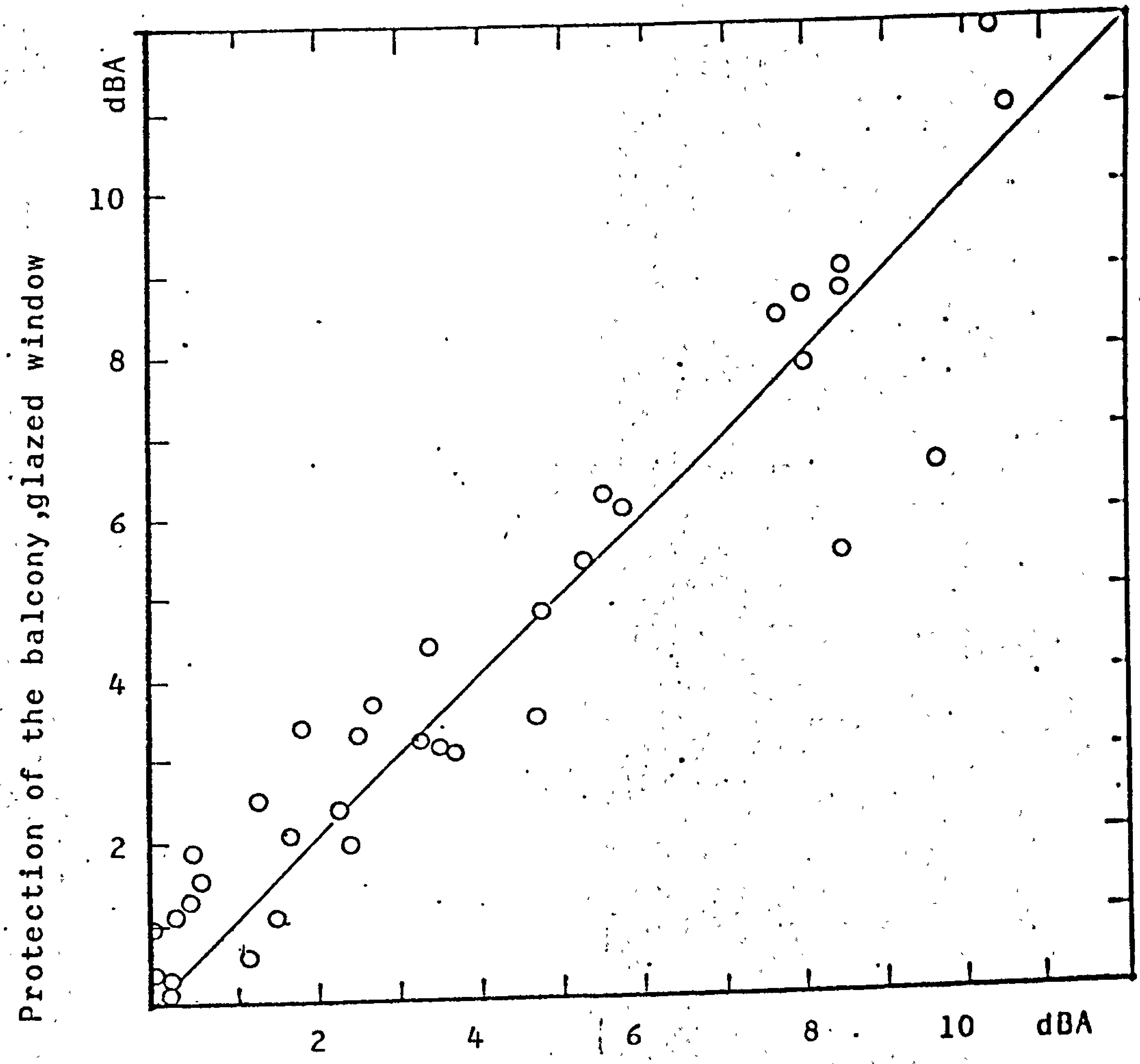


Fig. 8.13

Effect of glazing on performance of a balancony



Protection of the balcony with unglazed window

Fig. 8.14

Reverberation - time measurement

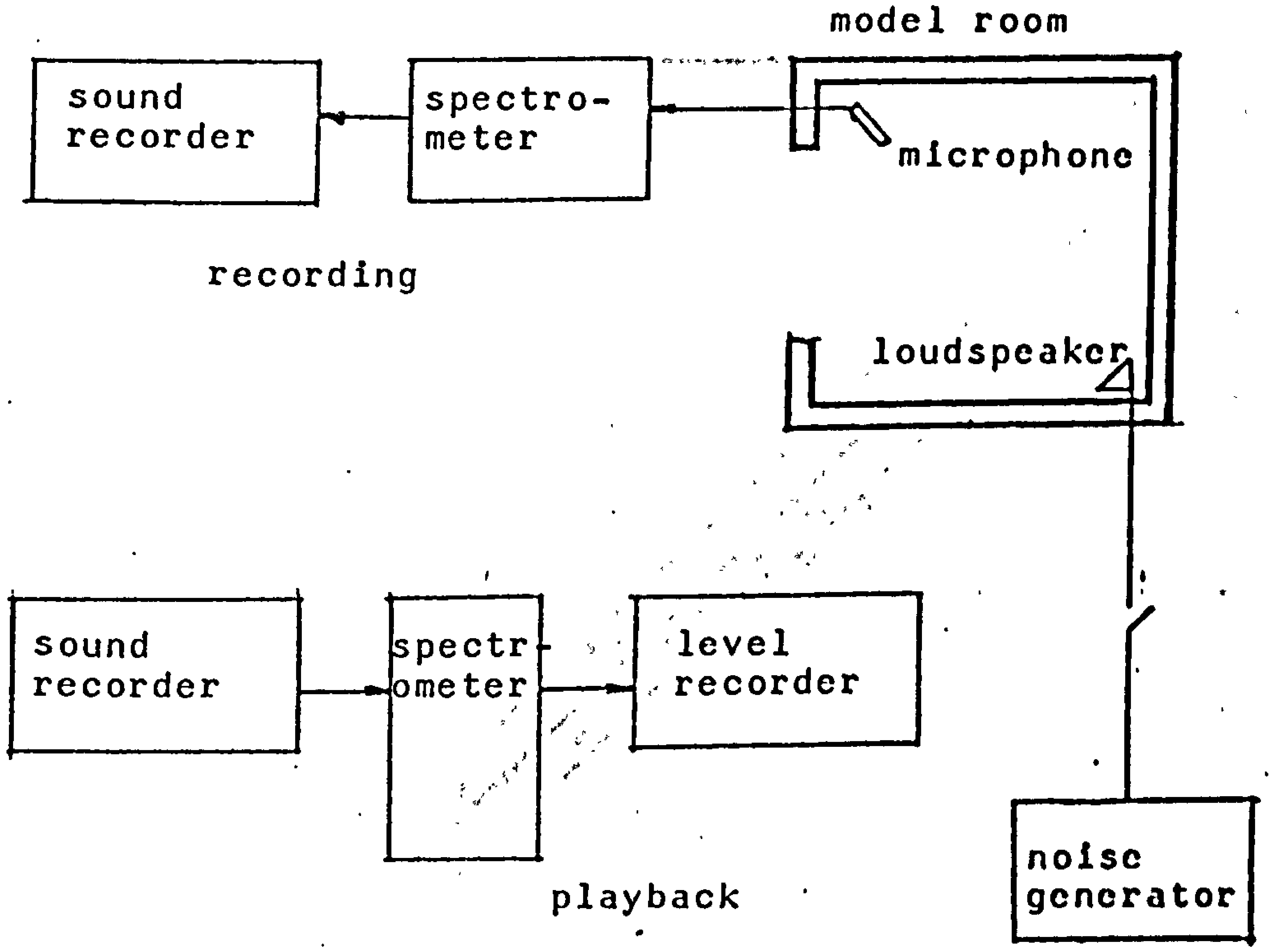


Fig.8.15 Reverberation time of the model room

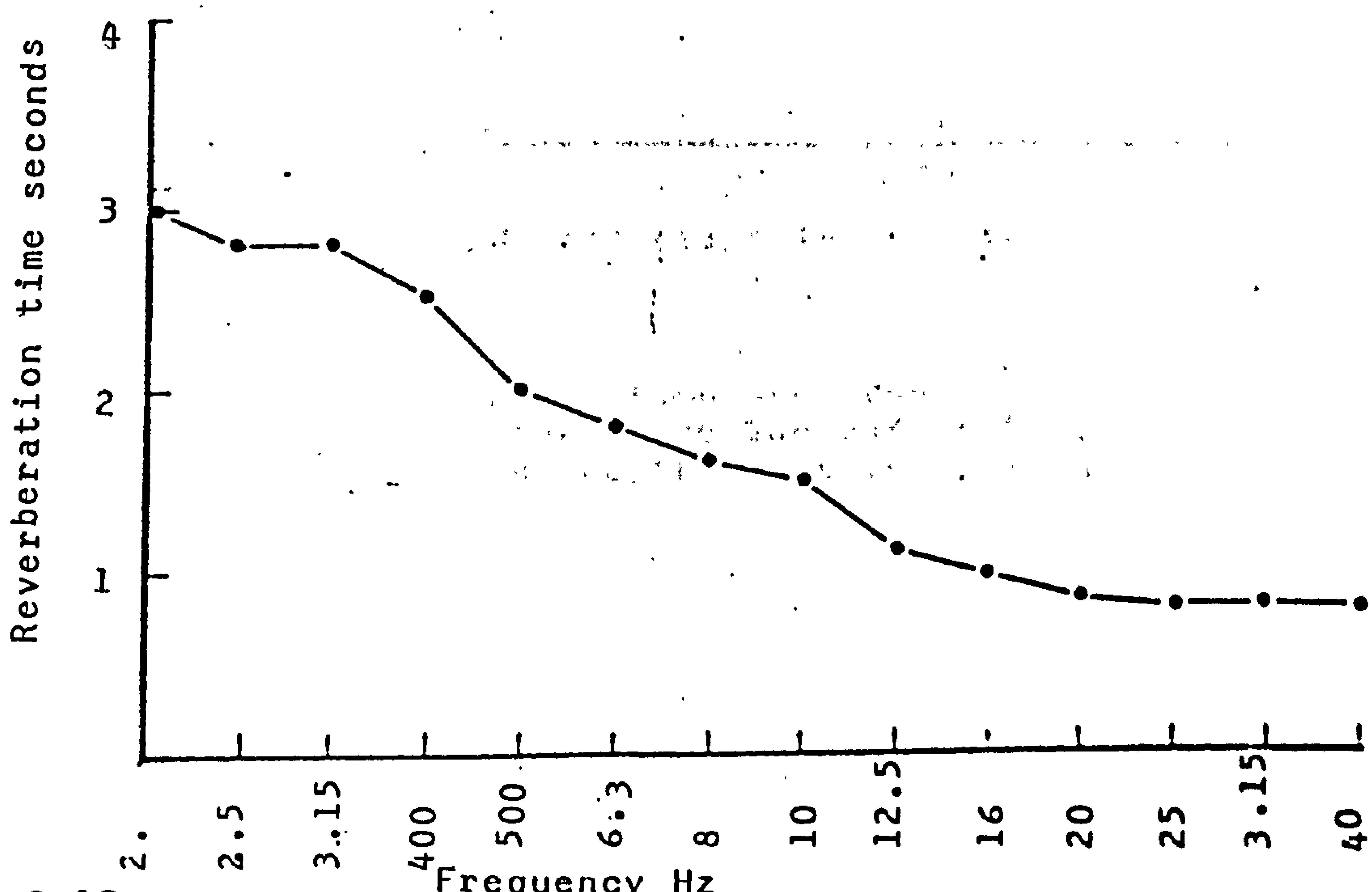
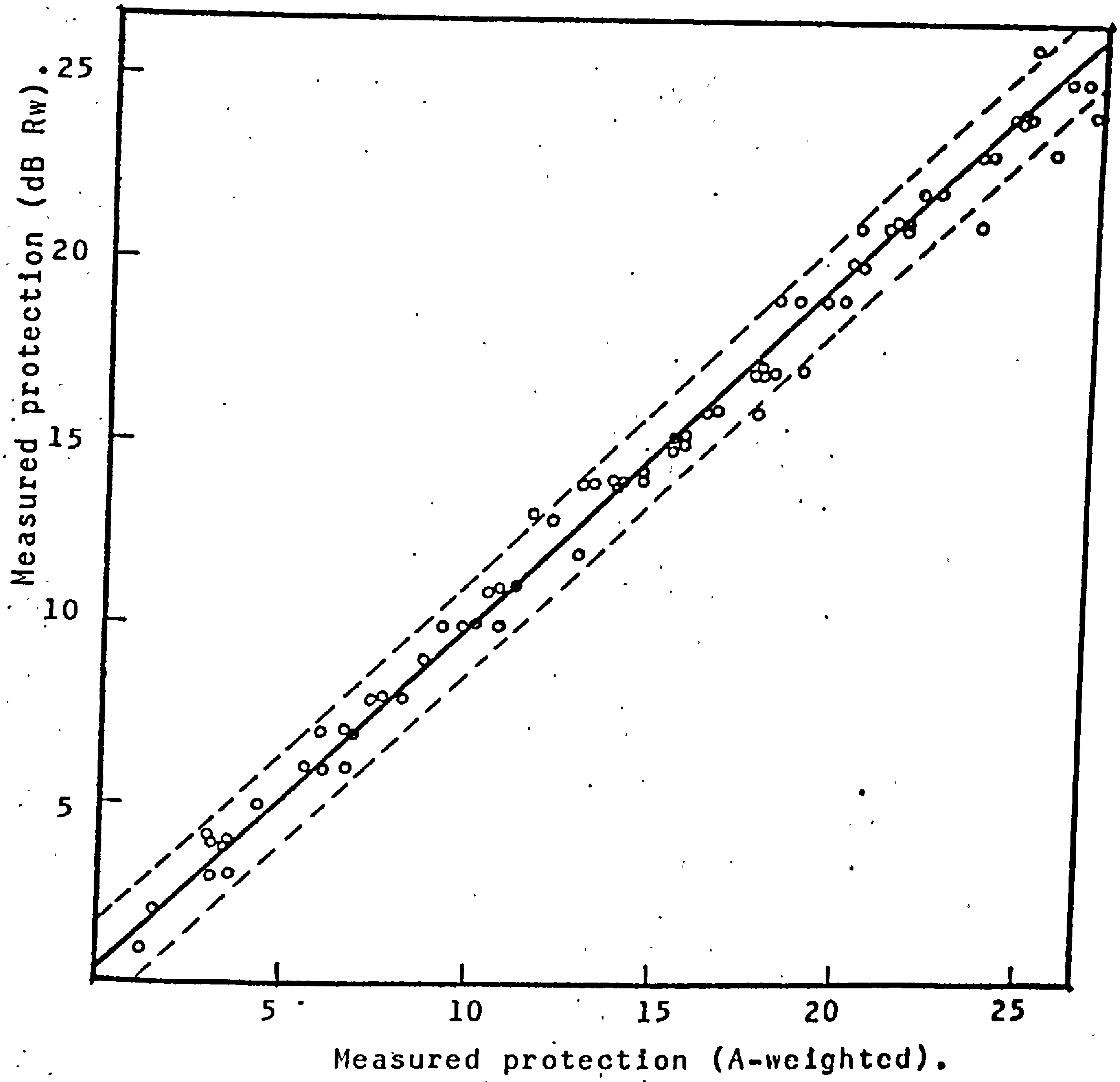
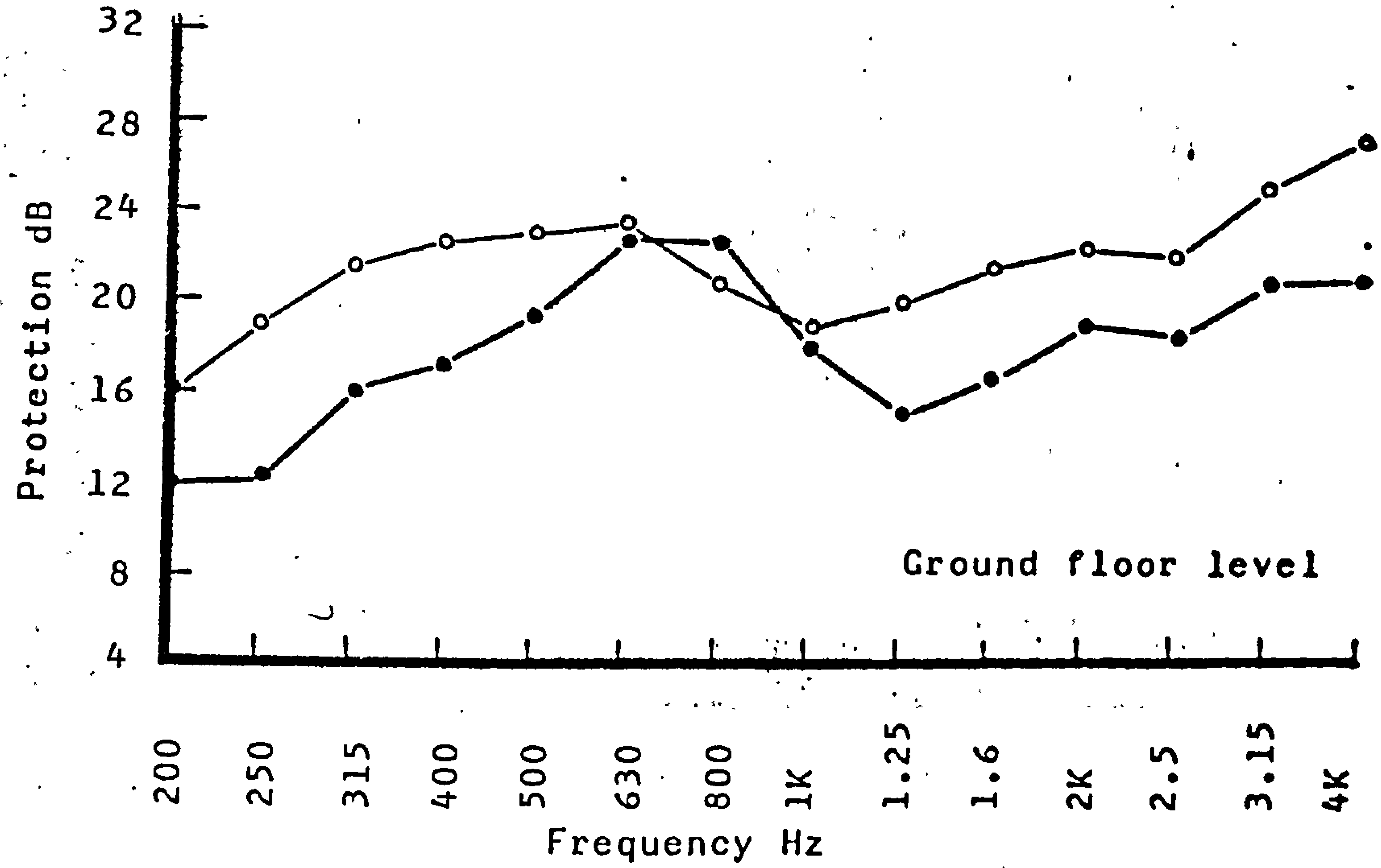


Fig.8.16



Comparison of A-weighted protection and sound insulation index rating (Rw). Also shown are the 95% confidence limits where the correlation coefficient is 0.994.

Fig. 9.1



Measured protection of a courtyard with a thnadner or solid wall.

• Thnader wall
o solid wall

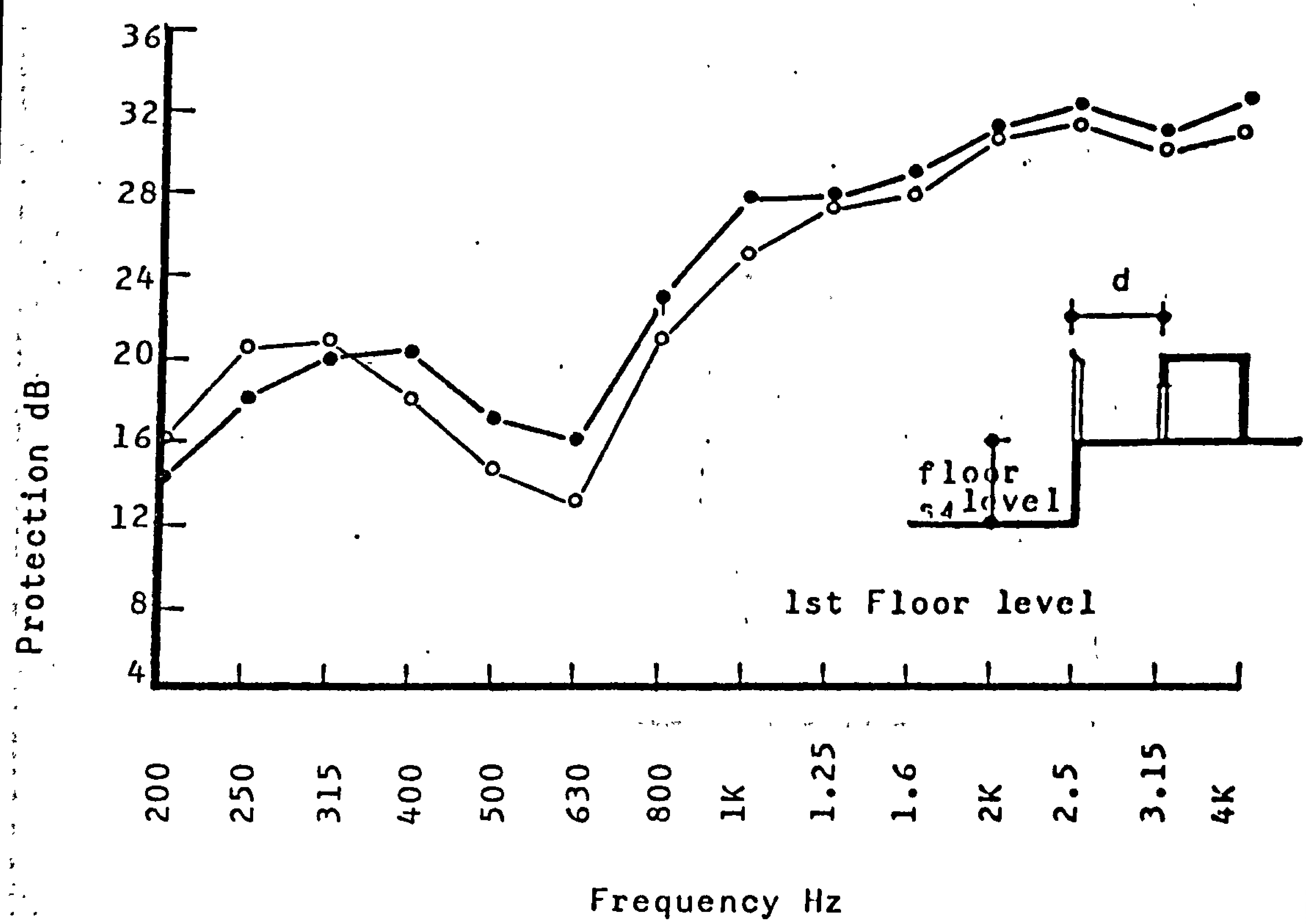
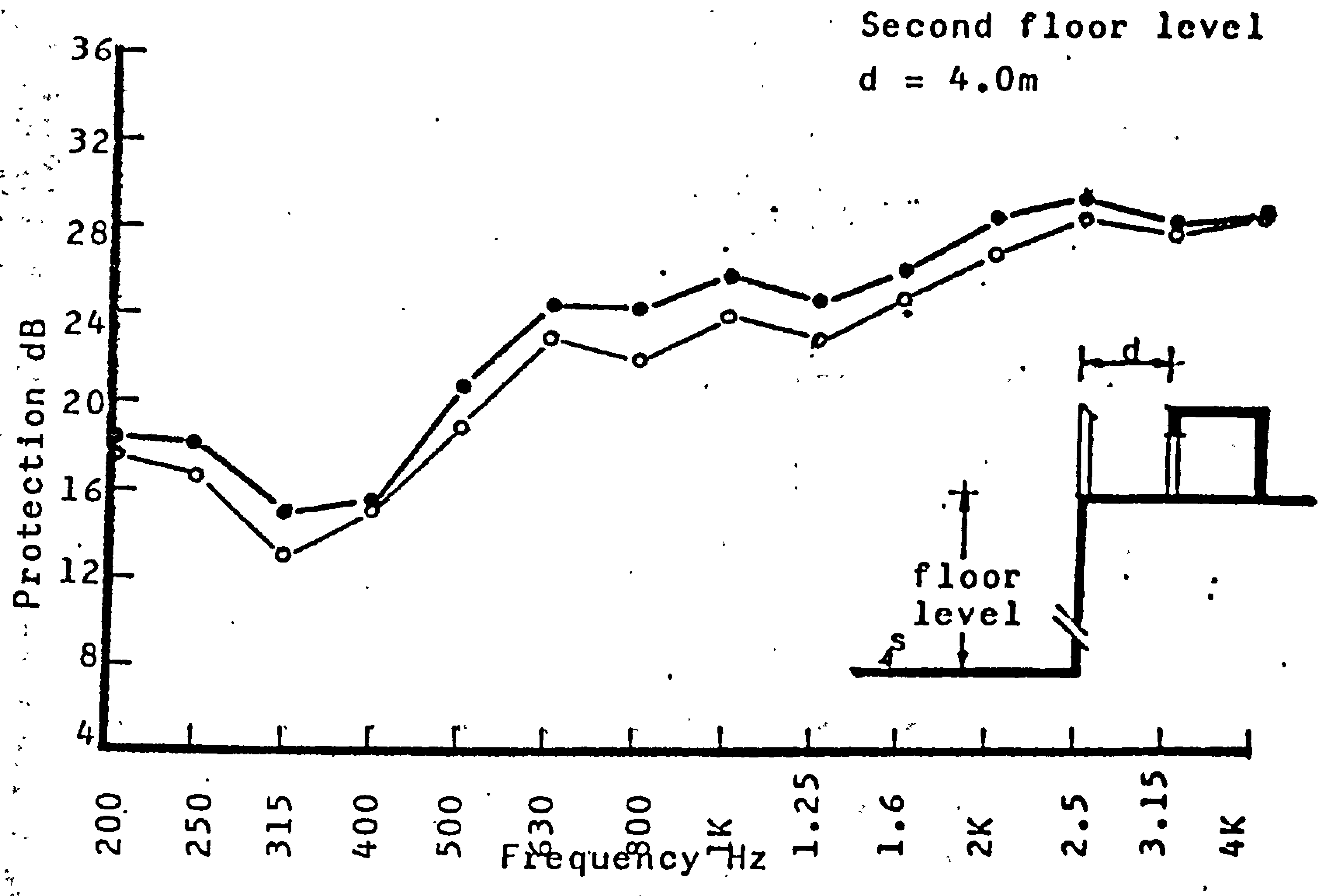


Fig. 9.2



Measured protection of a courtyard with a thnadner or solid wall.

