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Assessing the Acoustical Climate of Underground Stations

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Designing a proper acoustical environment—indispensable to speech recognition—in long enclosures is difficult. Although there is some literature on the acoustical conditions in underground stations, there is still little information about methods that make estimation of correct reverberation conditions possible. This paper discusses the assessment of the reverberation conditions of underground stations. A comparison of the measurements of reverberation time in Warsaw's underground stations with calculated data proves there are divergences between measured and calculated early decay time values, especially for long source–receiver distances. Rapid speech transmission index values for measured stations are also presented.

room acoustics   long enclosure

1. INTRODUCTION

The acoustical climate of enclosures is a very important parameter that determines the activity of architectural acousticians, who are particularly interested in special enclosures, e.g., concert halls, theatres and cinemas. Recently acousticians have also focused on more common enclosures, e.g., libraries, reading rooms, swimming pools, offices and railway stations, where people spend a lot of time. Acoustical conditions of long rooms, e.g., underground stations, corridors, tunnels and streets are also discussed.

Many papers discuss the assessment of acoustical climate of large enclosures concentrating mainly on sacral rooms and halls. The acoustical climate of rooms, especially sacral structures, is determined by reverberant conditions, speech intelligibility, external disturbances and the quality of sound [1]. Similar factors influence the acoustical quality and climate of long enclosures.

2. ACOUSTICAL CLIMATE OF LONG ENCLOSURES

A long enclosure can be defined as an enclosure whose length is much longer than its width and height and those two dimensions are much larger than the sound wavelength [2]. It can also be defined as an enclosure in which the proportion of width to length is 3:2 [3].

Good acoustical quality is a very important feature of long enclosures, especially if there is a reinforcement system for speech intelligibility. Unfortunately in many long rooms speech intelligibility, measured with the speech transmission index, is not satisfactory. Many acoustical measurements considered constant and lining conditions. That is why they cannot be taken into account when looking for architectural solutions.

Long rooms are enclosures with a non-diffusive acoustical field. Models of acoustical fields of long rooms differ from the predicted acoustical conditions in diffusive fields. Measurements and research were started to improve models on the

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basis of the ray tracing method to visualize sound fields of long enclosures with regard to rooms like underground stations—rooms with regular cross-sections [4]. Prediction of different parameters indicated high correlation with measurement results in the full frequency range, particularly in the far sound field.

In long enclosures, e.g., underground stations, classic acoustical theories are not applicable, because assumptions about the diffusive field are not applicable in such extreme dimensions. In the last few years some publications discussed this problem, e.g., Kang and Orlowski [5] presented clear conclusions of theoretical research and design guidelines based on projects and scientific measurements of underground stations conducted in Hong Kong. Theoretical models were applied to predict reverberation time and speech intelligibility. Kang and Orlowski introduced a semi-empirical equation to calculate reverberation time:

$$T_d = \frac{150}{850\,M - 10\log\left[\frac{d}{d+850}(1-\alpha)^{25.6\left(\frac{1}{H}+\frac{1}{W}\right)\sqrt{d+425}}\right]}\,(\mathrm{s}), \quad (1)$$

where *d*—source–receiver distance (m), *W*—width of enclosure (m), *H*—height of enclosure (m), α—average absorption coefficient of boundaries, *M*—air absorption coefficient (dB/m) [6]. Because of the large volume of the measured enclosures, the parameter *M* has to be taken into account when assessing the reverberant conditions of long rooms.

Kang also indicated that between many methods and formulas concerning sound attenuation in long enclosures, only the geometric method seems to be practical. Kang concluded that it was necessary to make methods of acoustical designing of long enclosures more precise [7, 8].

3. MEASUREMENT OF REVERBERATION CONDITIONS OF UNDERGROUND STATIONS

Measurements were carried out in three Warsaw underground stations: Metro Politechnika, Metro Wierzbno and Metro Stokłosy. The enclosures were one-platform stations with 10- to 11-m-wide platforms. The volume of the stations was 14 900, 10 900 and 10 050 m^3, respectively (Figure 1).

