ACOUSTICAL ASSESSMENT OF SUBWAY STATIONS BY DIFFUSION EQUATION MODELLING

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The acoustical criteria to be applied for design and assessment of subway stations have been well defined by Environmental Noise Control Act of Turkey, since 2005. In architectural design phase the material and geometrical attributes are adjusted to fit related criteria mostly by application of ray tracing simulations. Reverberation time and sound pressure levels are two major indicators. The basic limitation of ray tracing is that the method is more valid as the sound field is closer to a diffuse field. Subway stations on the other hand are longitudinal volumes and depending upon the source location the sound is not always evenly distributed. This problem appears when subsequent field tests are compared to the simulation results. For this reason, in this research an alternative method is searched, namely, diffusion equation modelling (DEM), in order to better estimate the acoustical parameters in such disproportionate rooms. Diffusion coefficient in DEM takes its form from mean free path, so the mesh sizes are not even high for mid to high frequencies to be applied in a finite element medium, which is one basic advantage of this model. This new method is previously searched for its reliability in long rooms as well as in rooms with some sound absorptive surfaces. Two cases of İstanbul Metropolitan subway lines are selected, namely, station BAG and station USK, to comparatively evaluate ray tracing and DEM solutions. The results indicate that ray-tracing simulations underestimates the sound attenuation in the case stations and results in higher reverberation times in comparison to DEM solution. Sound pressure level distributions provide a similar pattern of decay, while in ray-tracing the levels are still higher as the receiver is moved away from the source. DEM results are found to be more coherent with field test results, and computationally more efficient than ray-tracing. There is still a variation for specific receiver positions in between field and DEM results. The reasons of deviations per receiver positions need to be further investigated. In optimization of acoustical material application in subway stations, which is highly important for economic purposes, DEM can be used as a reliable and practical method.

1. Introduction

Subway systems are integral parts of public transportation in urban fabric. Station acoustics is a comfort parameter, which has to be satisfied relying on acoustical criteria defined in regional regulations and codes. Turkish Environmental Noise act [1] covers maximum allowable noise limits due to train pass by, due to emergency fan operation in relation to speech intelligibility and optimum reverberation times within stations. All these criteria are considered during design phases of stations. For a smooth design process and successful end product, reliable methods in the analysis of station acoustics are highly critical. This study focuses on the discussion of reliable tools and methods in estimation of sound fields of subway stations. Two cases of subways stations, one with circular, the other with rectangular cross section from Üsküdar-Ümraniye line in İstanbul Metropolitan metro system are selected for detailed analysis.

Metro stations are long enclosures with different acoustical properties to normal rooms, due to disproportionate room ratios. Therefore, the classical statistical theory of acoustics may not always be appropriate for their sound field investigations. The sound prediction studies of subway systems, or long enclosures, have utilized either scale model experiments [2], image-source [3] or ray-tracing techniques [4-5]. A comparatively new methodology is the diffusion equation model applications in room acoustics [6-8]. Transport equation is another recent model applied for sound field analysis of long rooms [9].

Volume, room shape and surface materials direct the acoustical characteristics of metro stations. The reverberation control is the initial step of acoustical design. Due to maintenance and hygiene issues, the interior surfaces are mostly sound reflective in such high-circulation public areas such as stone cladded floors or ceramic tiled or painted masonry walls. Acoustical materials and their effects are also studied by some researchers for increasing the intelligibility of public announce systems [2,10]. The most applicable surface for sound absorptive treatment are ceilings.

One of the concerns that has motivated this study is the optimization of sound absorptive treatment applications in subway stations. In İstanbul, there are quite many number of metro lines and tens of stations under construction. Economically the amount of absorptive materials is of main interest. The most common and practical tool for acoustical design is ray-tracing simulations. The reliability of this technique is questioned by its comparison to a more recent method, namely, diffusion equation modelling. Both techniques are compared with field tests, as discussed in following sections.

2. Methodology

In this study two different methods are applied, which includes ray-tracing simulations and diffusion equation model (DEM) analysis, in the assessment of sound fields of subway stations. Out of two case stations within the one with circular cross-section (BAG) field-tests are performed. Acoustical models are tuned by given material information as well as field tests. The station with rectangular cross section (USK) have identical surface finish materials so the data obtained from the initial assessment is also valid for this second station. The details of field tests are not included in the paper for the sake of briefness. On the other hand, it should be noted that the source-receiver locations presented in this section are identical in station BAG to its field tested configurations.