- • Thnadner wall
- o Solid wall

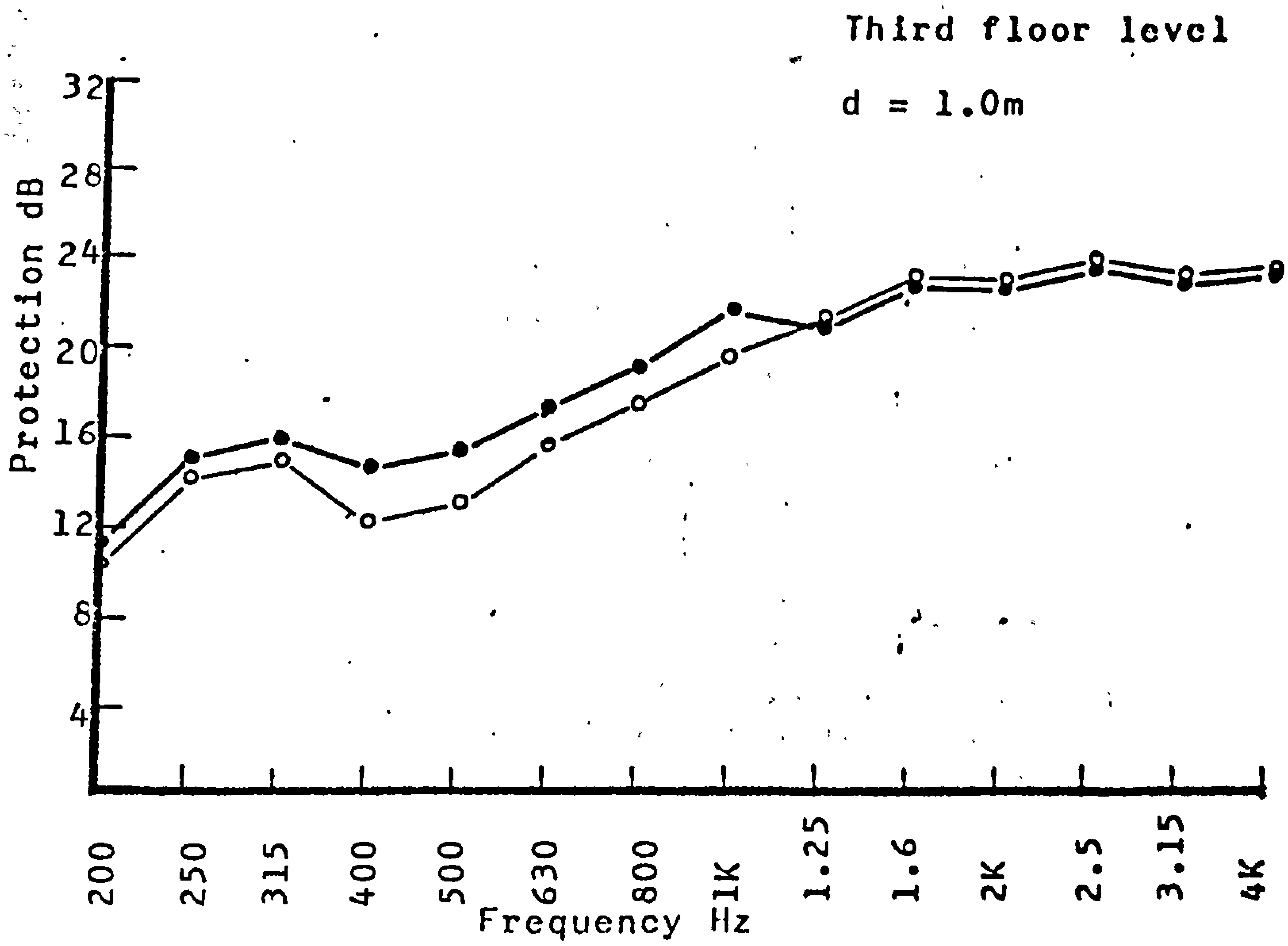
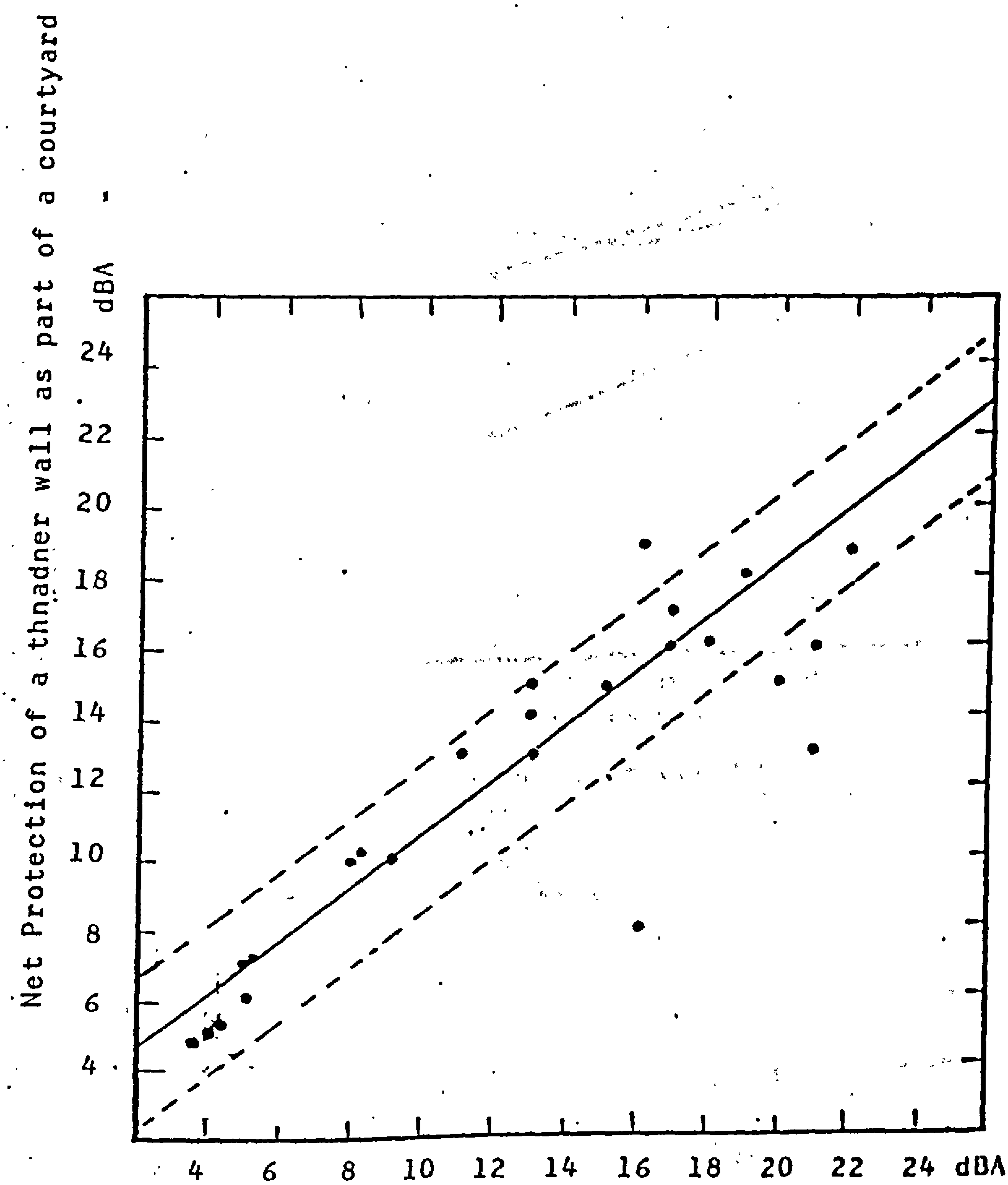


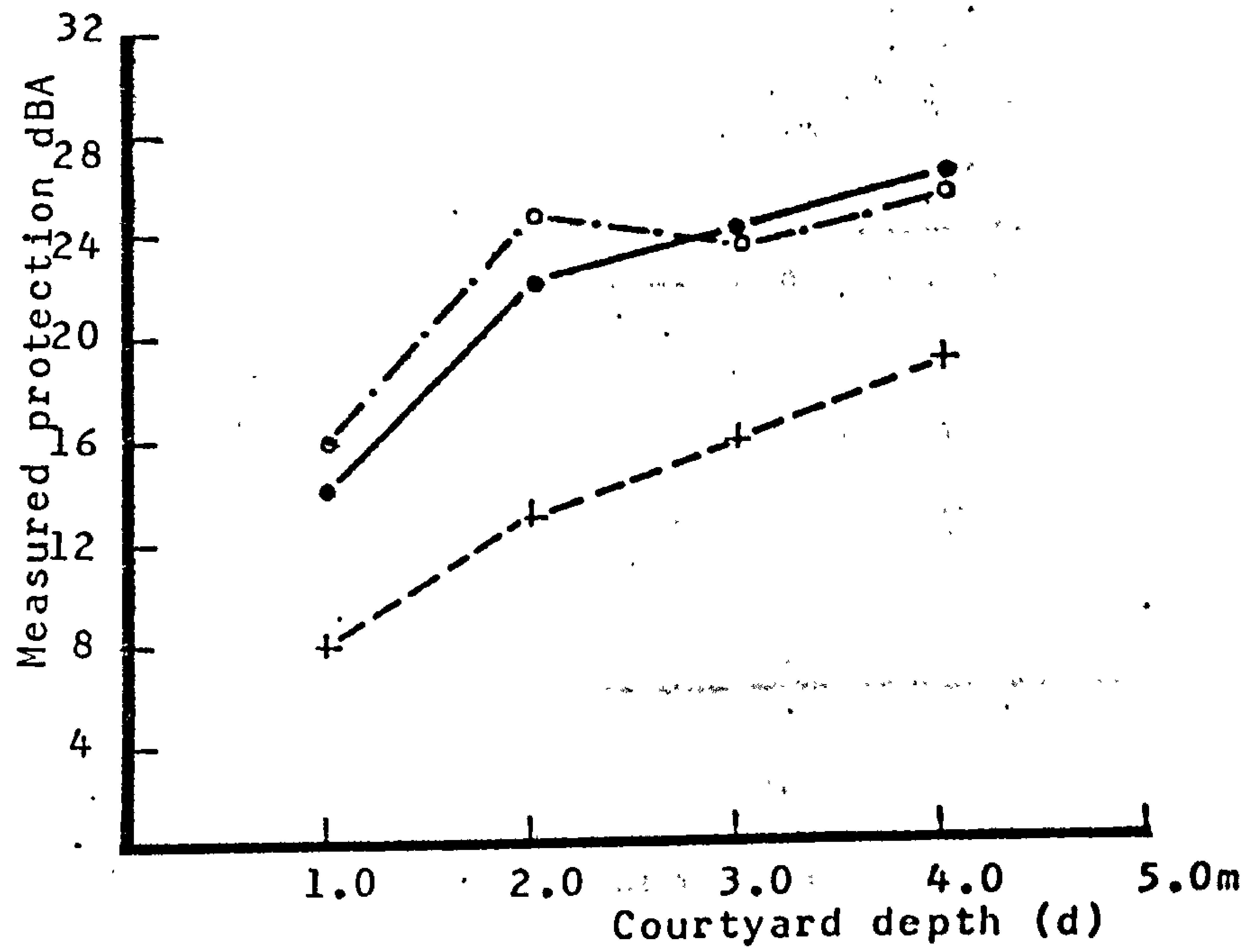
Fig. 9.3



Net protection of a solid barrier as a part of a courtyard.

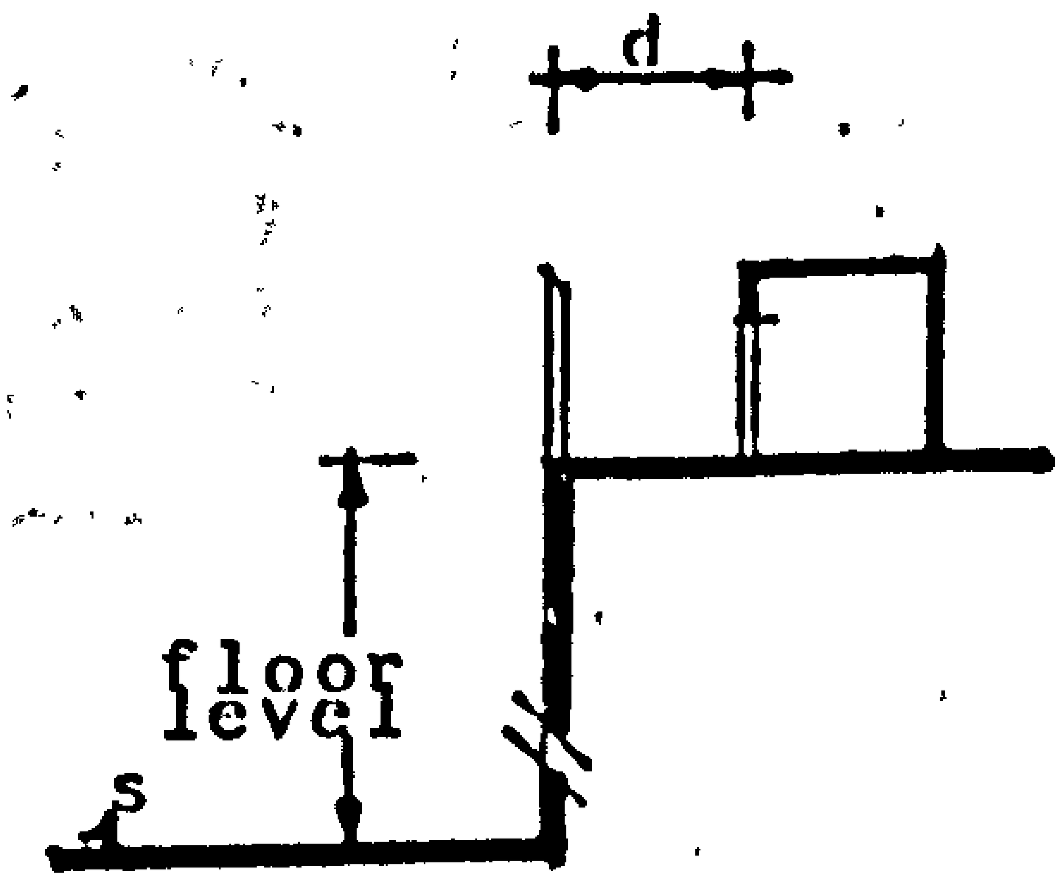
Comparison of net protection of a thnadner and solid wall as a part of a courtyard. Also shown are the 80% confidence limits where the correlation coefficient is 0.8

Fig. 9.4



Measured protection of a thnadner courtyard.
Effect of courtyard depth.

+ Gr. levels; - ● 1st;
o 2nd; ▲ 3rd; ▽ 4th;
□ 5th



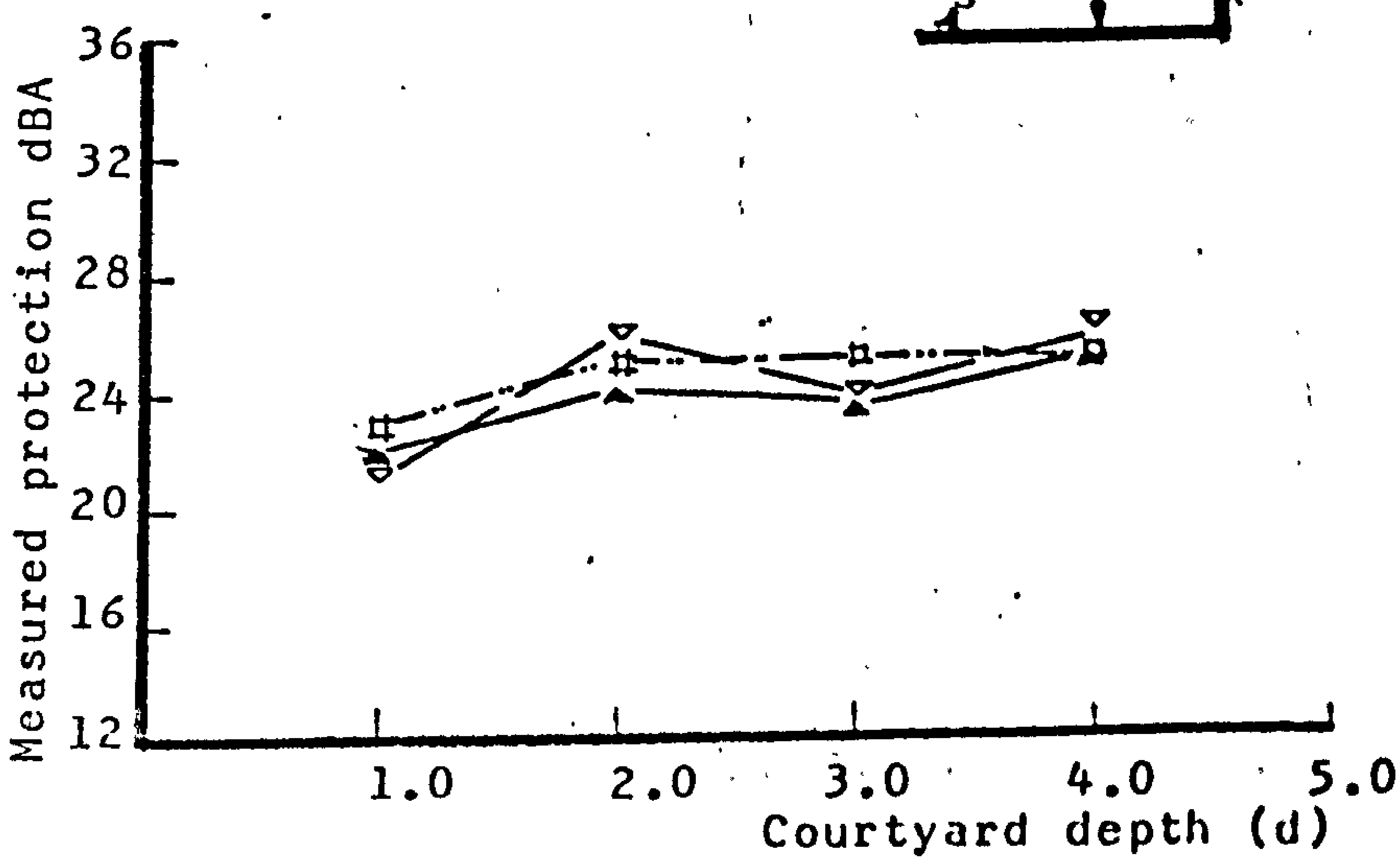


Fig. 9.5

Effect of Height from the Ground.

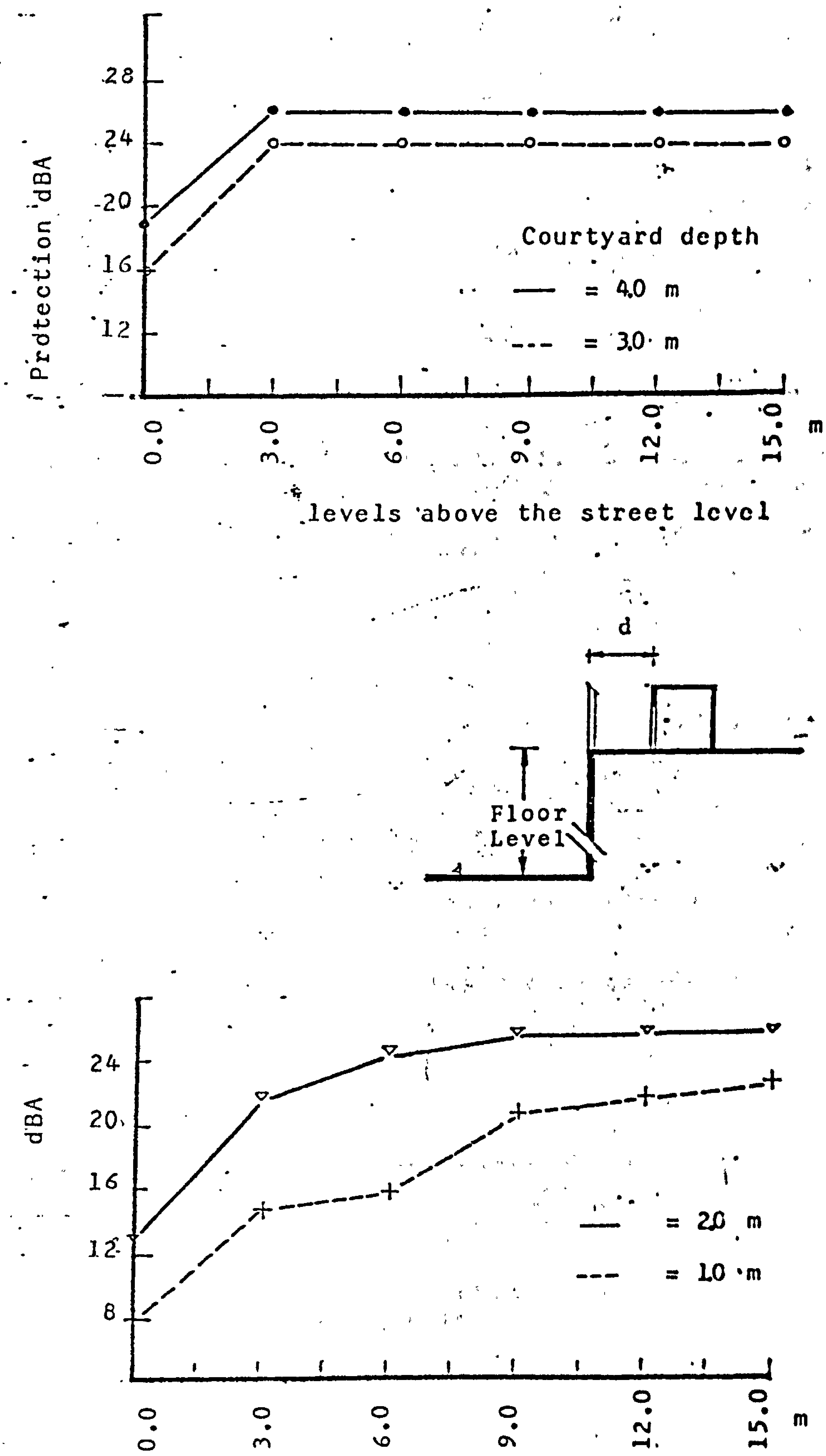
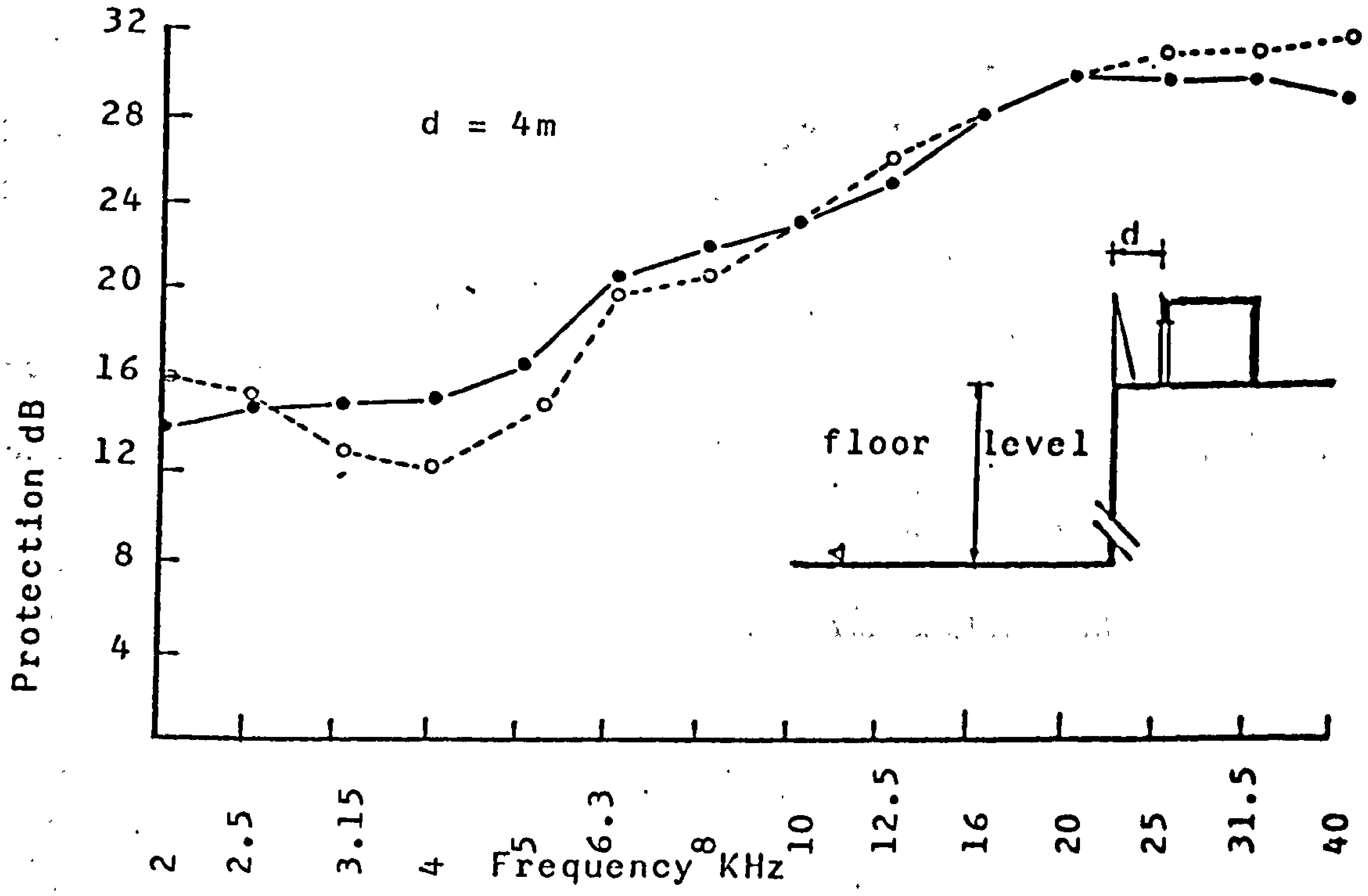
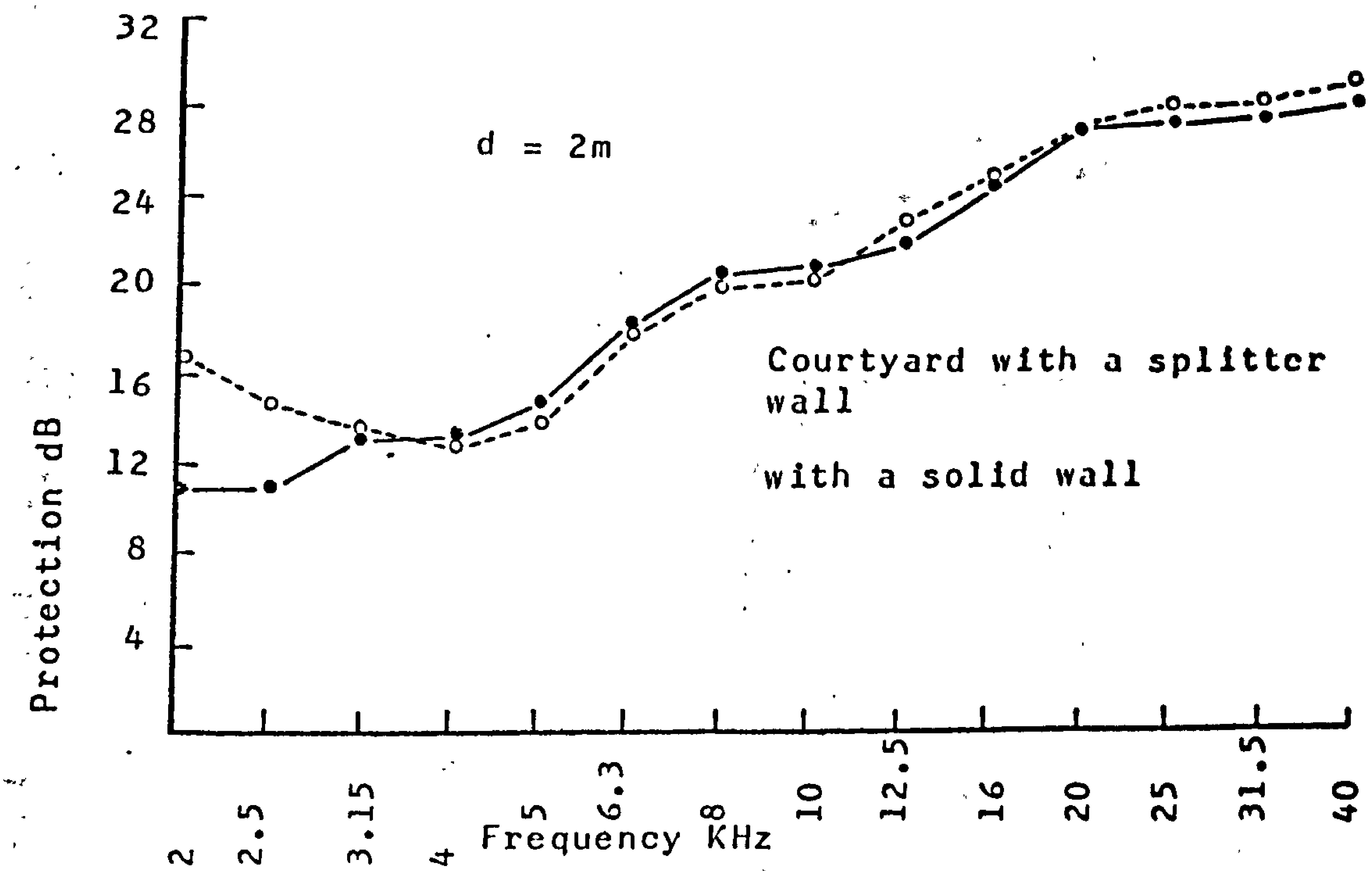