The height and width (at platform level) of the enclosures were the same, 6 and 20 m, respectively. All enclosures were open at their ends, by the stairs. All boundaries of two stations were reflective, whereas Metro Stokłosy had an absorptive ceiling and a row of pillars running through the long axis of the station.

Measurements were carried out in six receiving points along the platforms, every 20 m (source–receiving distances: 20, 40, 60, 80, 100 and 120 m) (Figure 2). Measurements were carried out with maximum-length sequence techniques.

All three enclosures were open at their ends (stairs and train tunnels). Even though the stations

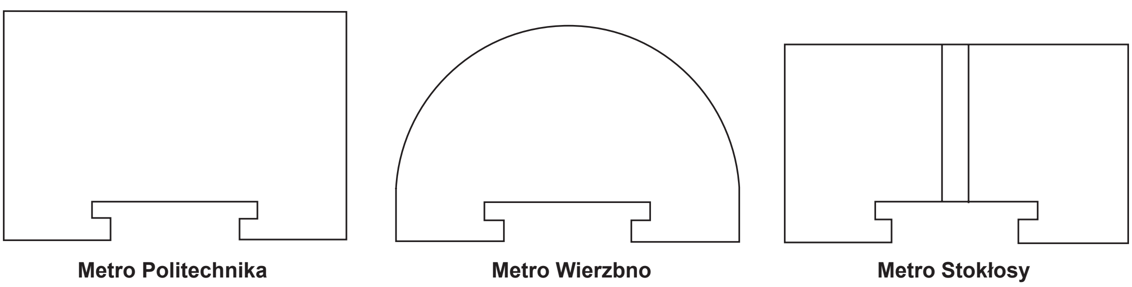

Figure 1. Cross-section of measured enclosures.

were connected by train tunnels, they were not considered to be coupled rooms.

Figure 3 shows results of measurements of reverberation time for all three underground stations in dependence of the source–receiving distance. In two stations, Metro Politechnika and Metro Wierzbno reverberation time has flat characteristics. This value is independent of the source–receiver distance.

The lowest reverberation values in Metro Stokłosy were caused by the absorptive ceiling over the platform. It was in this station only that there was an increase in reverberation time in the function of the source–receiving distance. The highest values of reverberation time were in Metro Wierzbno. In this station the boundary walls are the most reflective. This station has a circular cross-section, too.

Figure 4 compares the results of the measurements of reverberation time in Metro Politechnika and Metro Wierzbno (enclosures with reflective boundaries) with data calculated with Equation 1. Those enclosures have the same height and width at platform level but their cross-sections are different. Calculations were made with the average absorption coefficient of boundaries $\alpha = .01$ (value for concrete and terracotta), the air absorption coefficient M = 0.00273 dB/m (value for the average temperature of 20 °C and 50% humidity). These values have to be taken into account because of the factor of 850 in the equation.

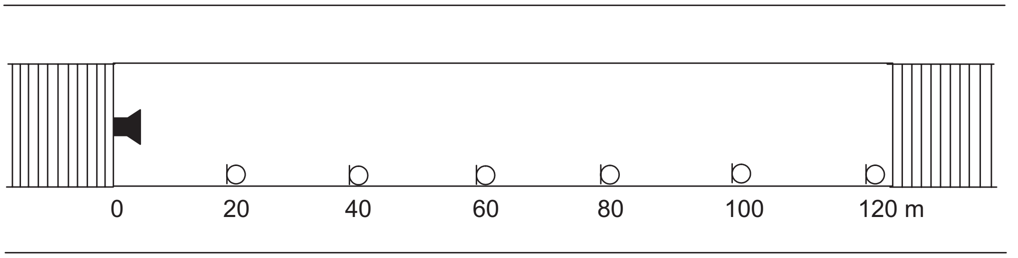

Figure 2. Location of the sound source and receiving points during measurements in underground stations.