2.1 Ray-tracing simulations

Initially the simplified acoustical models of station BAG and station USK are generated to be imported in a ray-tracing software. The total length of platform in station BAG is 140 m and the overall width of the platform level is 37 m. The total length of platform in station USK is 150 m and the overall width of the platform level is 22 m. Surface materials of these stations include ceramic tiles, painted concrete and glass (Platform Screen Doors) for walls and stone cladding (platform) and concrete (under rail) for floors. Perforated metal panels with %20 percentage of opening ratio and

25 mm 50 kg/m^3 mineral wool with 20 cm air-gap behind is the section of the suspended ceiling system. The tested sound absorptive ceiling treatment displays an absorption coefficient of 0.83 in 1 kHz. Average sound absorption of wall and floor surfaces is 0.03. Interior views from acoustical models are presented in Fig. 1., sound and receiver configurations are highlighted in Fig 2. Darker colours (brown) in ray-tracing model indicates sound absorptive ceiling surfaces.

Figure 1. Interior views of subway stations platform levels; station BAG (on the left), station USK (on the right)

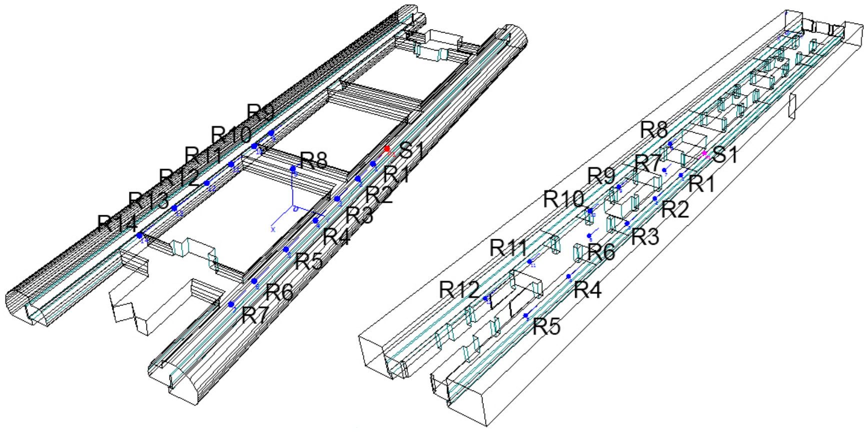


Figure 2. Interior views of subway stations platform levels; station BAG (on the left), station USK (on the right)

2.2 Diffusion equation model

This section presents the governing and boundary equations within scope of the DEM that fits most properly to the subway stations under discussion. The advantage of DEM especially in mid-to-high frequencies is that, meshing size takes its value from the mean free path (λ), that is 4V/S, instead of wavelength. As long as the maximum mesh size is smaller than the mean free path of the room then the DEM is applicable. So, the computational load is lower. In Eq. 1 interior diffusion equation is presented for within the domain from which the sound energy density w at position (r), and time (t) can be expressed:

$$\frac{\partial w(r,t)}{\partial t} - D\nabla^2 w(r,t) = q(r,t), \ \in V \tag{1}$$

where ∇^2 is Laplace operator, c is speed of sound, D is the diffusion coefficient, that is λc/3. For modelling the local effects of the sound fields that have comparatively higher absorption on specific surfaces, modified absorption factor term is utilized for mixed-boundary condition [11]. The resulting system boundary equation is given in Eq. 2 in the following:

$$-D\frac{\partial w(r,t)}{\partial n} = \frac{c\alpha}{4(1-\alpha/2)} w(r,t), \text{ on } S \tag{2}$$