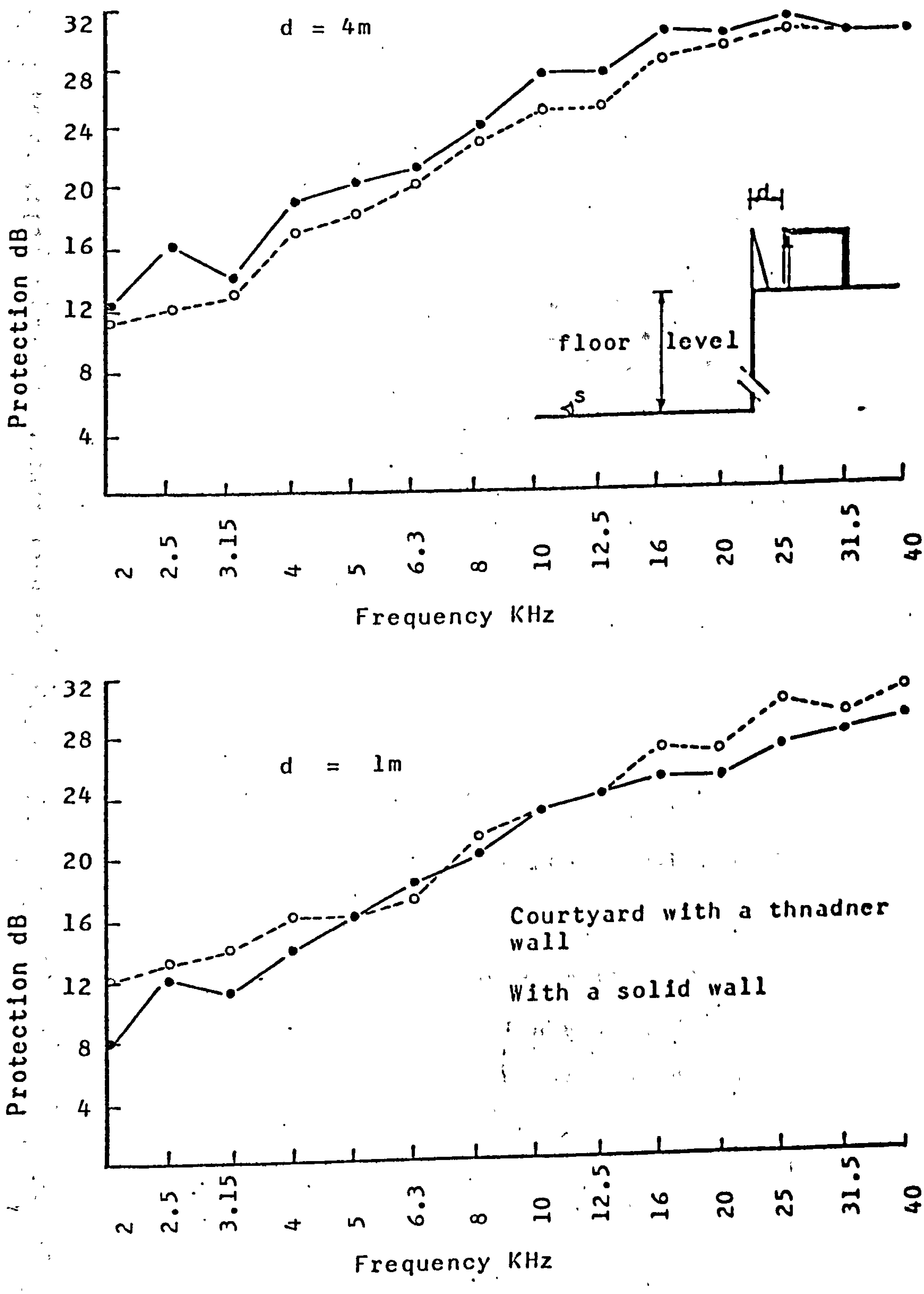
Fig. 9.6





Measured protection of a courtyard with a solid or splitter wall at 2nd floor level.

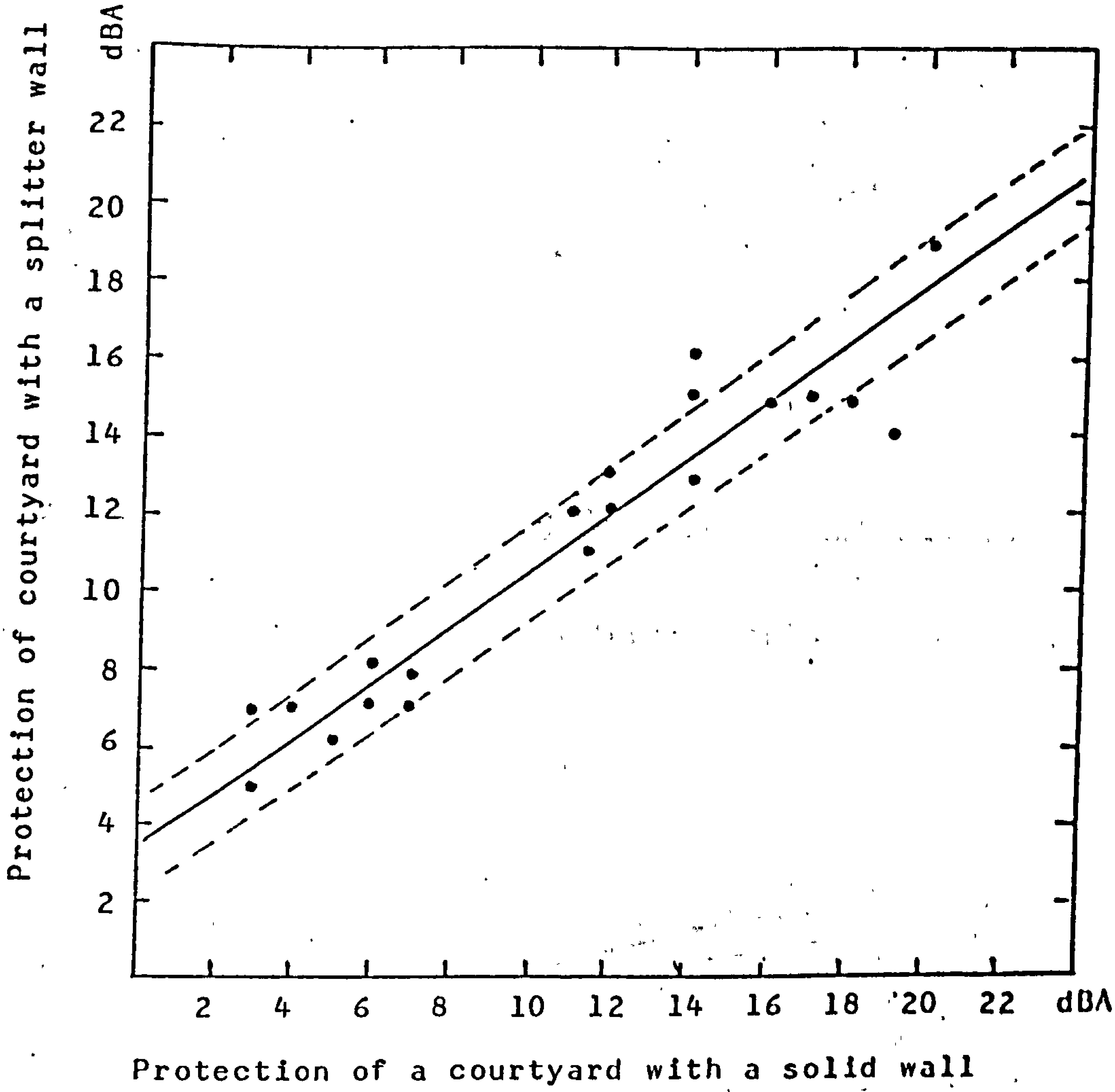
Fig. 9.7



Measured protection of a courtyard with a splitter wall at fourth floor level.

Fig. 9.8

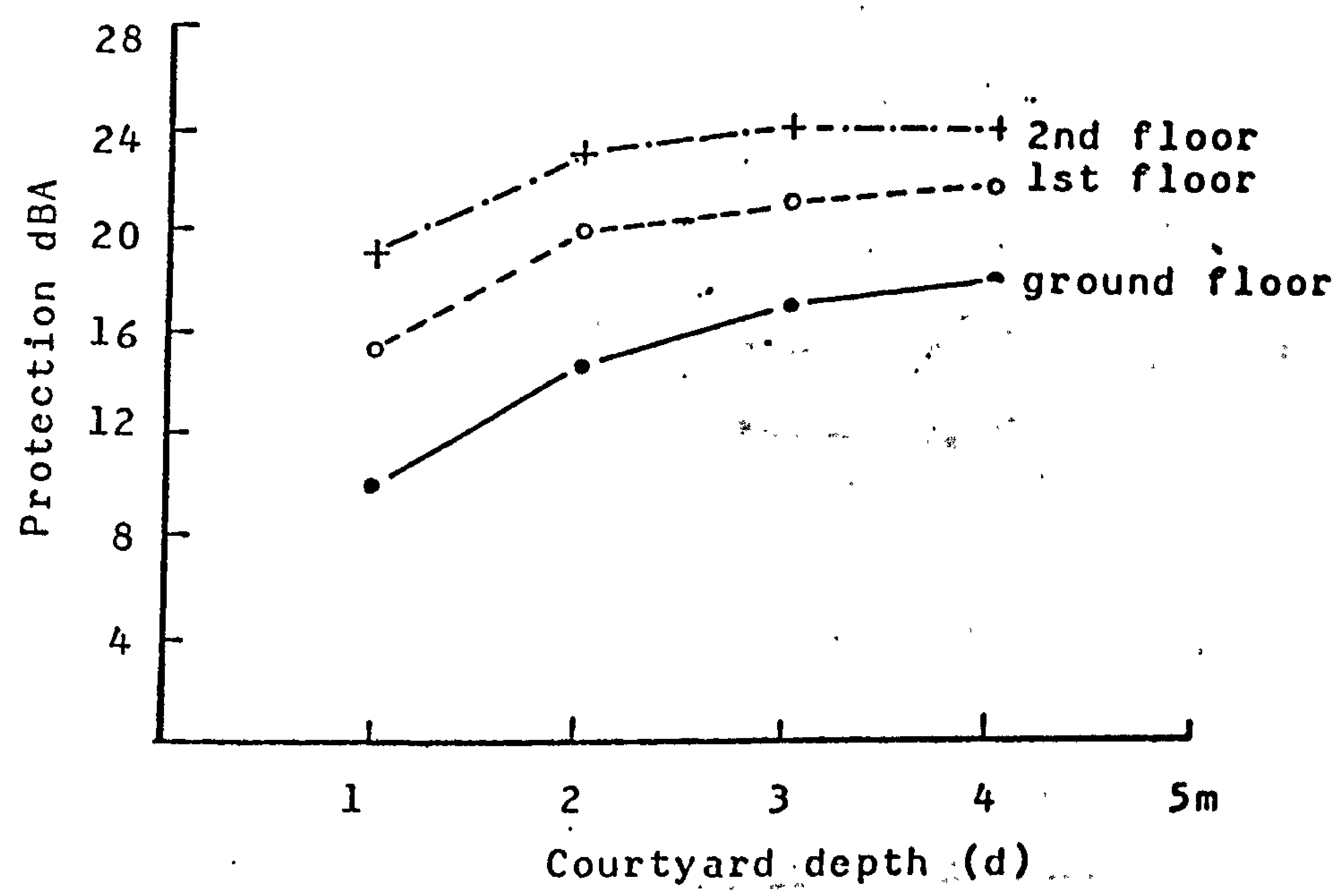
Measured protection of Courtyard.

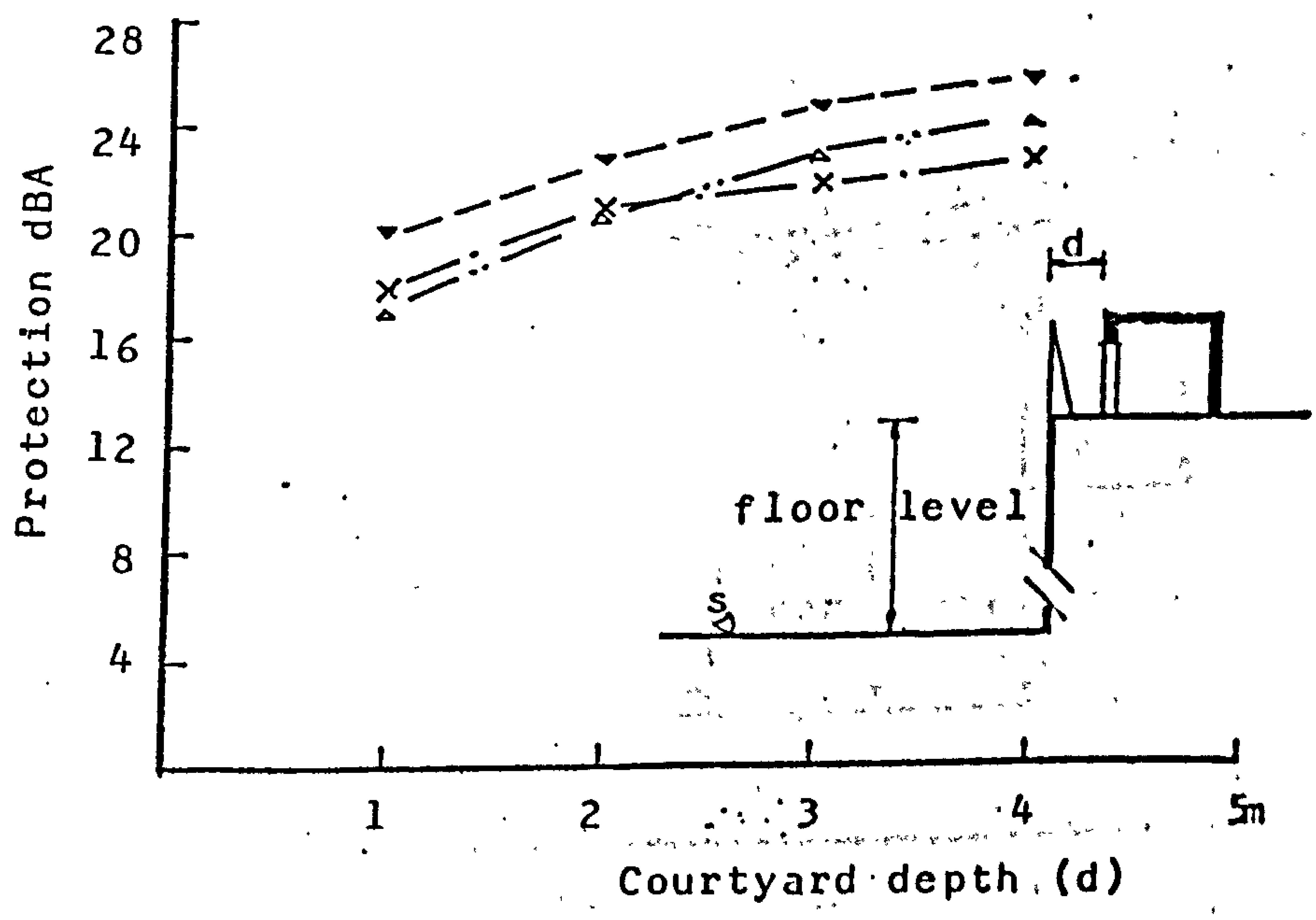


Comparison of the measured protection of a courtyard with a solid wall and that of the splitter wall; the 85% confident limit.

Fig. 9.9

Effect of courtyard depth

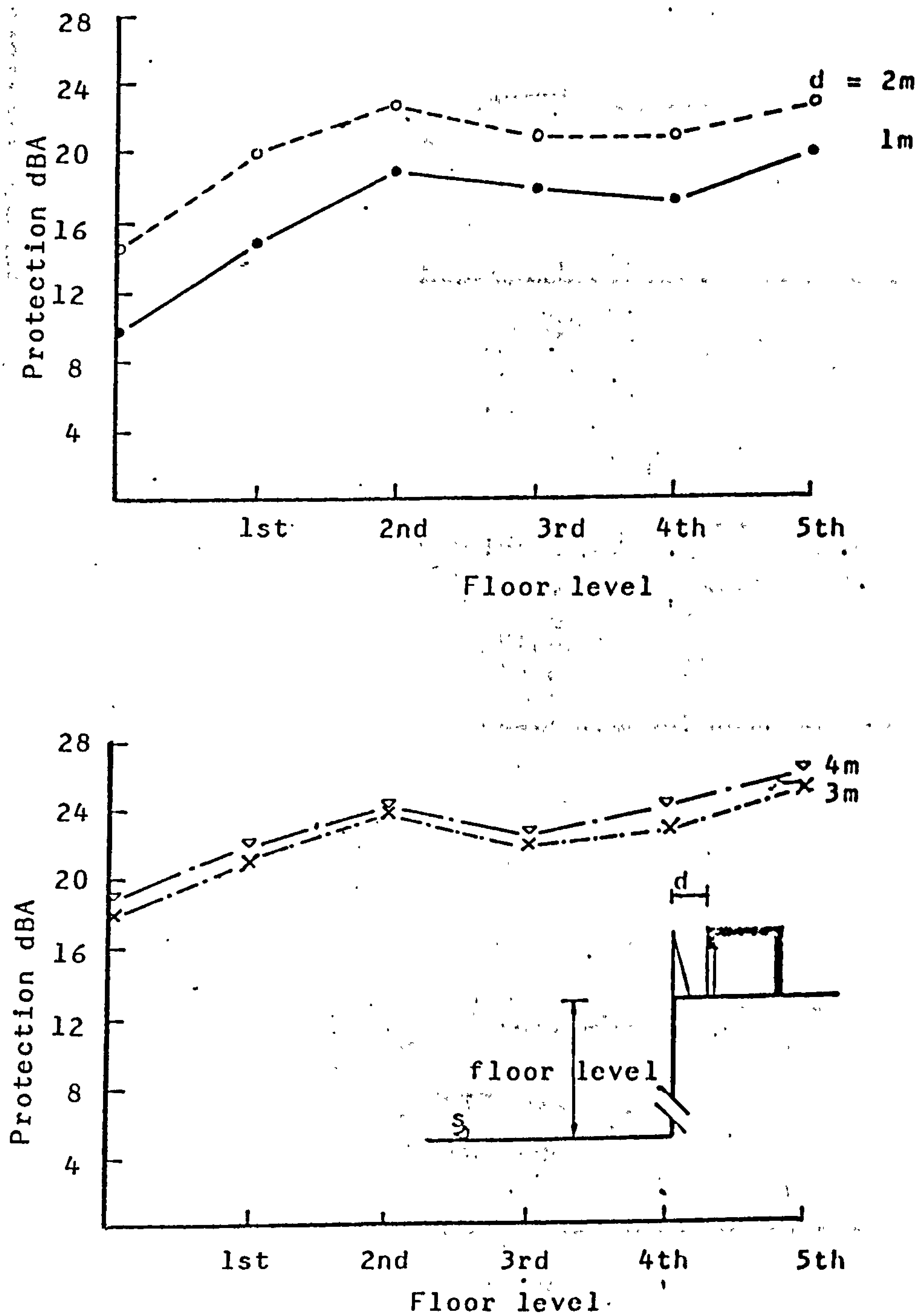




Measured protection of a courtyard with a splitter wall.

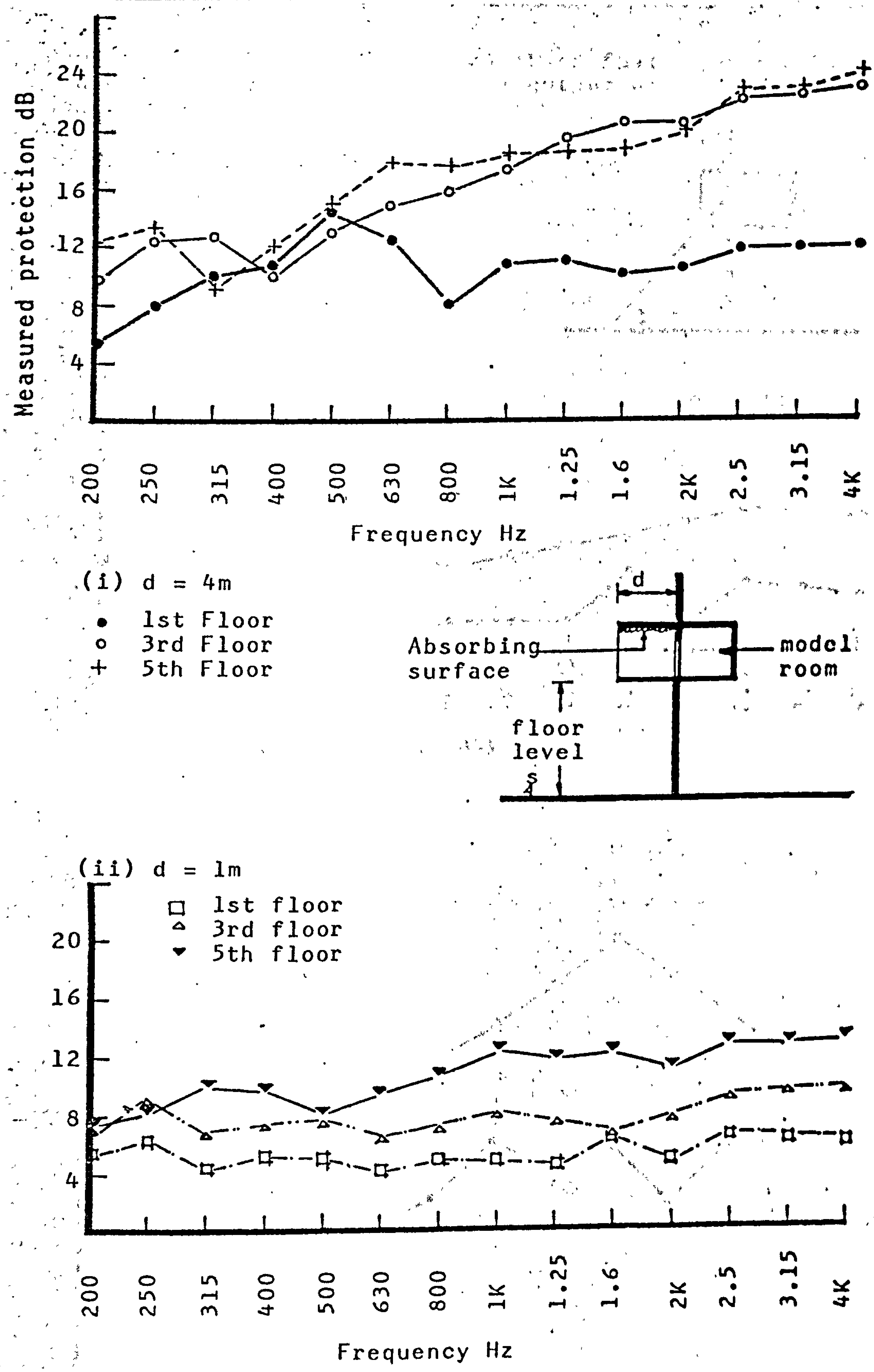
Fig. 9.10

Effect of height



Measured protection of a courtyard with a splitter wall.

Fig. 9.11



Measured protection afforded by a closed balcony.

Fig. 9.12

Comparison between Gilbert result on full scale structure and that of the author on scale models.