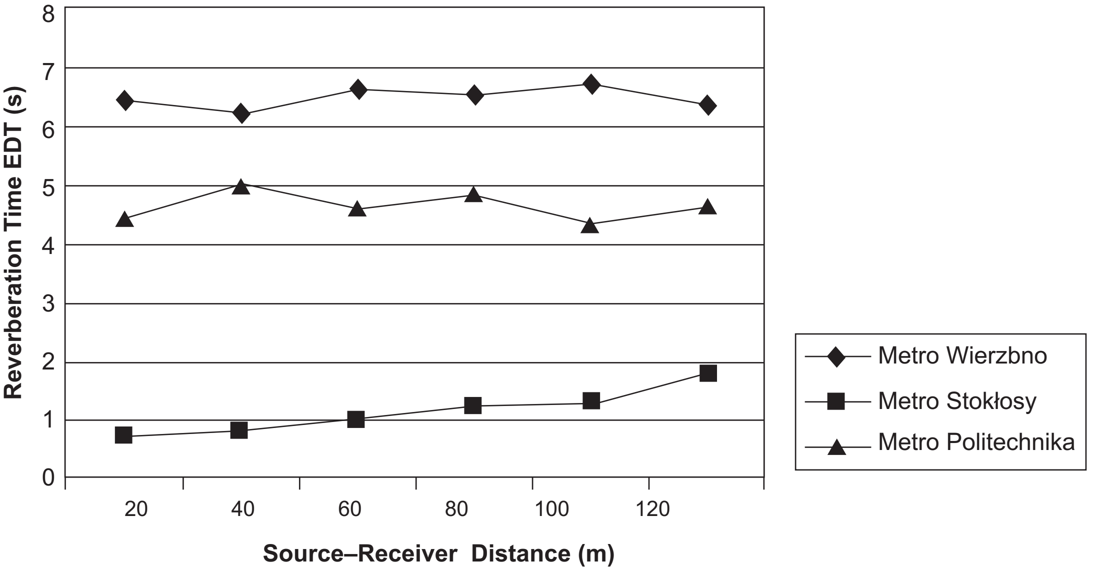

Figure 3. Reverberation time in Warsaw underground stations in dependence of distance receiving point from sound source (frequency 500 Hz). *Notes.* EDT—early decay time.

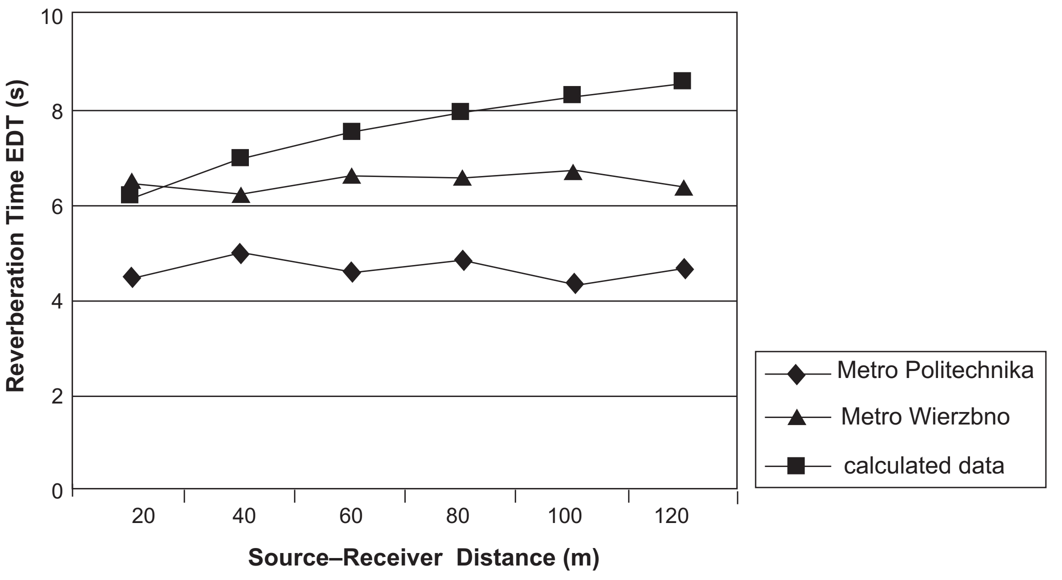

Figure 4. Comparison of measurement results with calculated data.