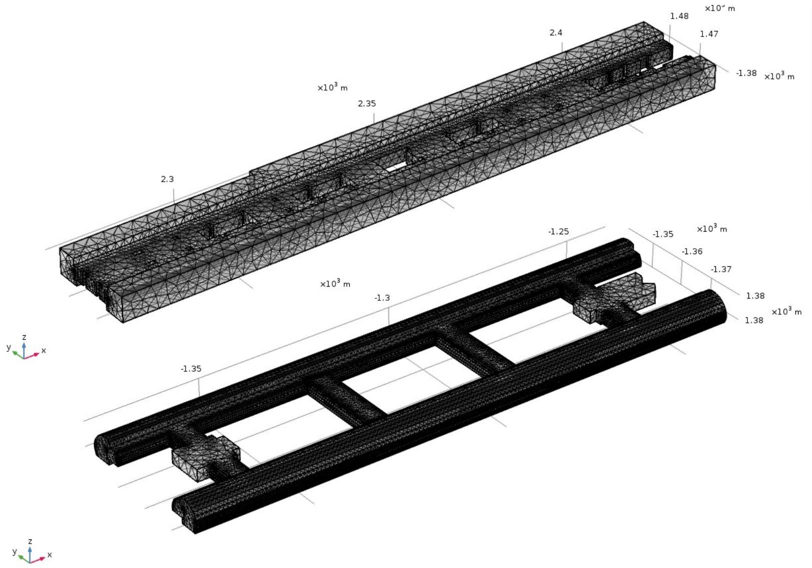
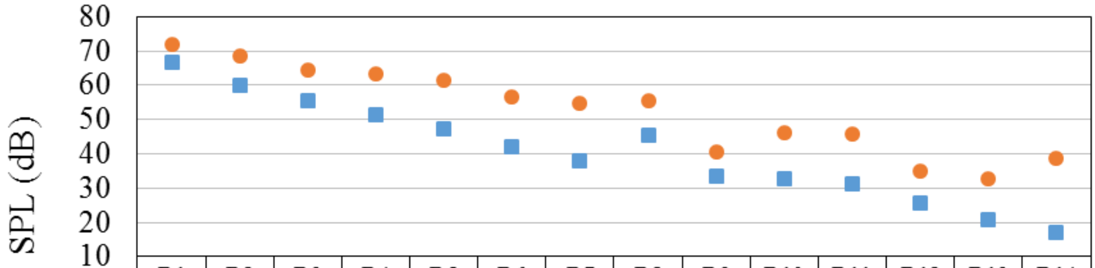


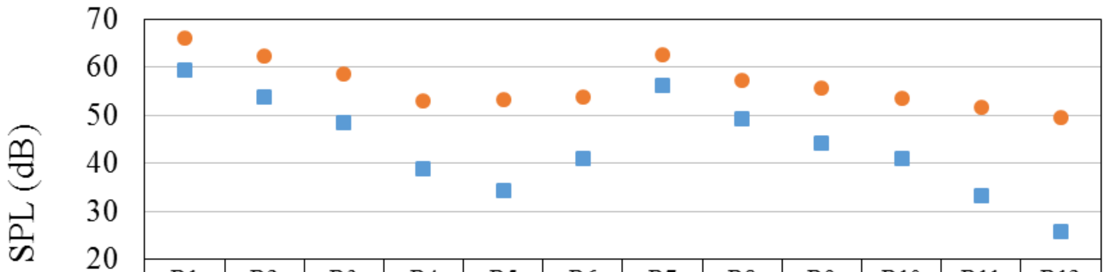
Figure 3. Mesh models of subway stations: station BAG (below), volume 12,988 m^3, total of linear Lagrange-type mesh elements 282701, max. mesh size 4.1 m; station USK (above), volume 14,187 m^3, total of linear Lagrange-type mesh elements 94,046, max. mesh size 4.9 m

3. Results and Discussion

This section presents ray-tracing simulation results and finite element solution of DEM for station BAG and station USK. Sound pressure level (SPL) estimations for tested source and receiver positions are compared to DEM versus ray-tracing in Fig 4. Field tested reverberation time (T30) results are compared to ray-tracing and DEM solutions of station BAG as presented in Fig. 4. Station USK T30 results are compared for ray-tracing versus DEM (Fig. 4). The results are presented for 1 kHz, as a representative octave band in relation to speech.