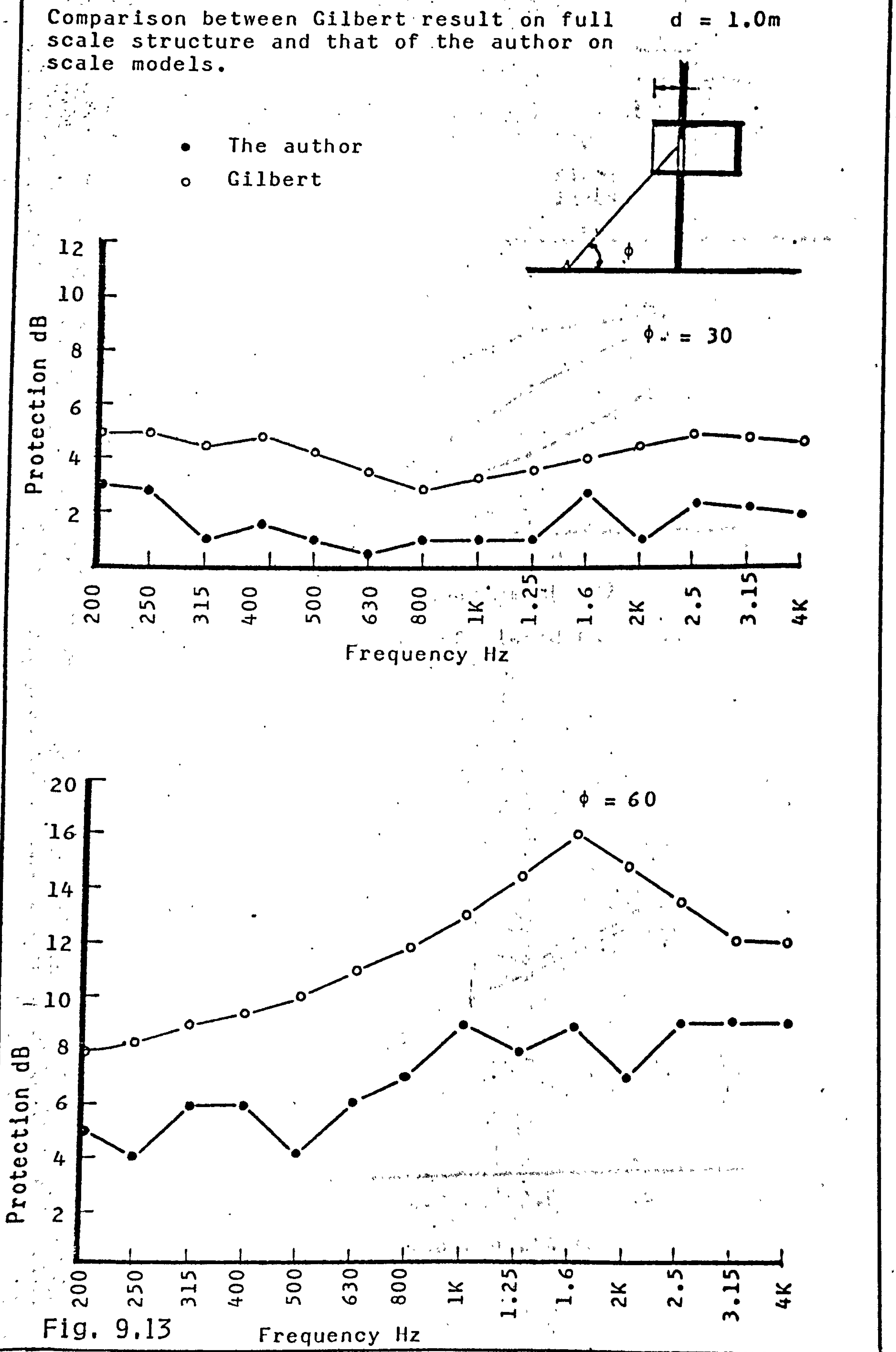
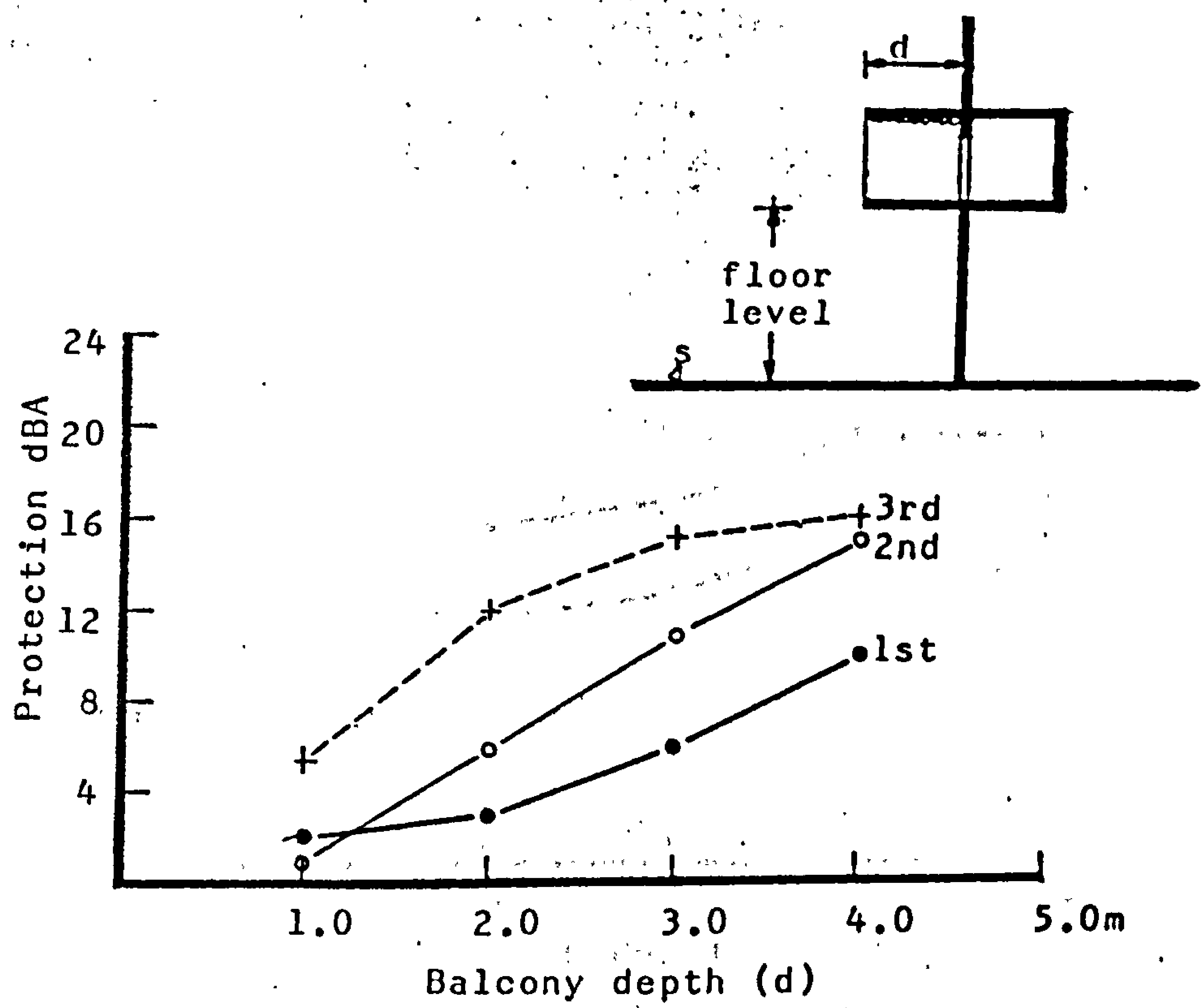


Fig. 9.13



Measured protection of closed balcony.
Effect ofbalcony depth.

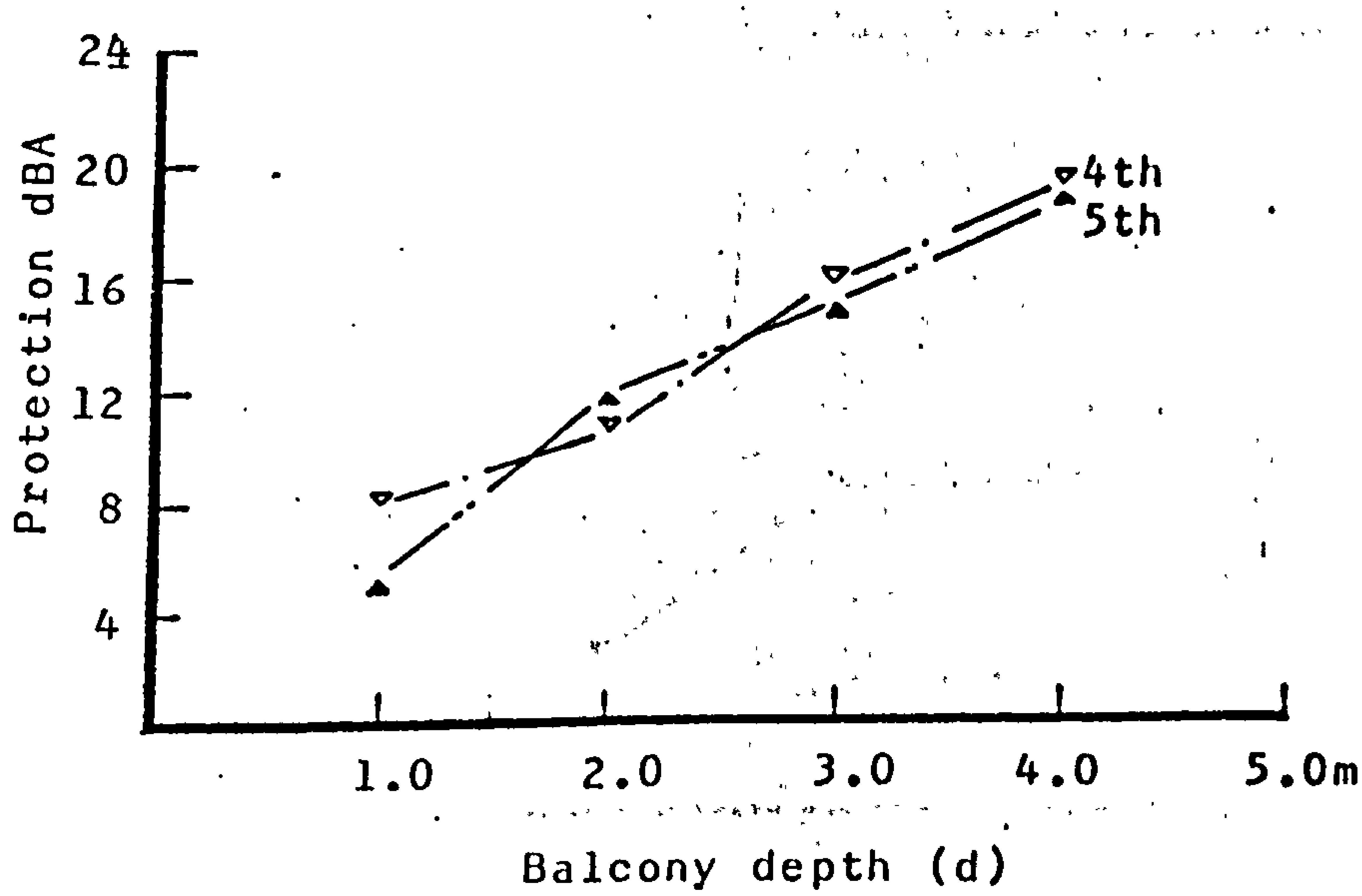


Fig. 9.14

Measured protection of closed balcony.
Effect of height.

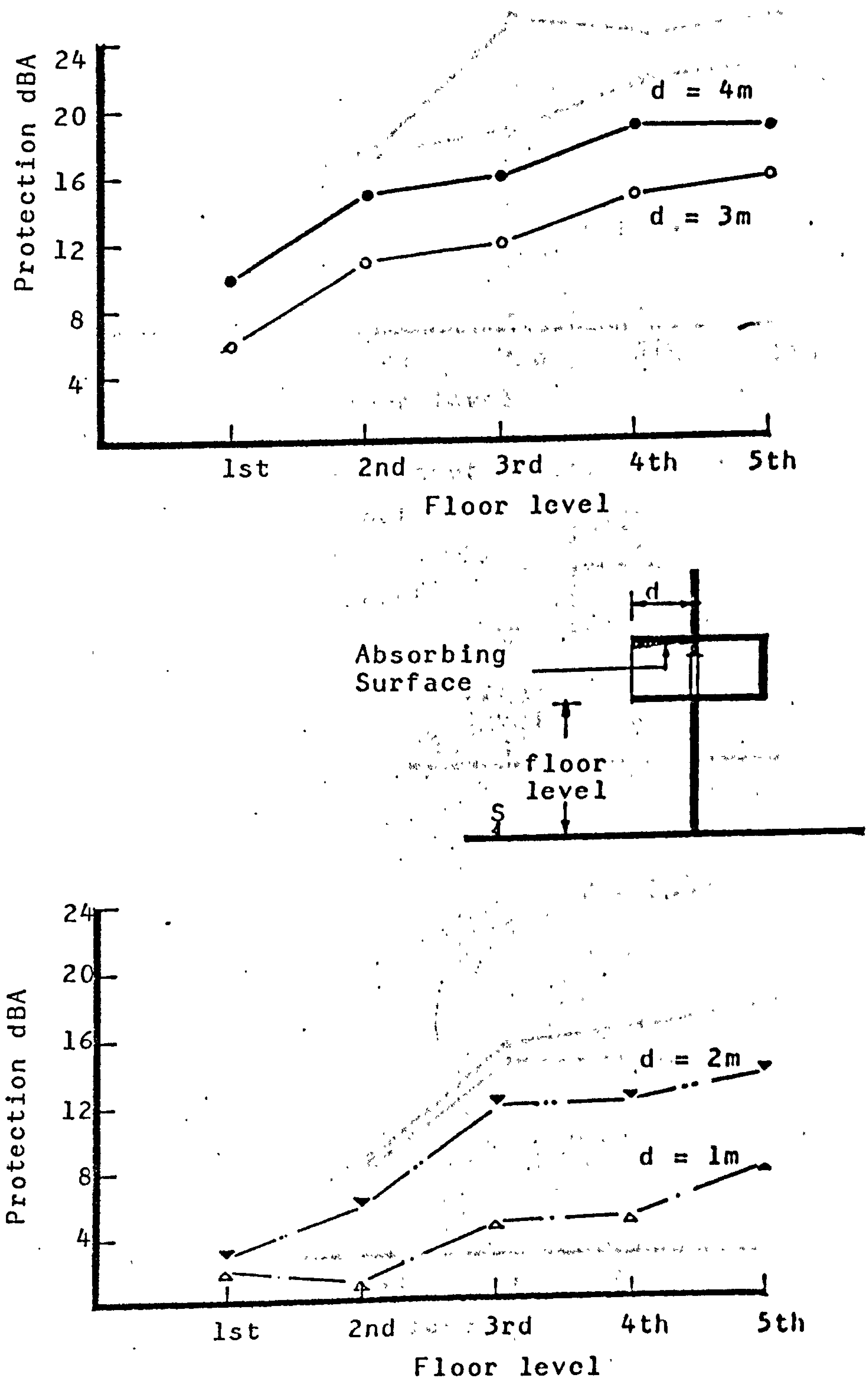


Fig. 9.15

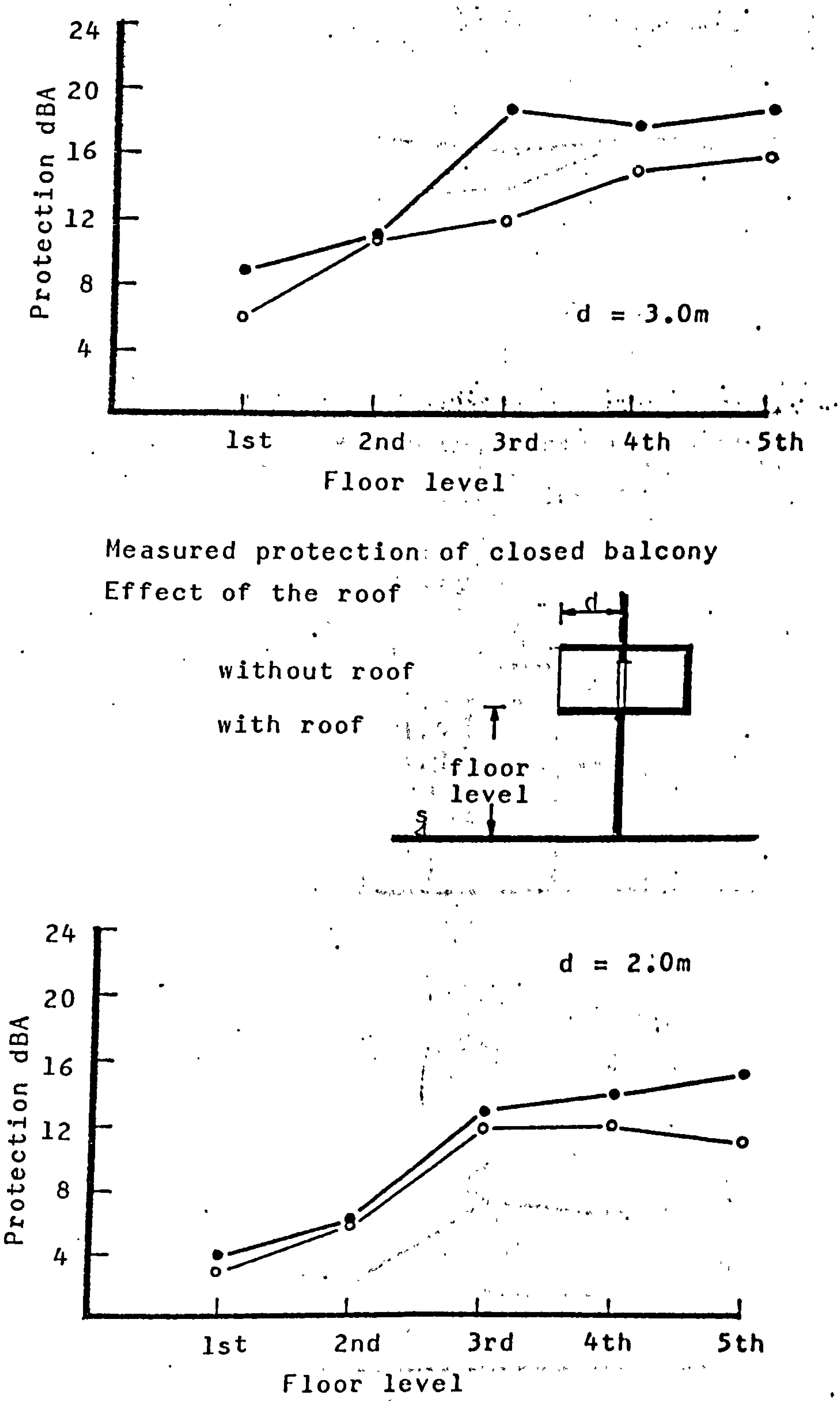

24
20
16
12
8
4
Protection dBA
d = 3.0m
1st
2nd
3rd
4th
5th
Floor level
Measured protection of closed balcony
Effect of the roof
without roof
with roof
d
floor level
24
20
16
12
8
4
Protection dBA
d = 2.0m
1st
2nd
3rd
4th
5th
Floor level

Fig. 9.16

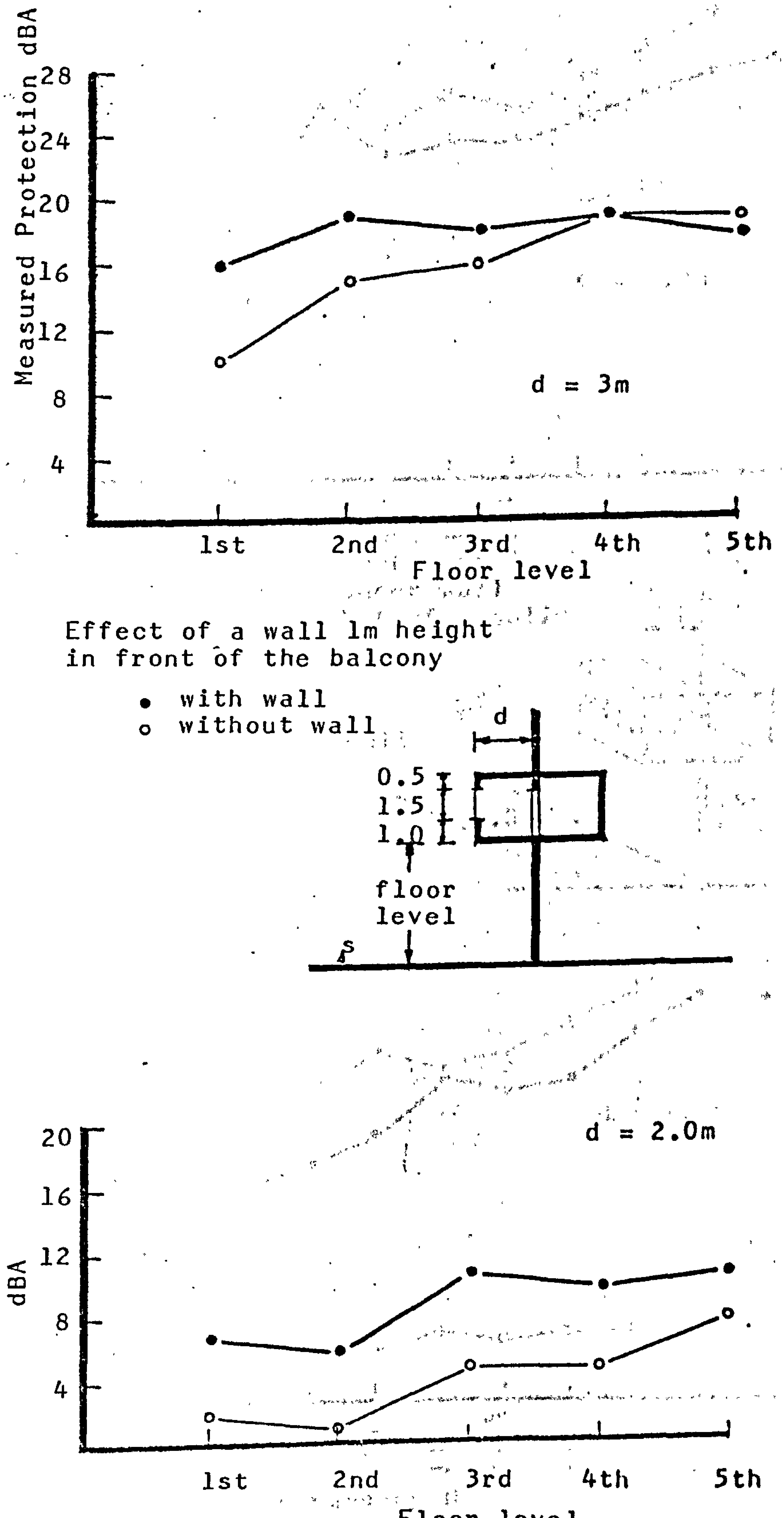
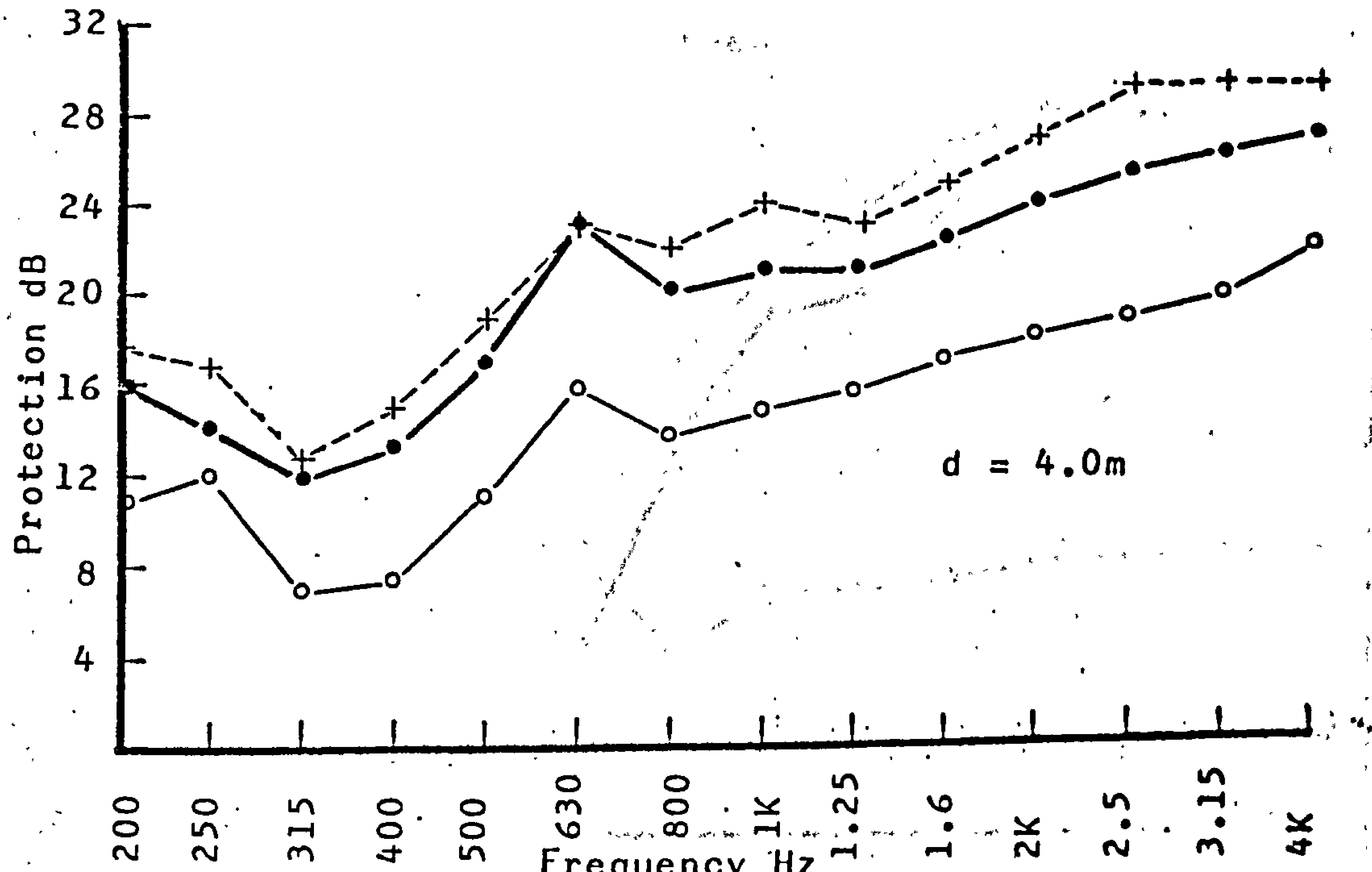
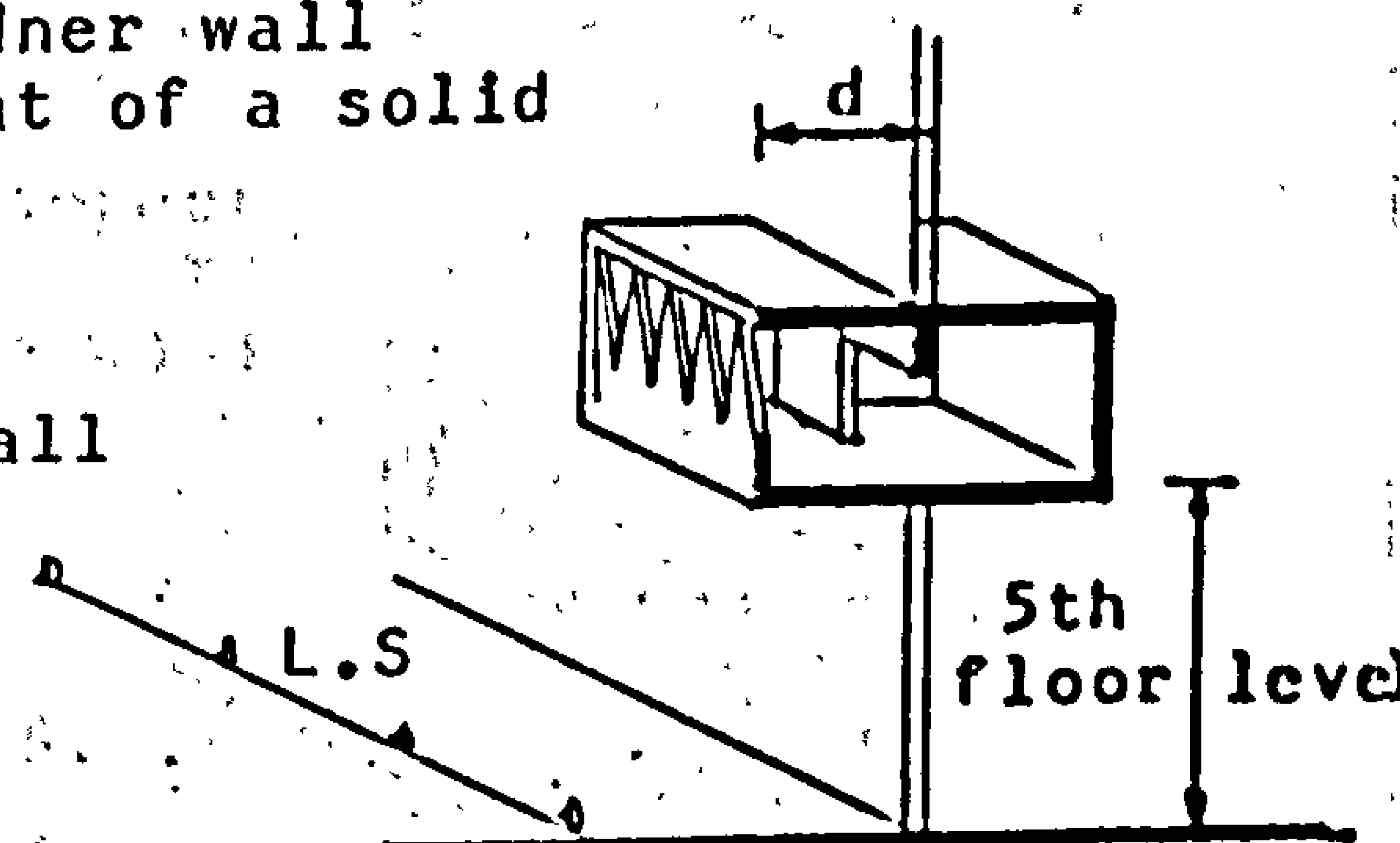

Measured Protection dBA
28
24
20
16
12
8
4
d = 3m
1st
2nd
3rd
4th
5th
Floor level
Effect of a wall 1m height
in front of the balcony
• with wall
o without wall
d
0.5
1.5
1.0
floor
level
S
d = 2.0m
20
16
12
8
4
dBA
1st
2nd
3rd
4th
5th
Floor level

Fig. 9.17



Measured protection of a thnadner wall as a part of a balcony and that of a solid wall as a part of a courtyard.