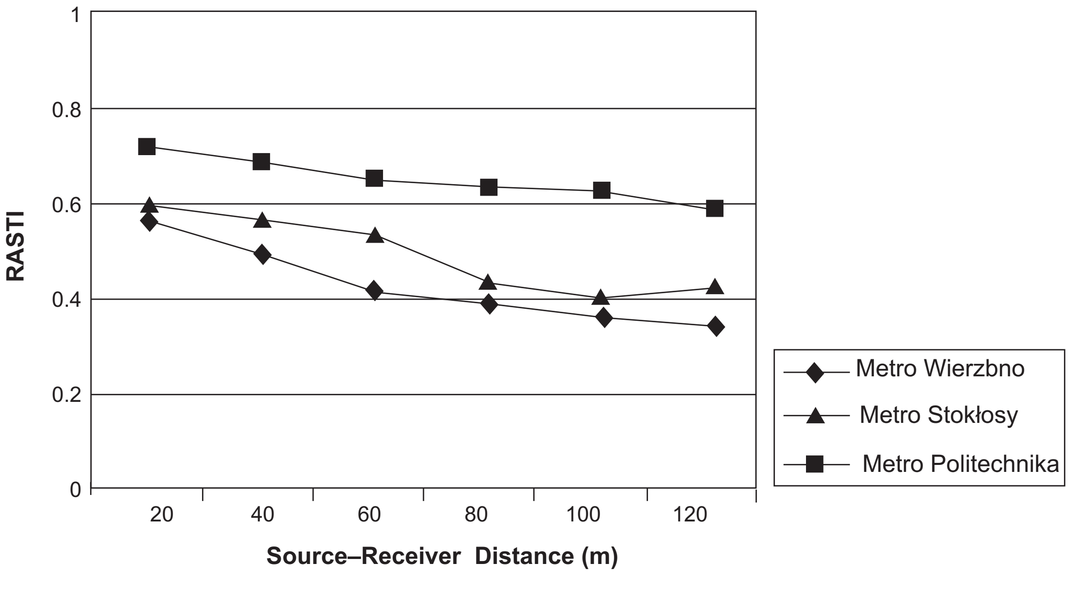

Figure 5. Rapid speech transmission index values (RASTI) in Warsaw underground stations in dependence of distance receiving point from sound source.

The values obtained from Equation 1 overestimated real-room reverberation conditions. By comparing early decay time values with the measured results, calculated data were longer by 4 s, especially for a long source–receiver distance.

Reverberation time has great influence on speech intelligibility. Figure 5 presents results of measurements of the rapid speech transmission index (RASTI) in Warsaw underground stations. Speech intelligibility in Metro Wierzbno and Metro Politechnika was poor; whereas it was fair and good in Metro Stokłosy (near the sound source). The results confirmed better reverberation conditions of stations with absorptive ceilings. A comparison of RASTI in enclosures with different shapes of cross-sections

(Metro Wierzbno and Metro Politechnika) indicated that in spite of larger volume, speech intelligibility was better in stations with a rectangular cross-section.

4. SUMMARY

1. Measurements carried out in three Warsaw underground stations indicated that two of them (Metro Politechnika and Metro Wierzbno) had worse acoustical conditions than the third one (Metro Stokłosy). This was so because of
   - the large volume of Metro Politechnika (over 14 000 m^3);
   - the reflective boundaries with the average absorption coefficient of $\alpha = .01$; and
   - the absorptive ceiling in Metro Stokłosy producing better reverberation conditions.
2. A comparison of the measured results with calculated data indicated that Equation 1 gave incorrect reverberation time values, especially in long enclosures with reflective boundaries. Values of measured reverberation time were immutable with an increased source–receiver distance, which can be seen in calculated data.
3. Kang and Orlowski's [5] equation is inexact because it does not take into account the volume of the enclosure (only its height and width). The method of measuring the width was not specified, either. Therefore, for stations with different cross-sections and volumes the values of calculated reverberation time were the same.
4. Speech intelligibility measured with the RASTI method was better in stations with a rectangular cross-section than in stations with an elliptic one, even if the volume of the enclosure was larger.

In addition to the measurements discussed in this paper, computer modelling will be used to obtain more precise equations and methods of assessing the acoustical climate of long enclosures.

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