- o Balcony
- ● Balcony and thnadner
- + Courtyard and solid wall



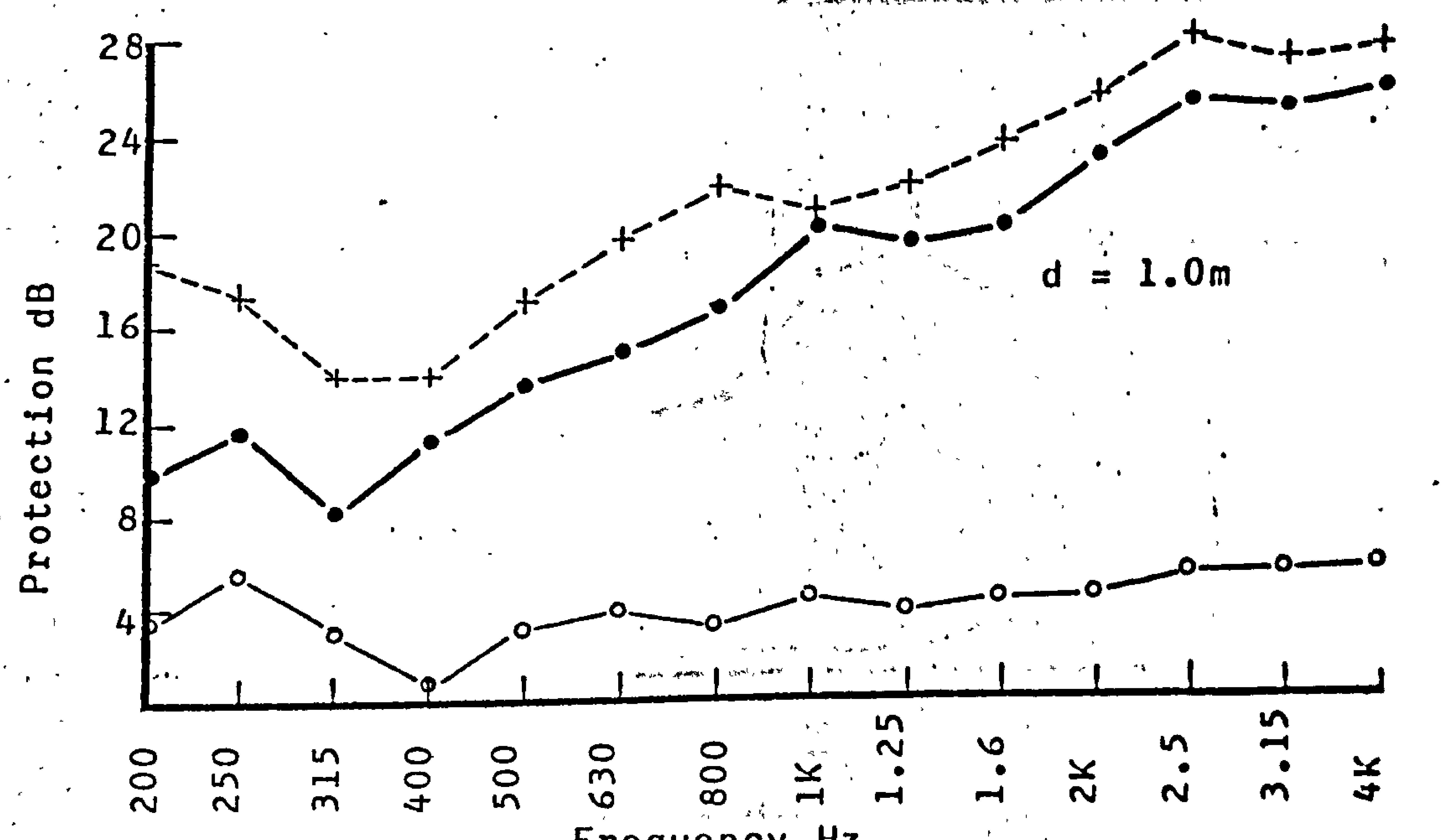
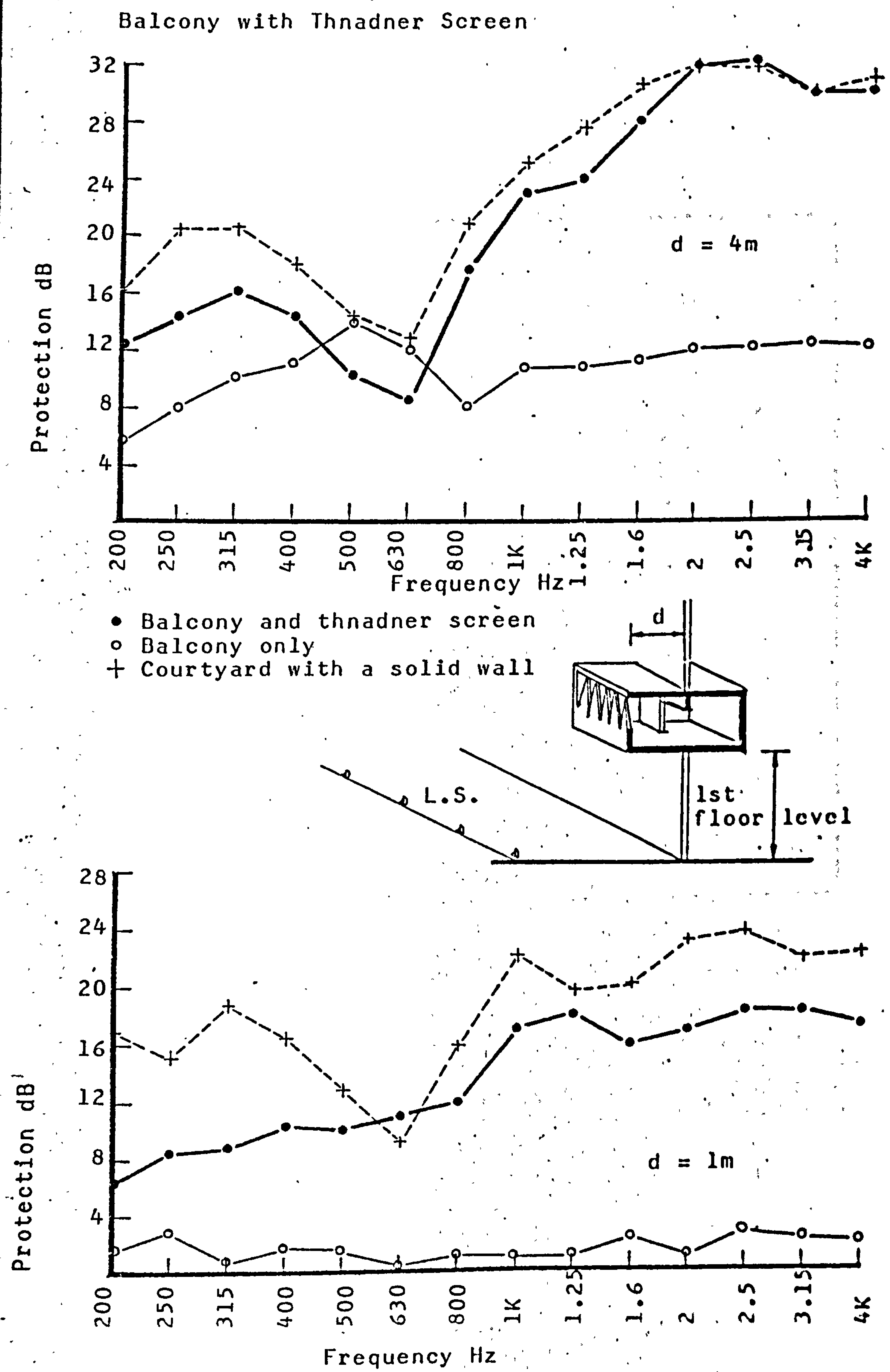
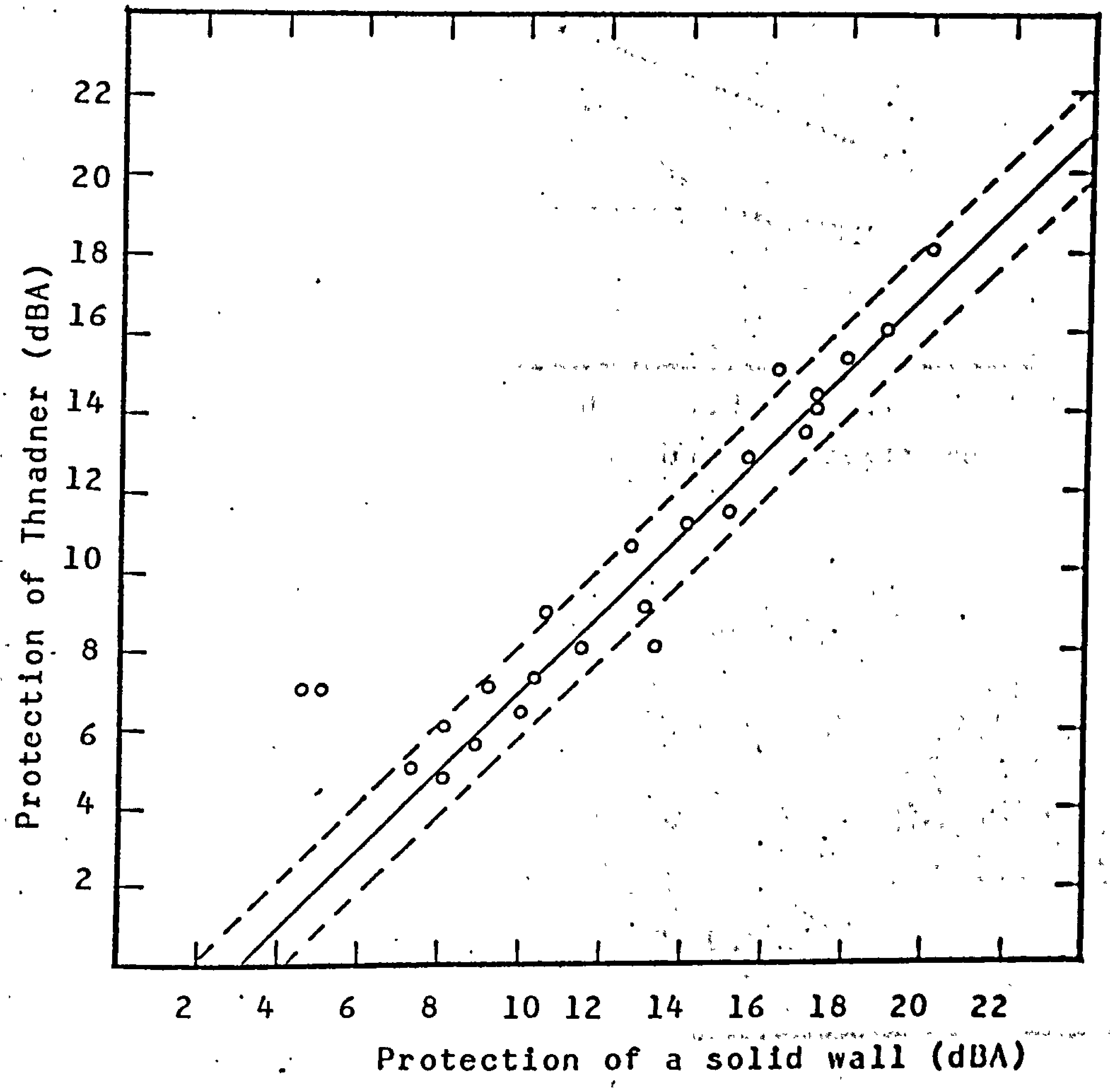


Fig. 9.18



Balcony with Thnadner Screen
Protection dB
d = 4m
Frequency Hz
200
250
315
400
500
630
800
1K
1.25
1.6
2
2.5
3.15
4K
● Balcony and thnadner screen
○ Balcony only
+ Courtyard with a solid wall
d
L.S.
1st floor level
d = 1m

Fig. 9.19



Comparison of the protection of a solid wall as a part of a courtyard and that of the Thnadner wall as a part of a closed balcony. Also shown the 85% confidence limits where the correlation coefficient is calculated to be 0.9142.

Fig. 9.20

Measured protection of thnadner wall as a part of a balcony. Effect of balcony depth.

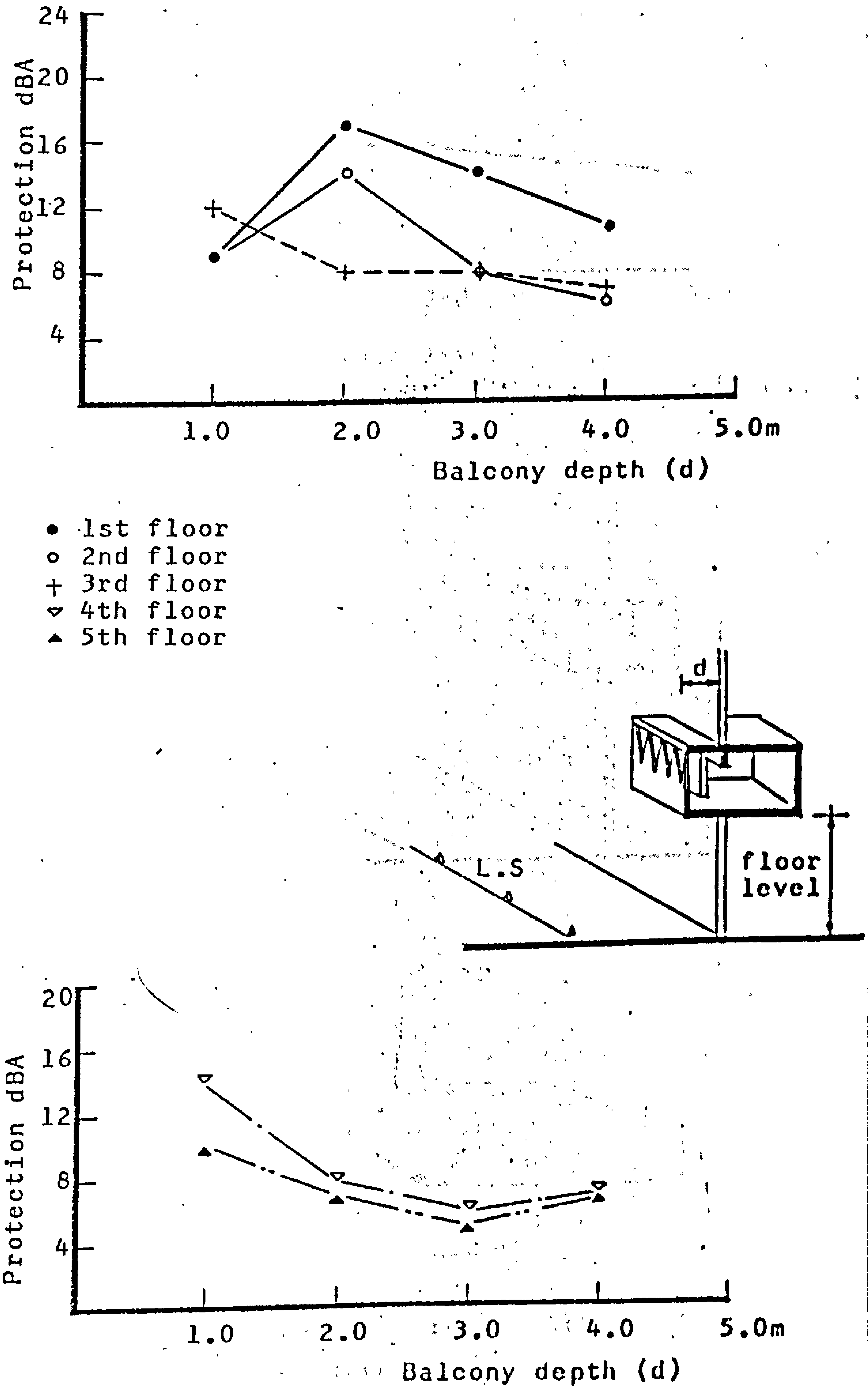


Fig. 9.21

Measured protection of Thnadner wall as a part of a balcony. Effect of height.

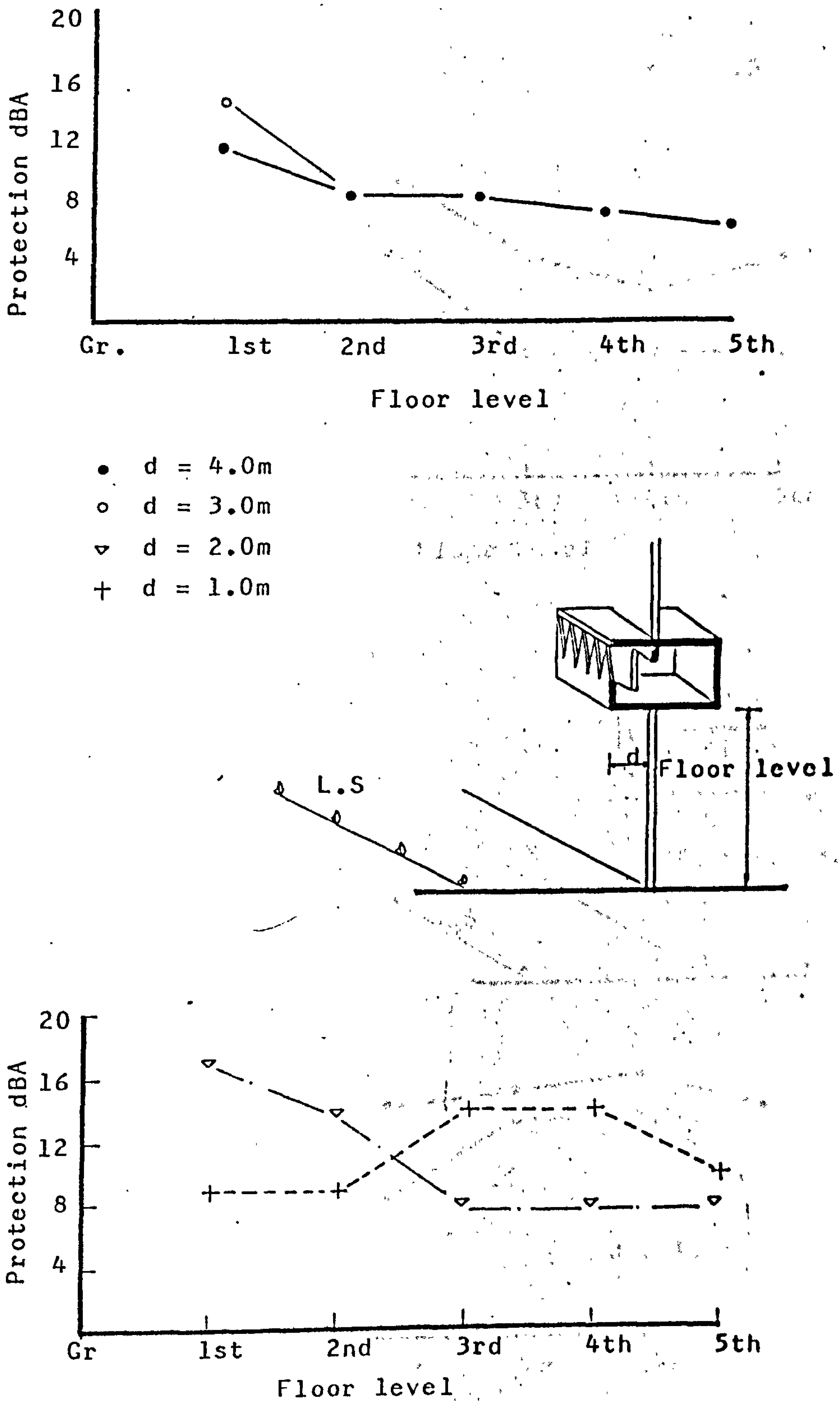


Fig. 9.22

Measured protection of Thnadner wall as part of a closed balcony. Effect of the ceiling reflection.

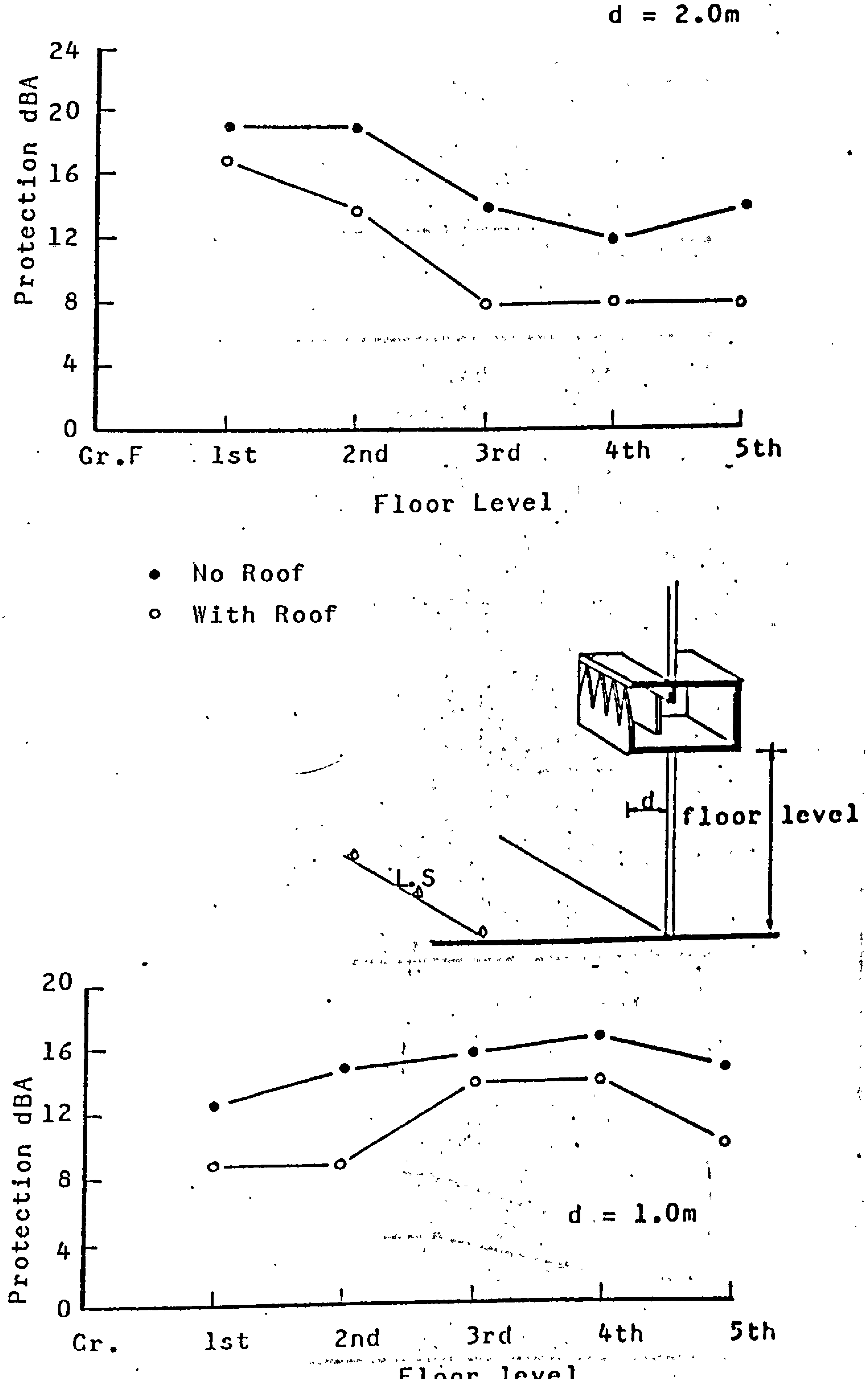


Fig. 9.23

Measured protection of Thnadner wall as a part of a balcony. Effect of Ceiling reflection

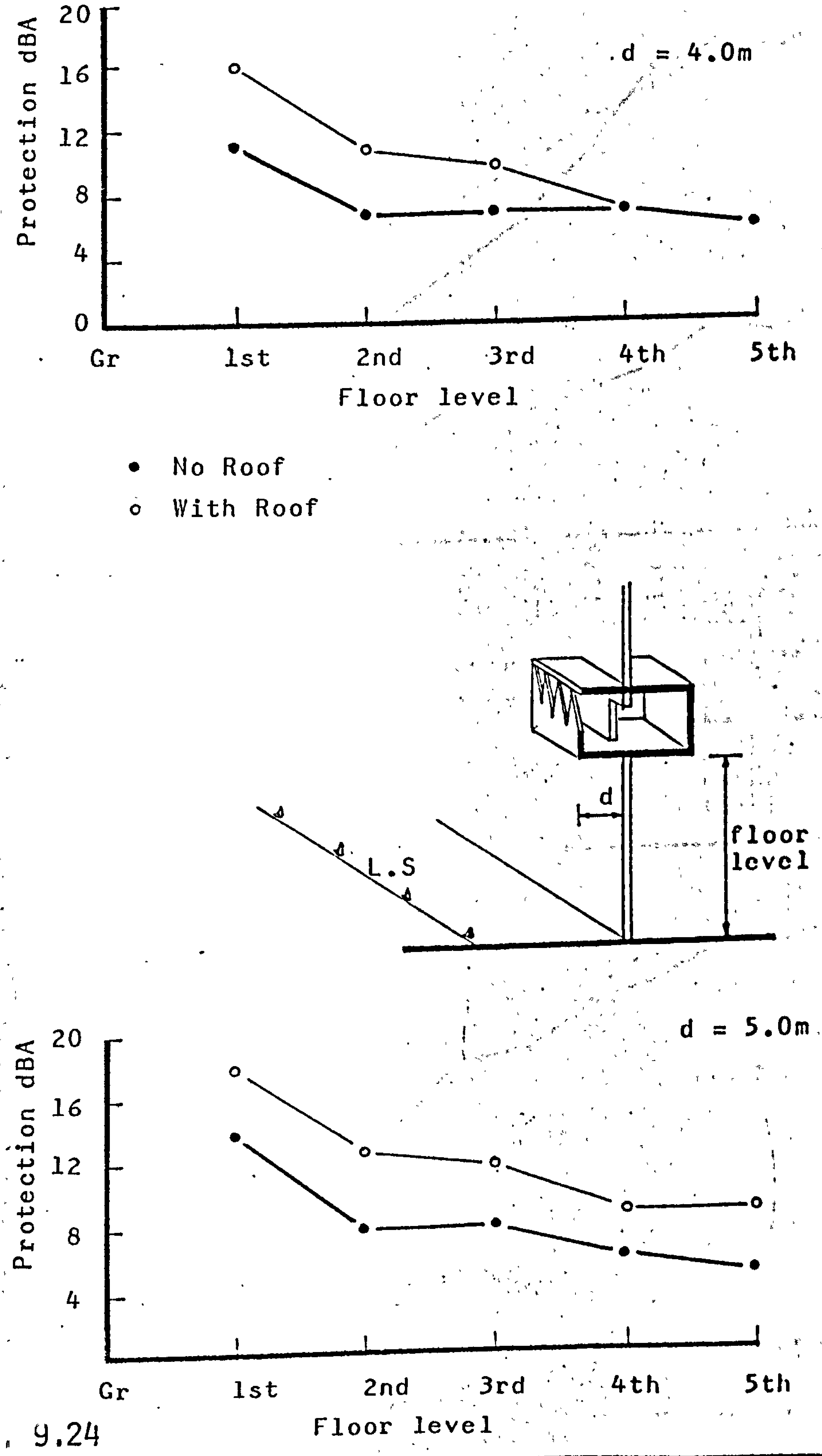


Fig. 9.24


Closed balcony and splitter screen
Protection dB
32
28
24
20
16
12
8
4
200
250
315
400
500
630
800
1K
1.25
1.6
2
2.5
3.15
4K
Frequency Hz
d = 4m
o closed balcony only
• closed balcony and splitter screen
+ balcony without roof and solid barrier
d
second floor level
S
d = 2m

Fig. 9.25

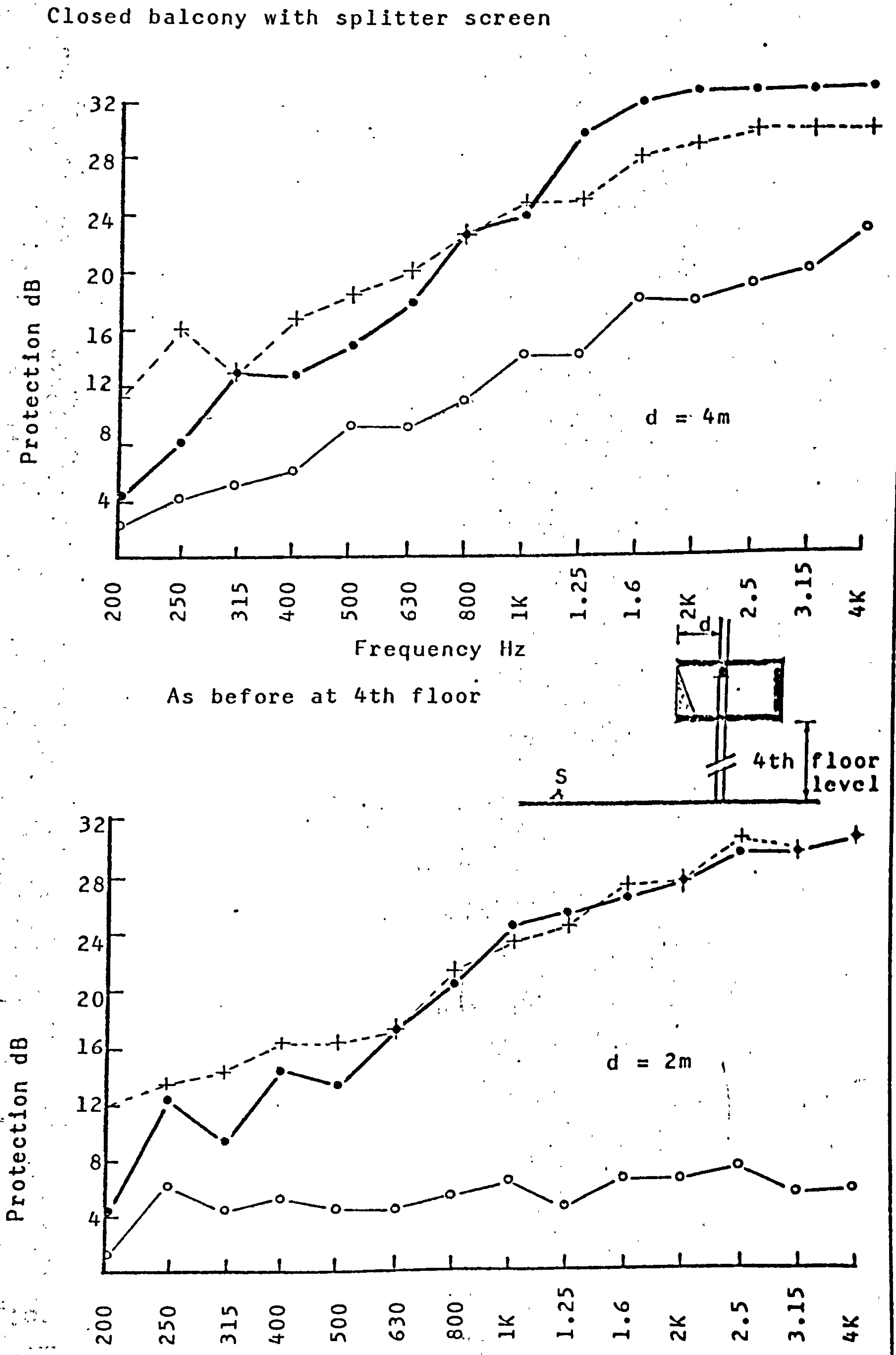
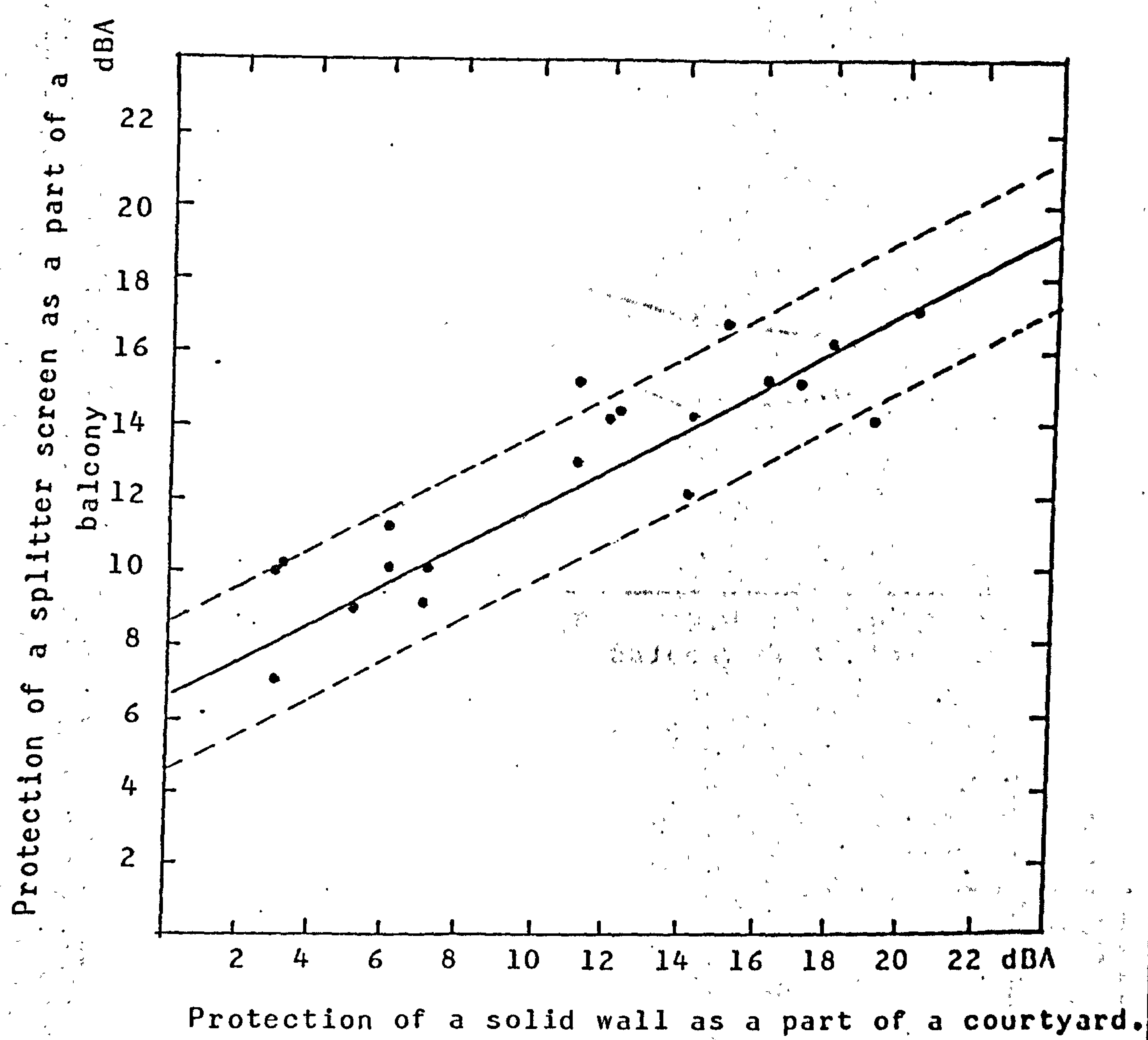

Closed balcony with splitter screen
32
28
24
20
16
12
8
4
Protection dB
d = 4m
200
250
315
400
500
630
800
1K
1.25
1.6
2K
2.5
3.15
4K
Frequency Hz
As before at 4th floor
d
S
4th floor level
32
28
24
20
16
12
8
4
Protection dB
d = 2m
200
250
315
400
500
630
800
1K
1.25
1.6
2K
2.5
3.15
4K
Frequency Hz

Fig. 9.26



Comparison of the measured protection of a courtyard with a solid wall and that of a balcony with a splitter screen.

the 85% confident limit.

Fig. 9.27

Net protection of splitter screen.
Effect of positioning

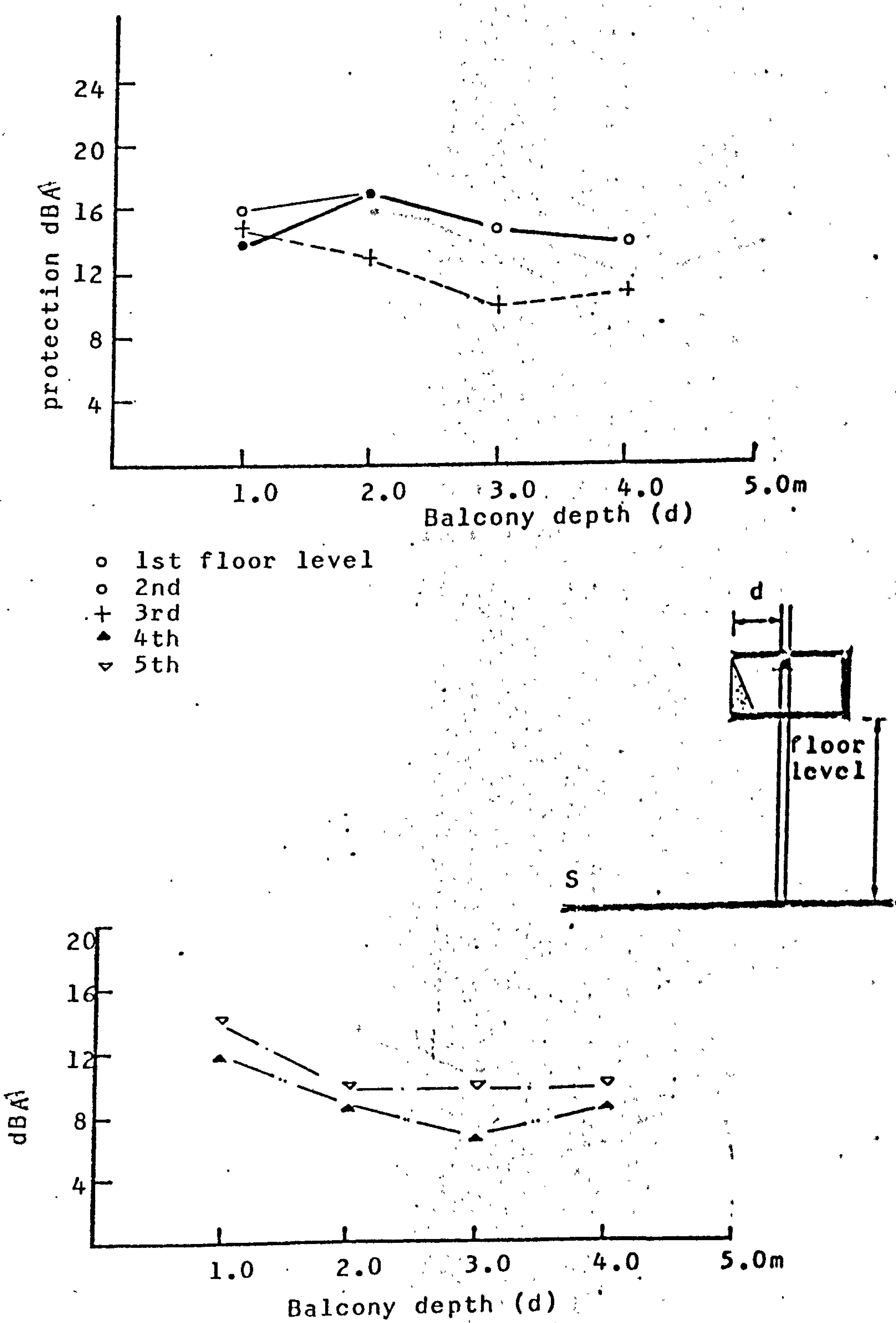


Fig. 9.28

Splitter screen - effect of height.

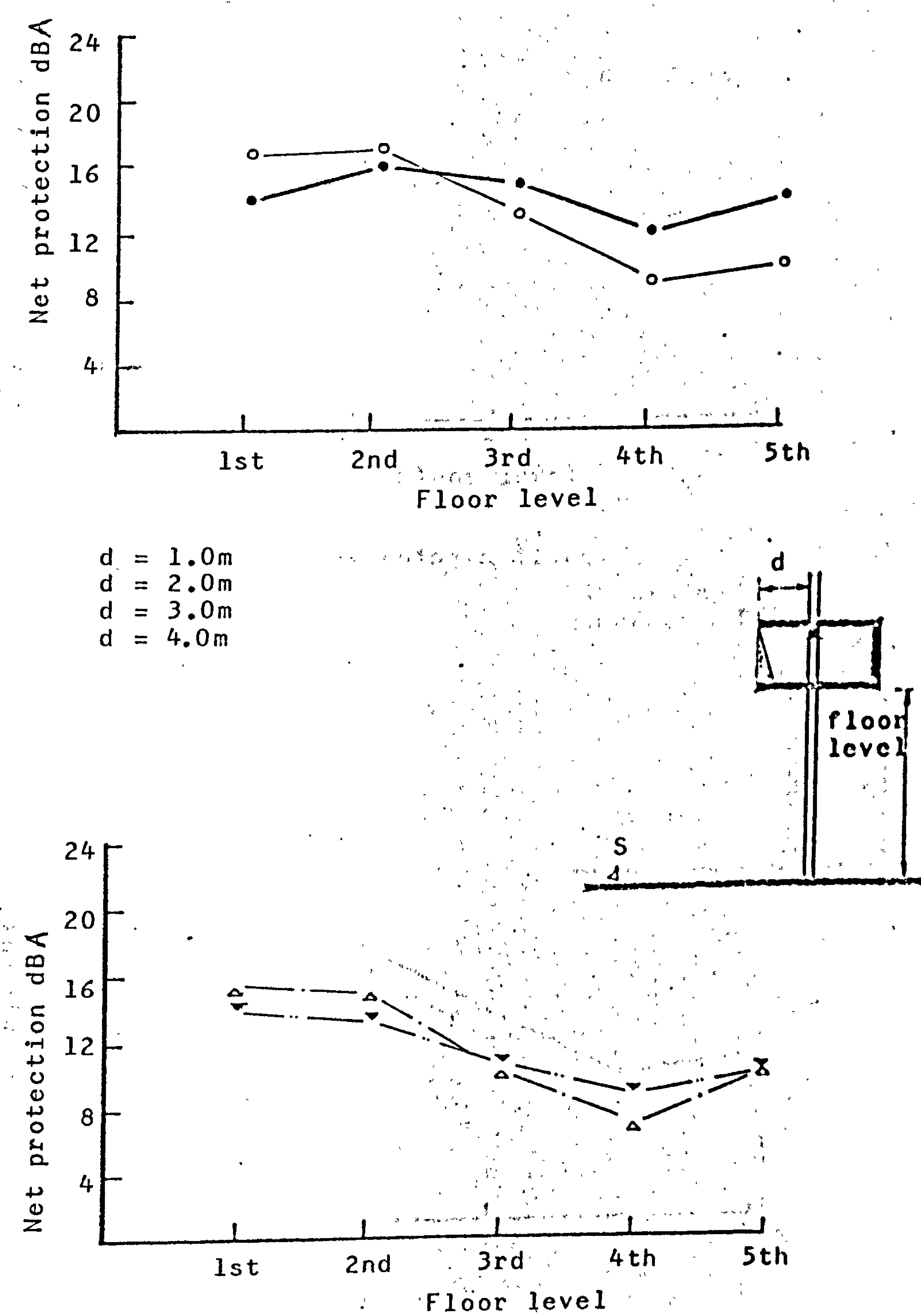


Fig. 9.29

Splitter screen - effect of ceiling reflection

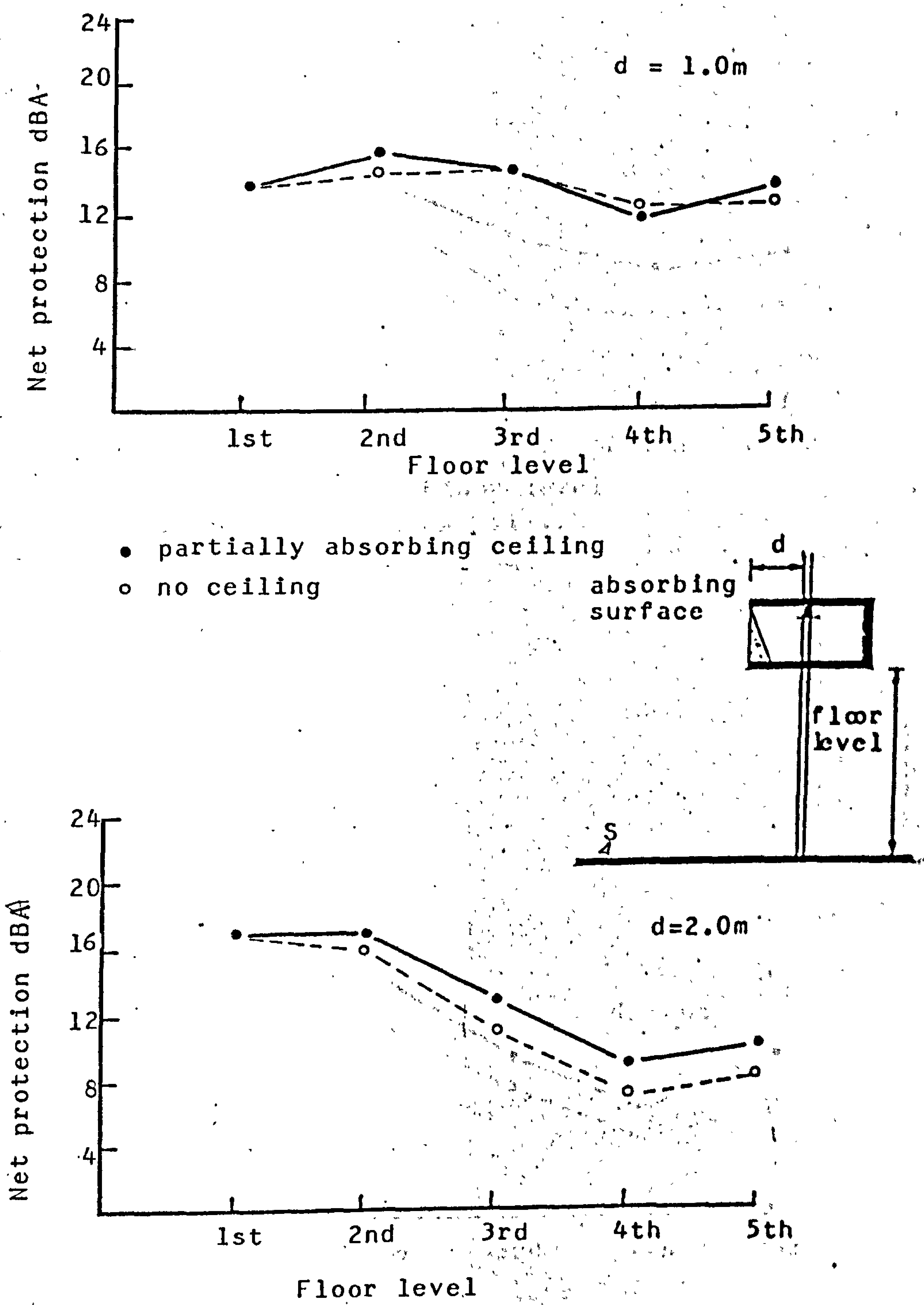
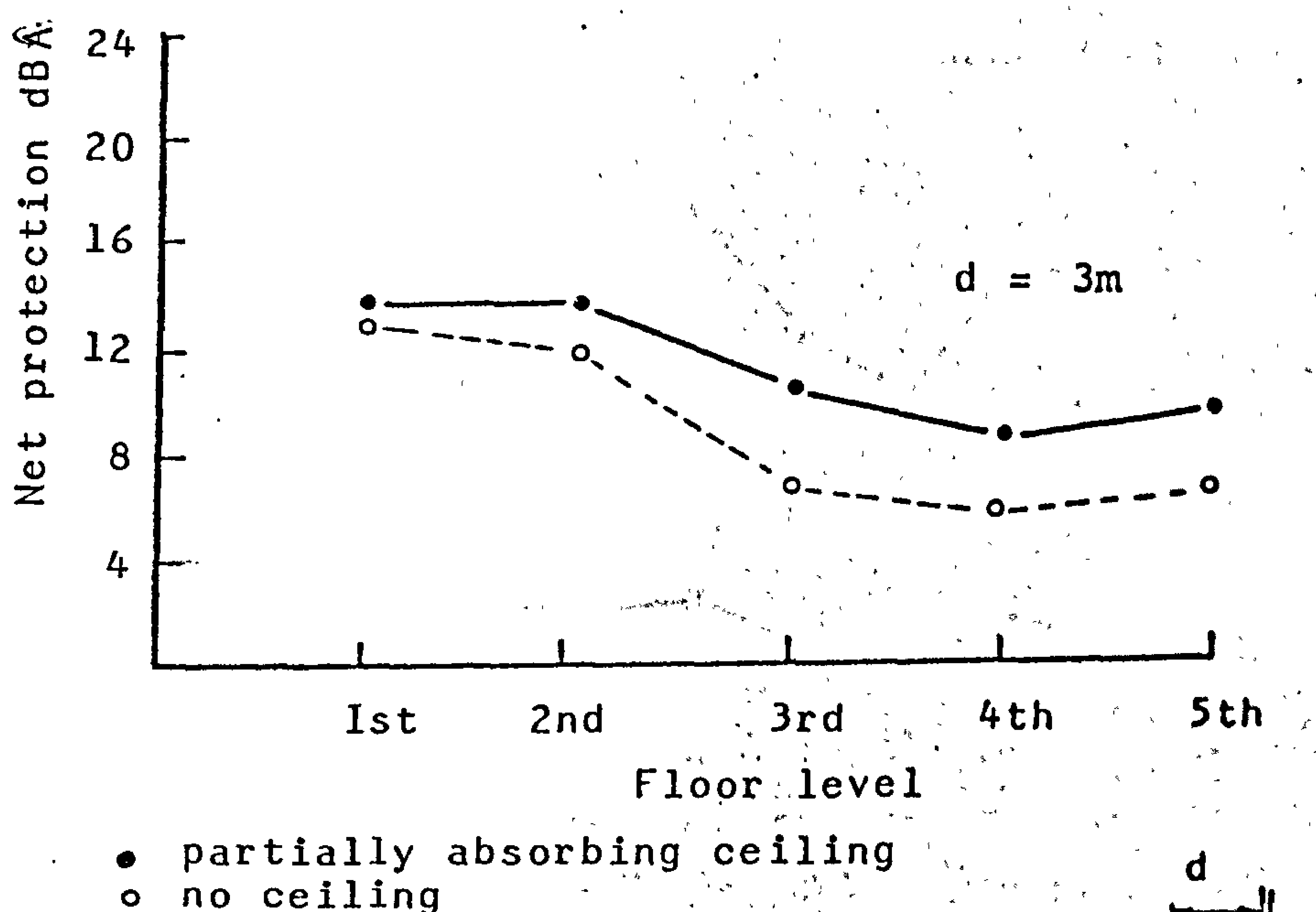
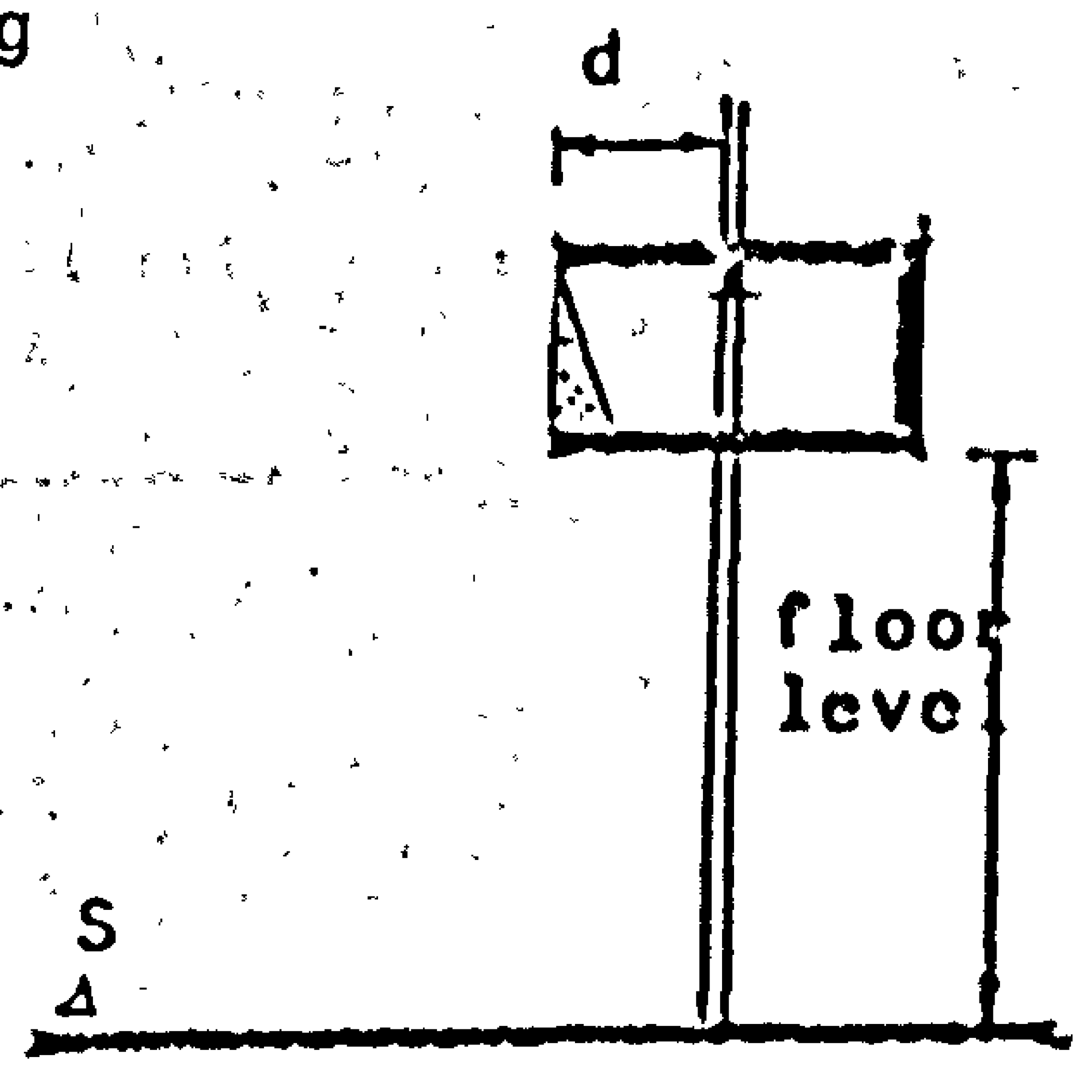


Fig. 9.30

Splitter screen
Effect of Ceiling Reflection





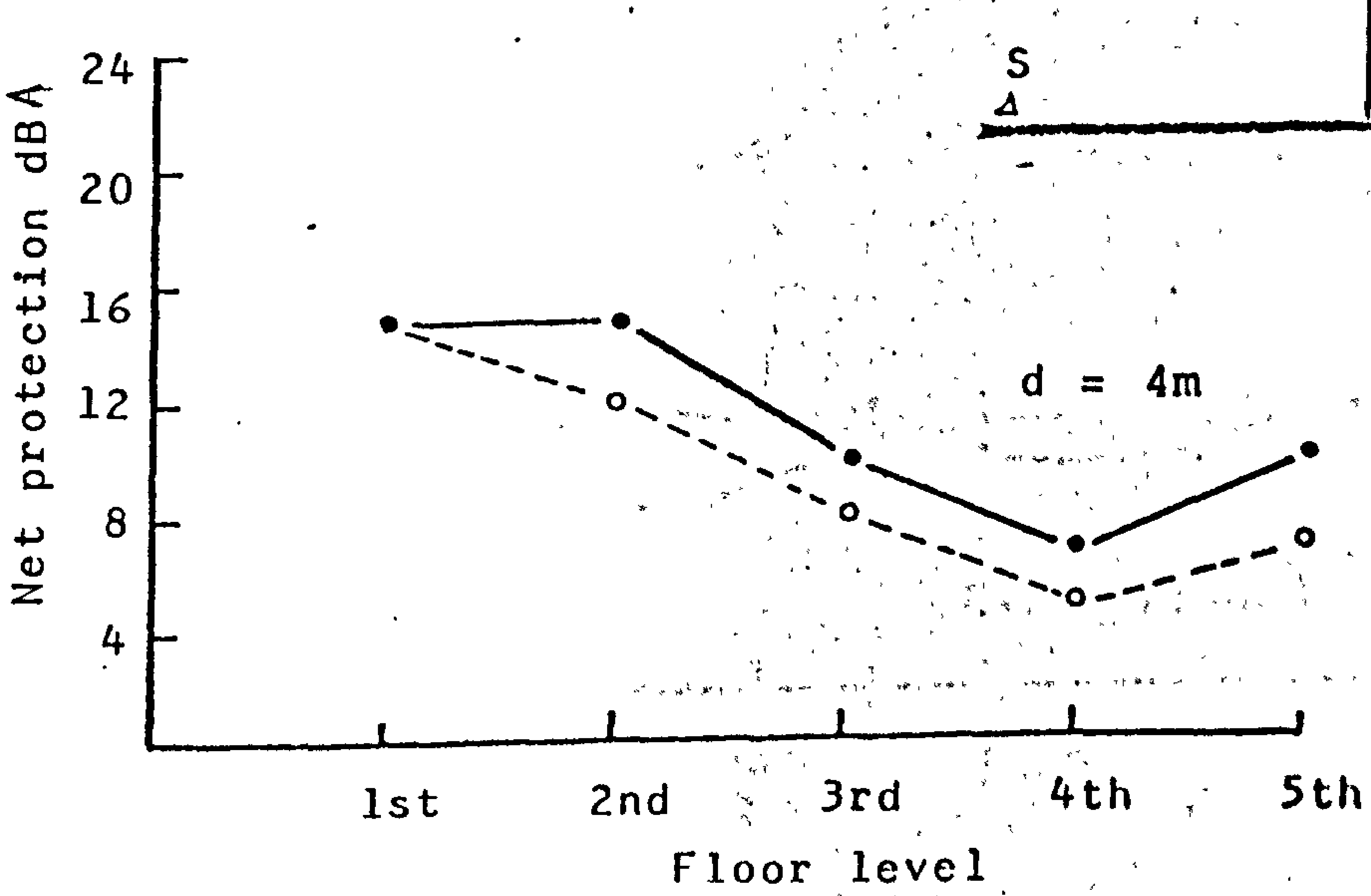


Fig. 9.31

Measured protection of a perforated units wall as a part of a courtyard.

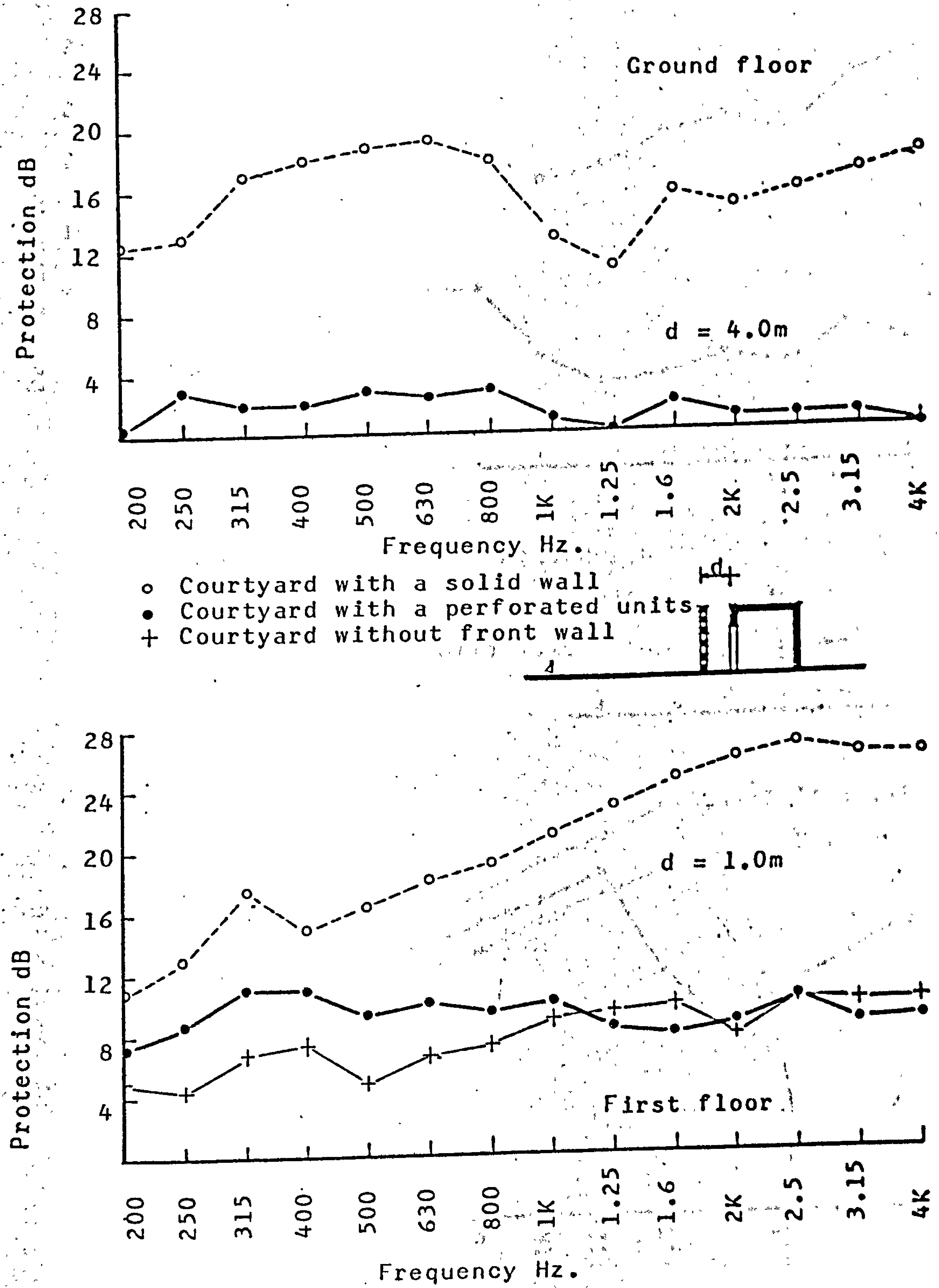


Fig. 9.32

Measured protection of courtyard with conventional perforation

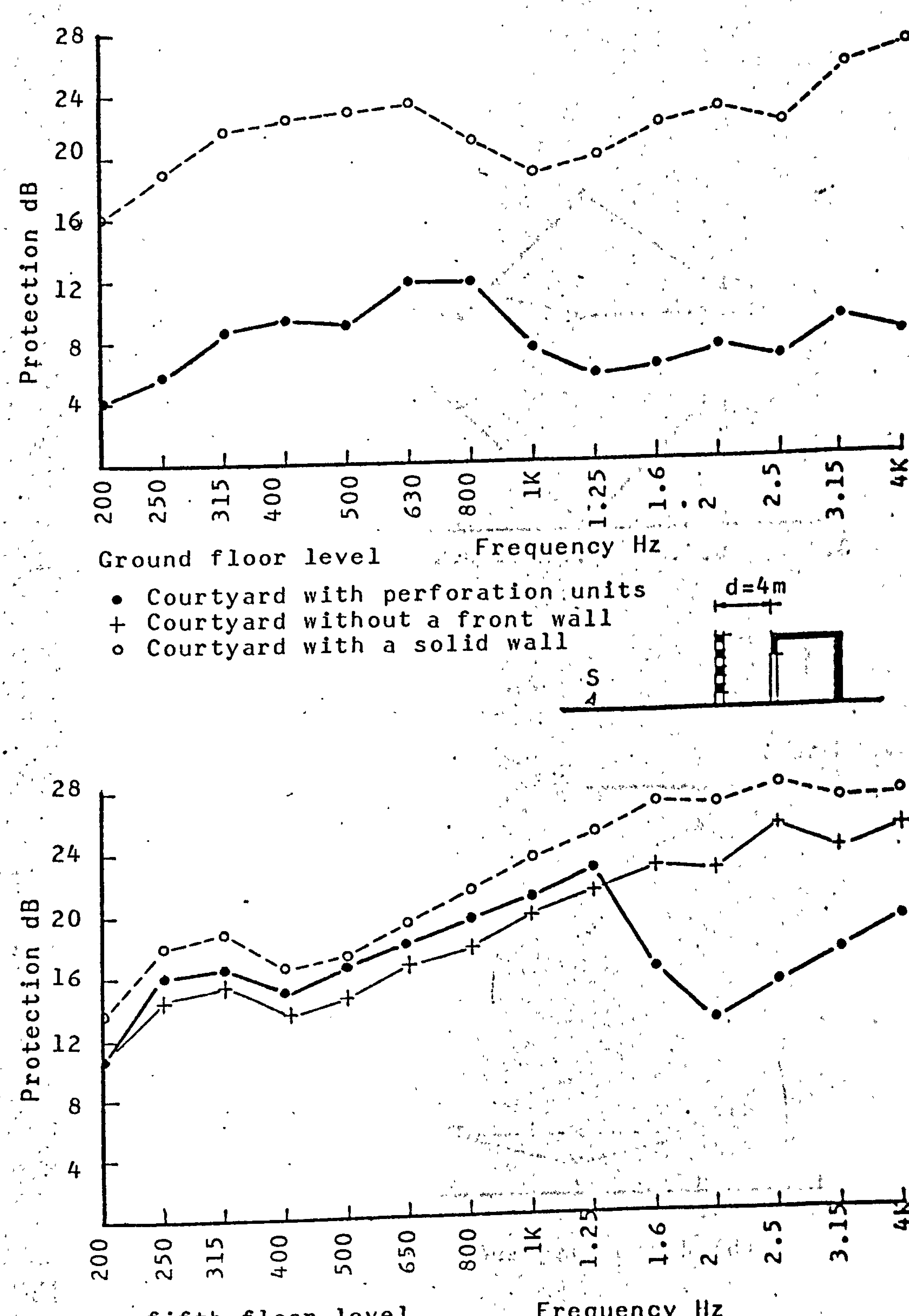


Fig. 9.33

Measured protection of a courtyard with
perated units wall. Effect of height

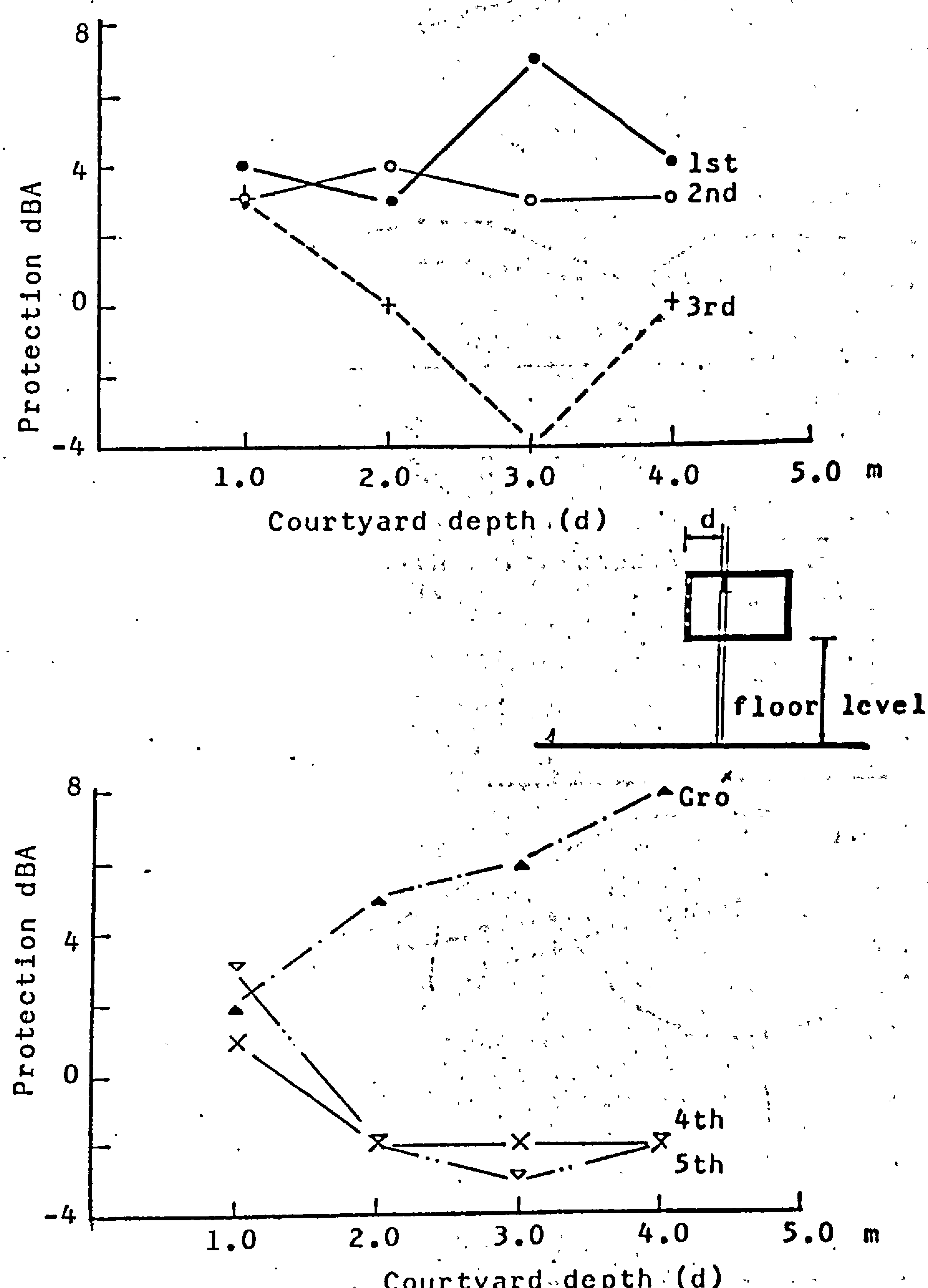


Fig. 9.34

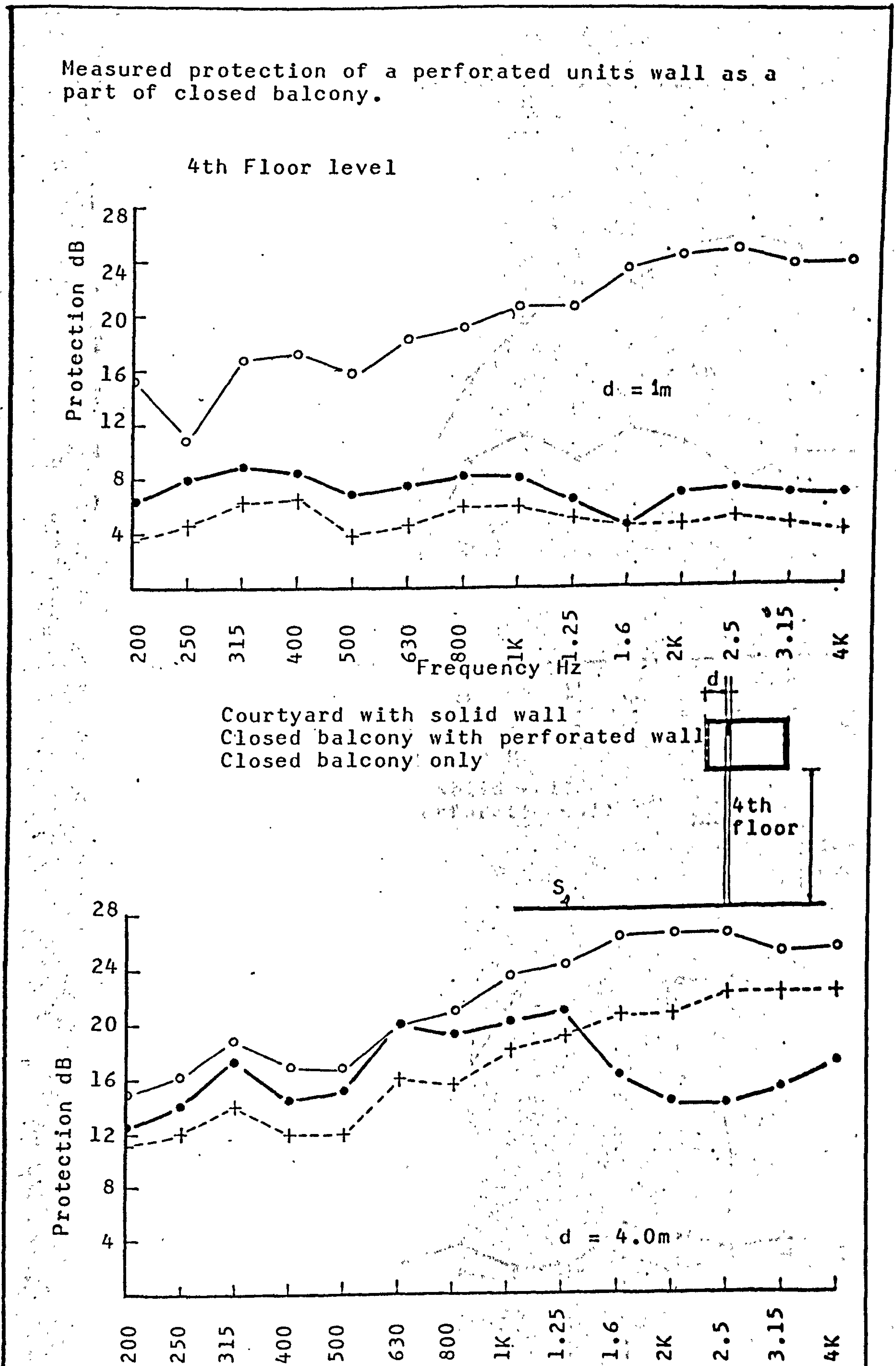

Measured protection of a perforated units wall as a part of closed balcony.
4th Floor level
Protection dB
28
24
20
16
12
8
4
d = 1m
200
250
315
400
500
630
800
1K
1.25
1.6
2K
2.5
3.15
4K
Frequency Hz
Courtyard with solid wall
Closed balcony with perforated wall
Closed balcony only
d
4th floor
S
Protection dB
28
24
20
16
12
8
4
d = 4.0m
200
250
315
400
500
630
800
1K
1.25
1.6
2K
2.5
3.15
4K
Frequency Hz

Fig. 9.35

Measured protection of a perforated units wall as a part of a balcony.

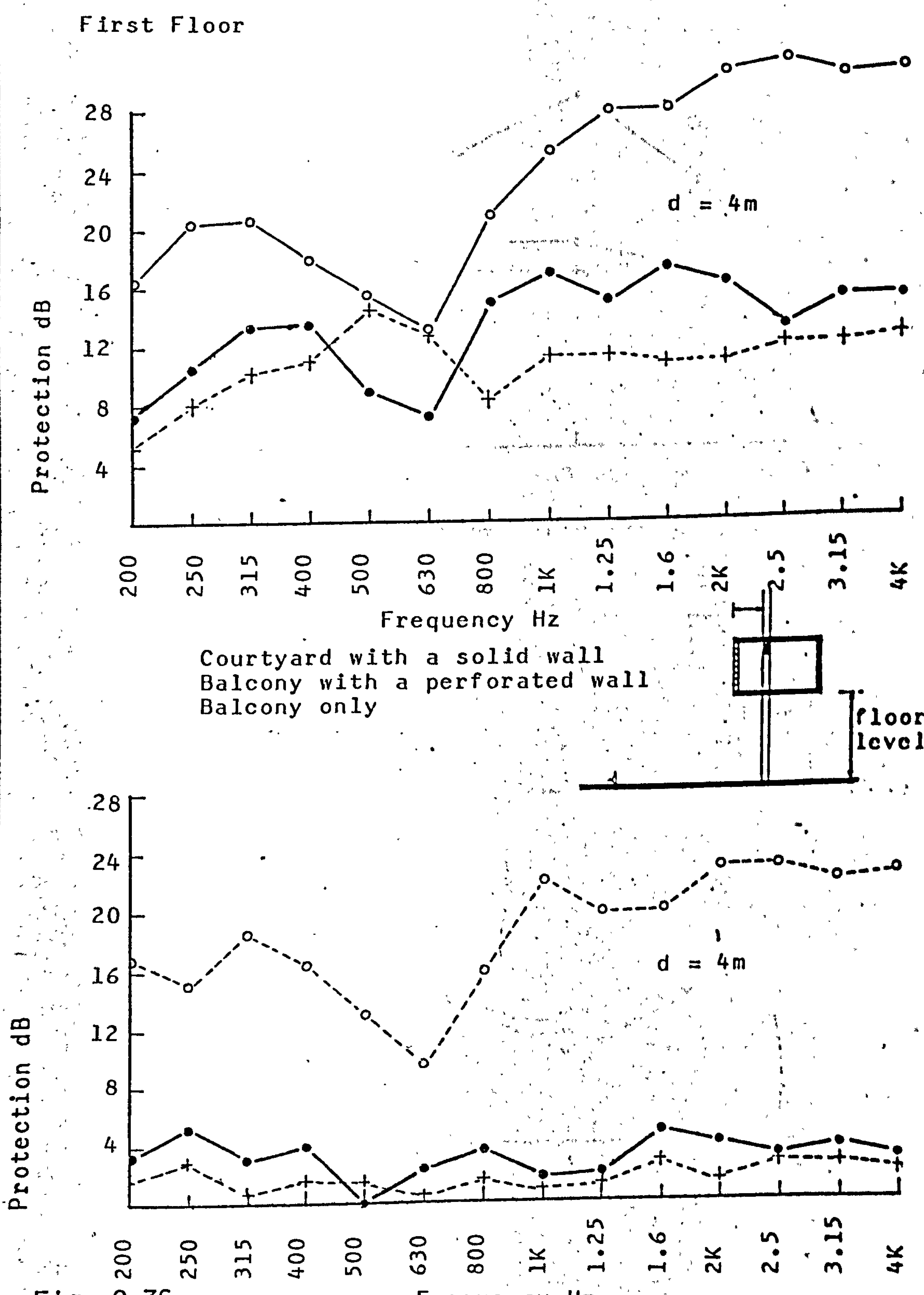


Fig. 9.36

Measured protection of a balcony with conventional perforation.

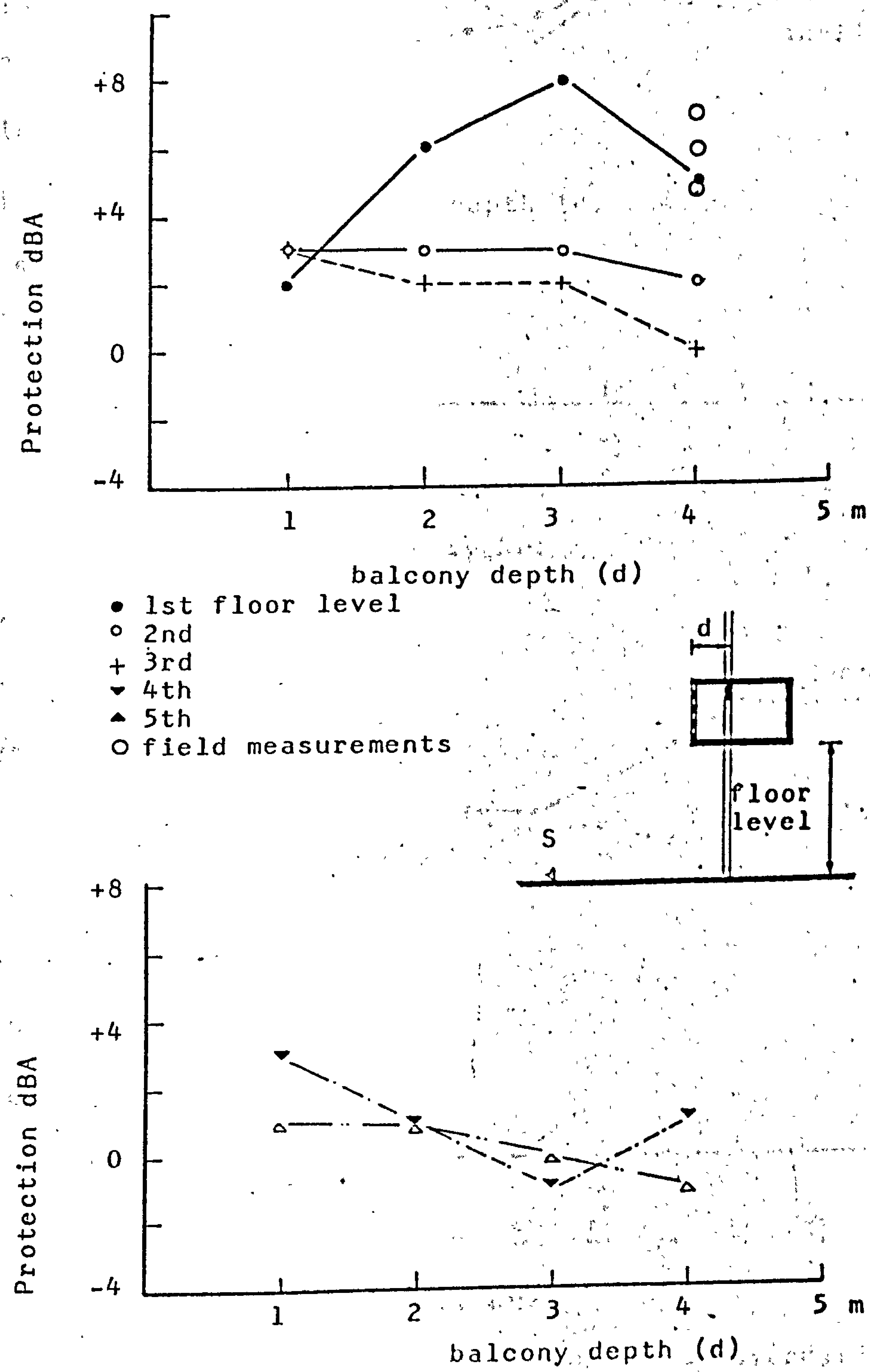
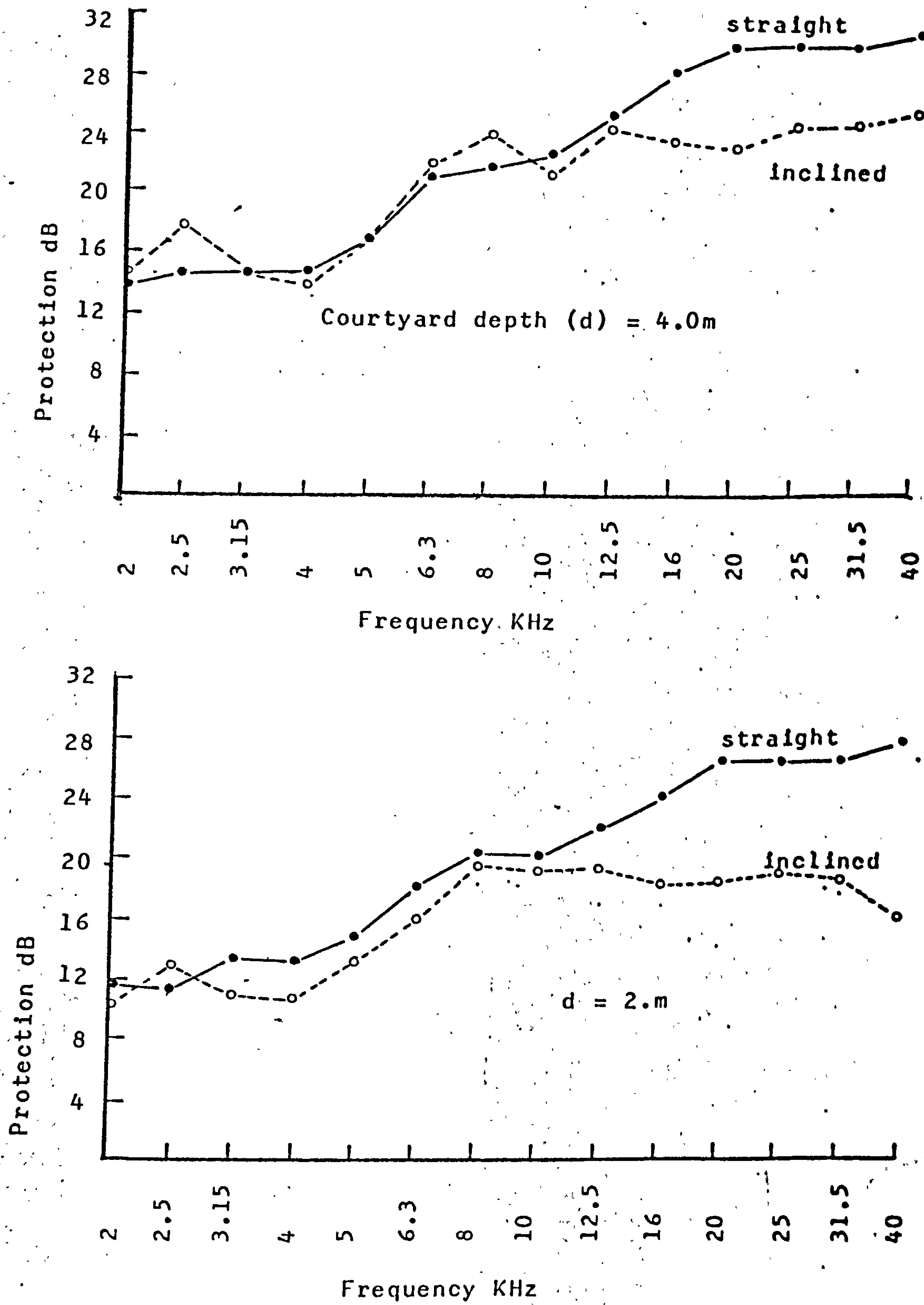


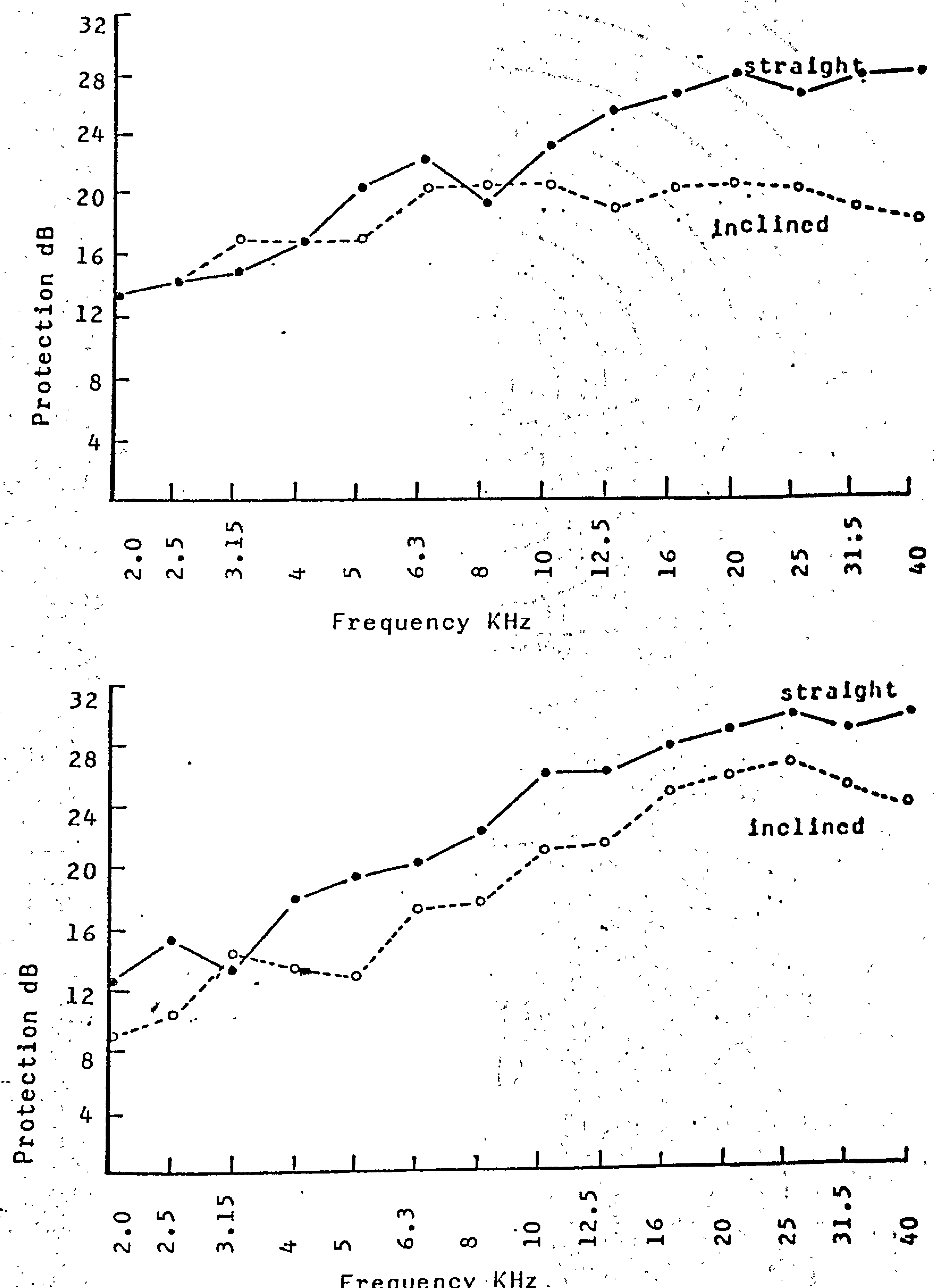
Fig. 9.37

Courtyard with splitter wall



Comparison of measured protection of courtyardswith straight and inclined splitters at second floor level.

Fig. 9.38



As before at second floor level.

Fig. 9.39

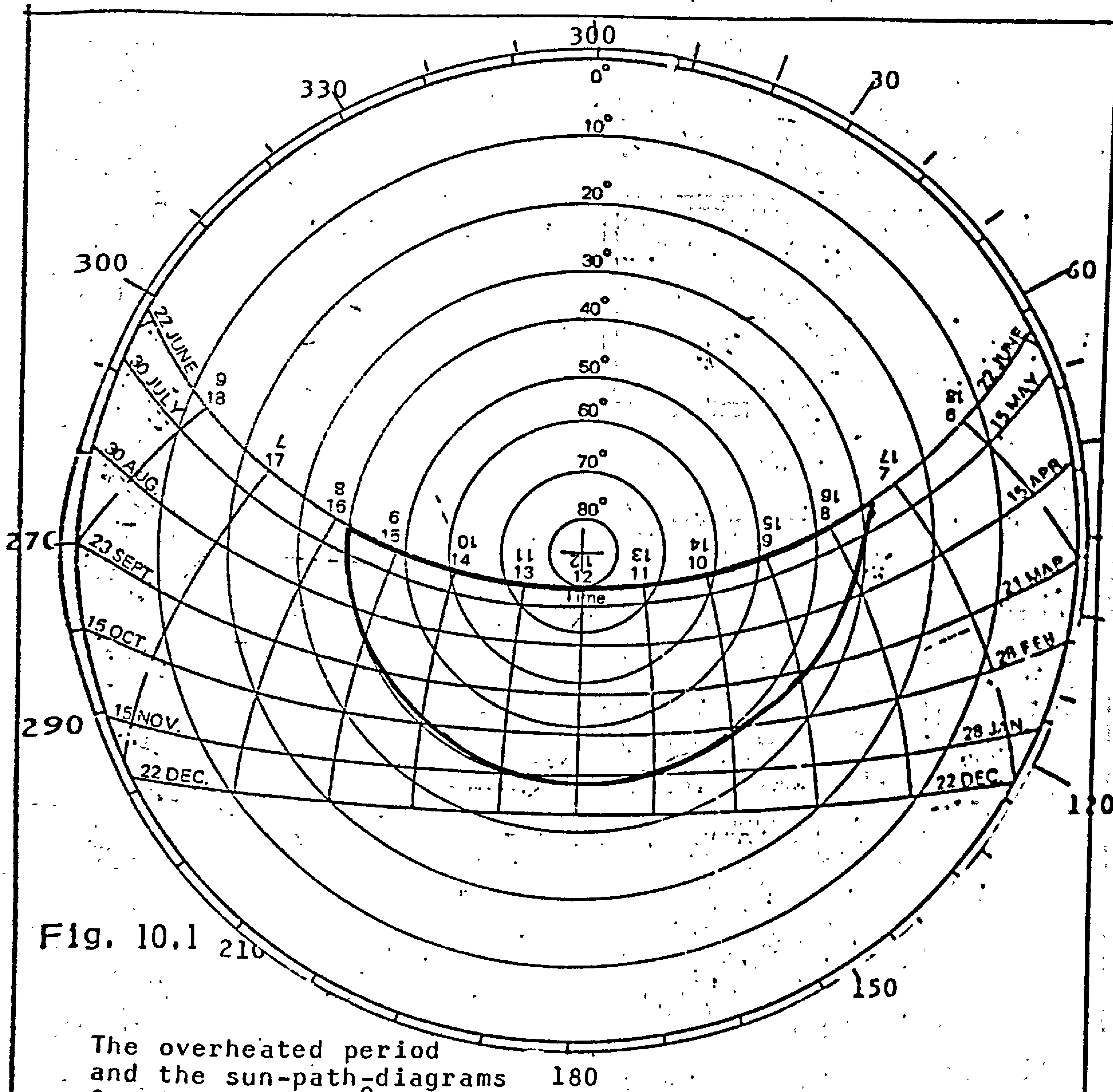


Fig. 10.1

The overheated period and the sun-path-diagrams for Altitudes 32° north.

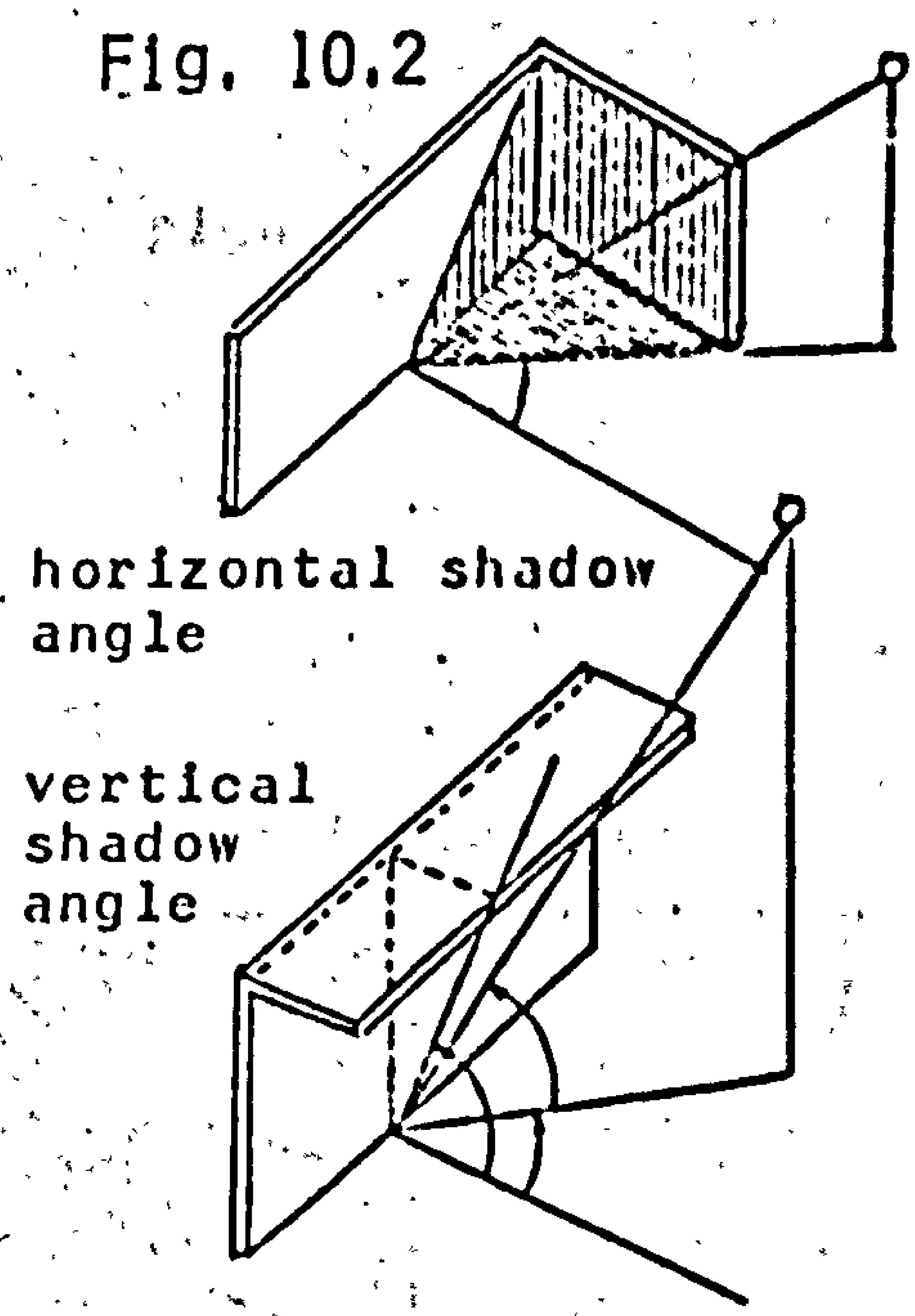
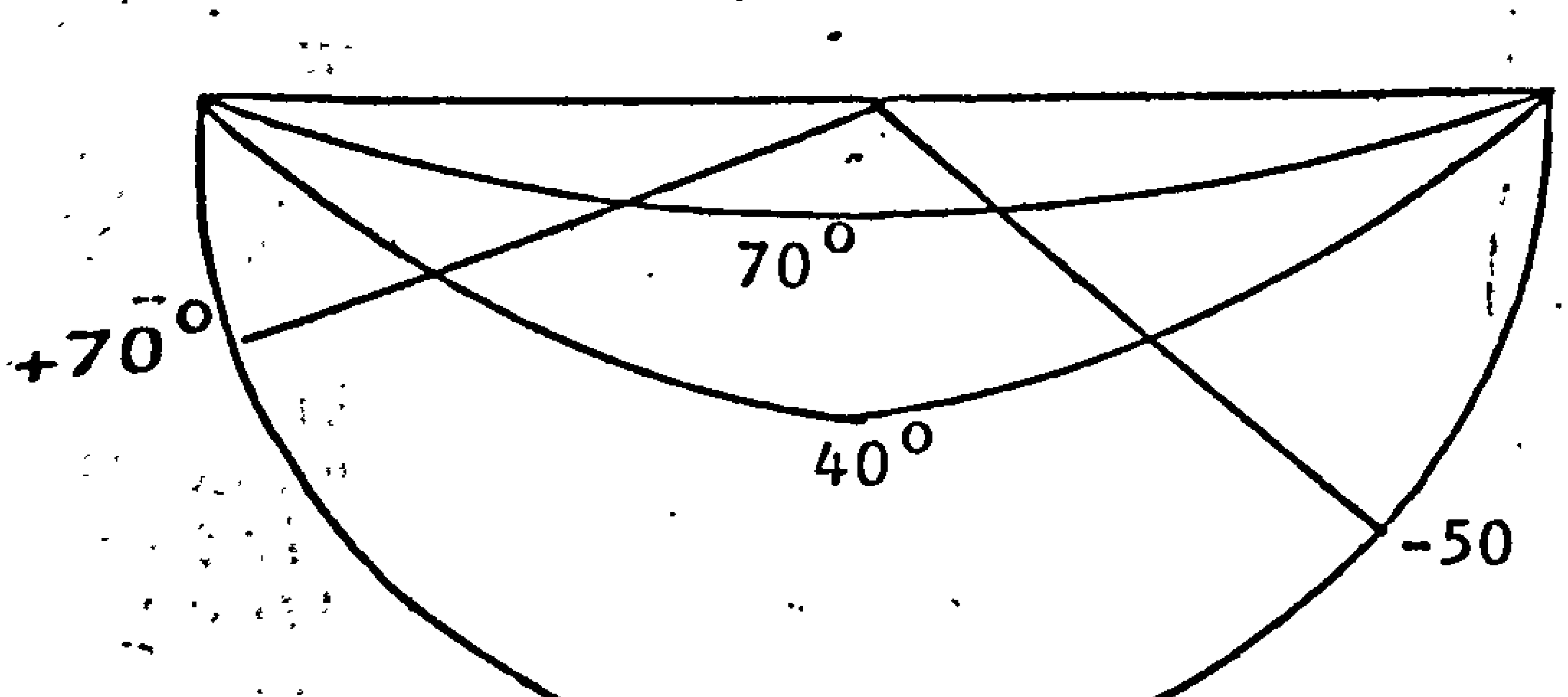
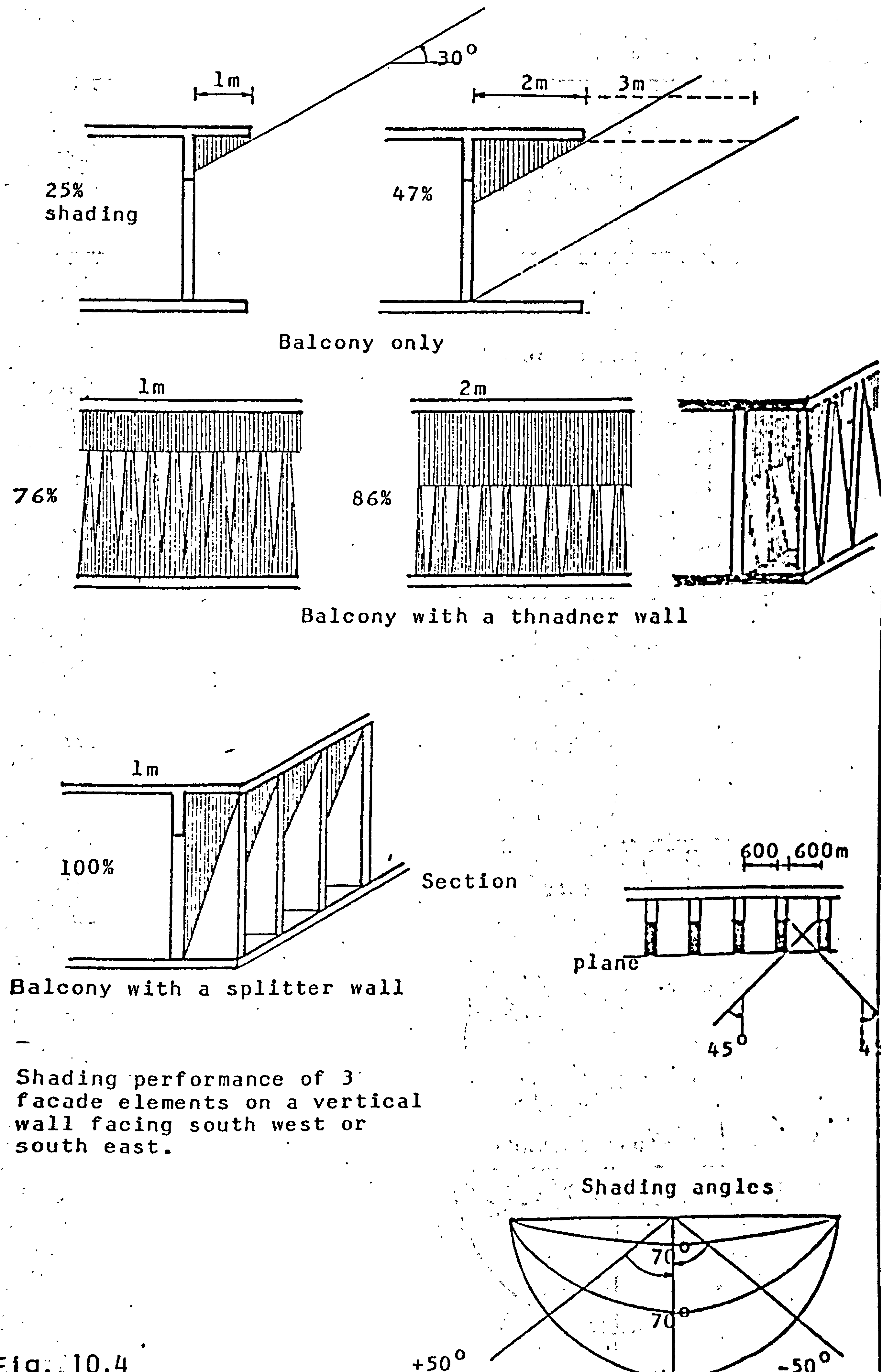


Fig. 10.2



The shading angles which covered the overheated area.

Fig. 10.3

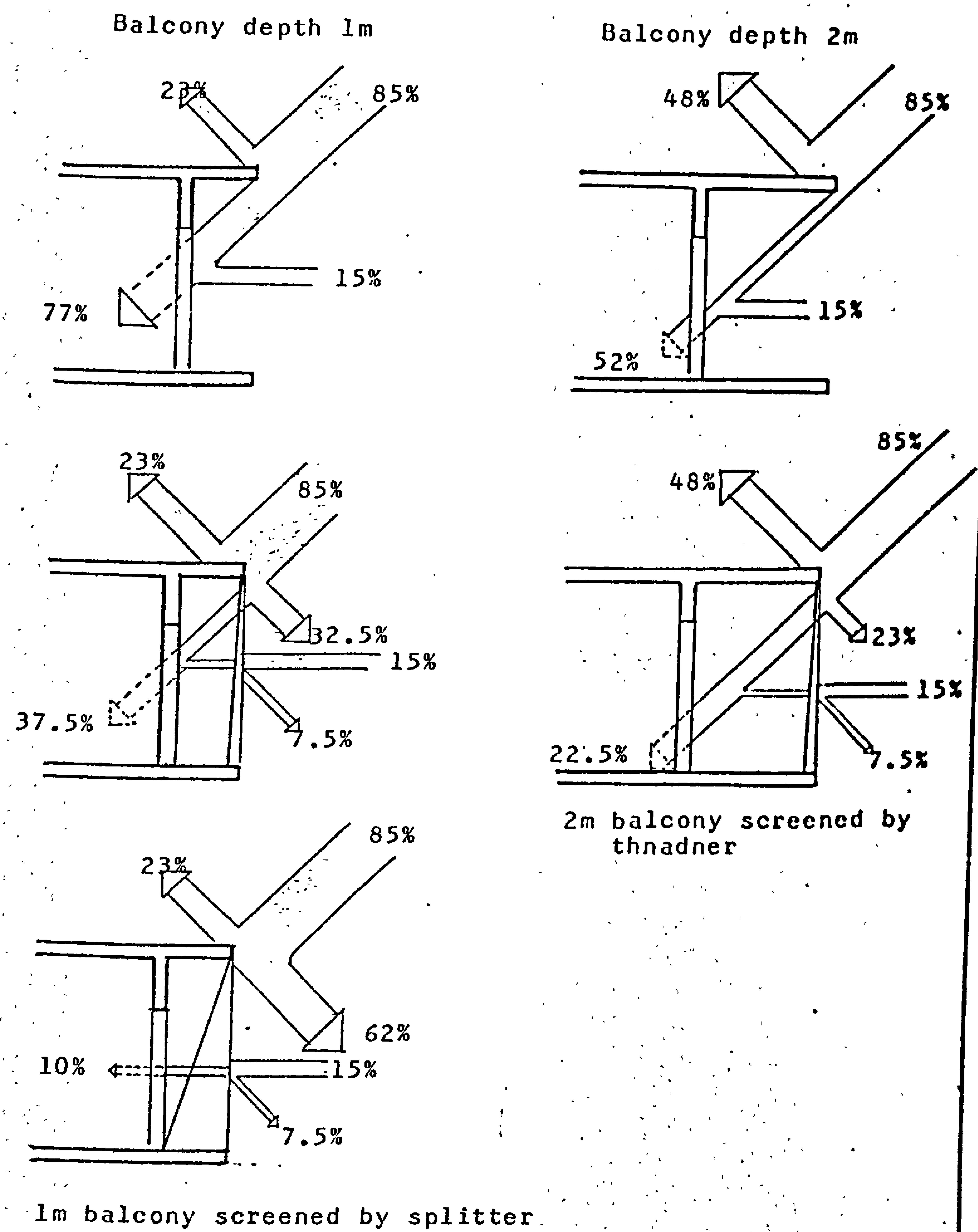


Shading performance of 3 facade elements on a vertical wall facing south west or south east.

Fig. 10.4


45°
1m
27%
shading
2m
1.5m
57%
shading
2m and thnadner screen
1m balcony and thnadner screen
76%
86%
100%
sec.
600m
plan
45°
45
1m balcony and splitter screen
As before for a wall facing south.
shading angles
80°
70°
+70°
-50°

Fig. 10.5



Average solar gain for a vertical wall facing south.

Fig. 10.6