	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
BAG_DEM	66,6	59,9	55,4	51,5	47,2	42,1	38,1	45,4	33,4	32,7	31,3	25,5	20,9	16,9
BAG_RAY TRACING	71,8	68,7	64,4	63,3	61,3	56,6	54,8	55,6	40,7	46	45,6	35,1	32,7	38,8

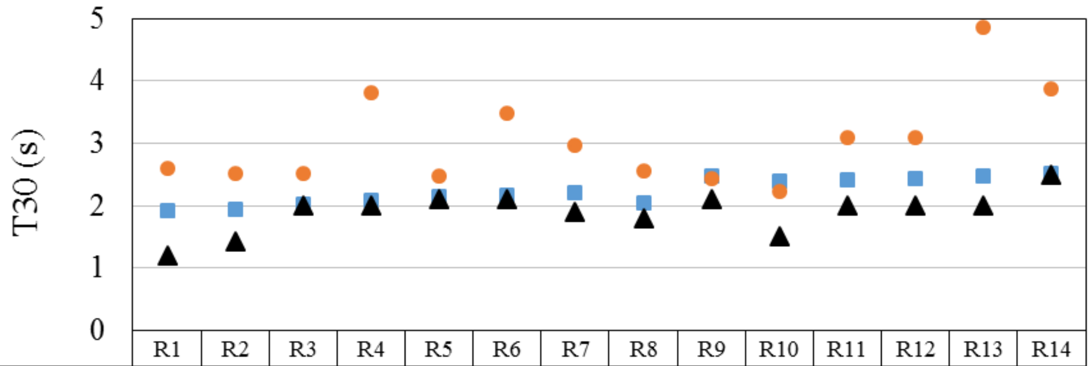


	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
USK_DEM	59,3	53,9	48,4	38,9	34,3	41,1	56,1	49,4	44,3	41	33,3	25,9
USK_RAY TRACING	66,2	62,4	58,6	53,1	53,3	53,9	62,7	57,4	55,8	53,6	51,8	49,5

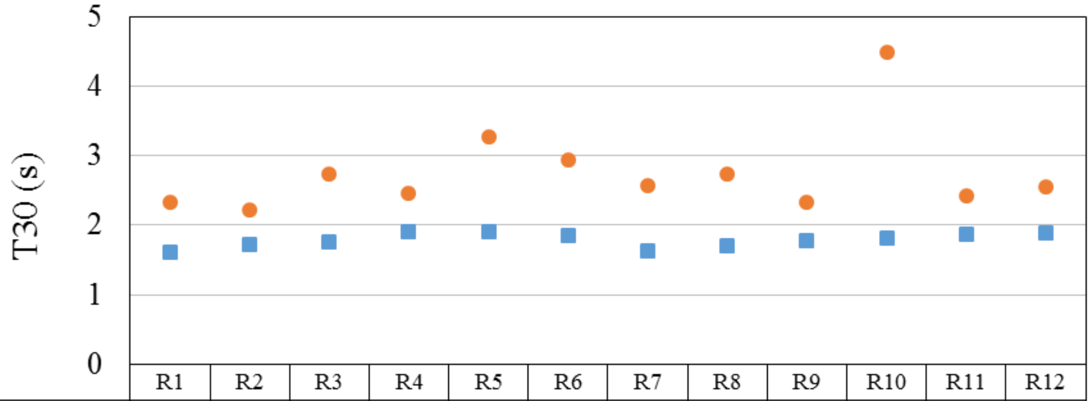
Figure 4. Comparison DEM and ray-tracing results of SPL(dB) in station BAG (above) and station USK (below) for different receiver (R) positions for 1 kHz

An omni-directional sound source is defined in both ray-tracing and DEM estimations. The same initial level is assigned in both models. In Fig. 4, it can be observed that both models depict a similar pattern, in form of sound decay level, as the receiver is moved away from the source. However, the deviation of sound level is sharp especially at further locations when the two models are compared. At the very closer locations to the source (as R1) the difference between DEM and ray-tracing is around 5 to 6 dB. The attenuation increases in DEM when the receiver positions are on the other side of the tunnel. And, the difference between sound levels, in model comparison, rises up to 20 dB, which is quite high. Sound pressure level is one of the criteria that has to be satisfied according to the codes. So, a reliable estimation is highly critical in design phase for economic and practical solutions.

For that reason, field tests (BAG_MEAS) are consulted in order to evaluate the efficiency of DEM versus ray-tracing in long rooms. As can be observed from Fig. 5, at most of the receiver positions of station BAG, the DEM and field test results are highly correlated. On the other hand, there are abrupt jumps or increase in reverberation time on different receiver positions in ray-tracing simulation results. Similarly, when station USK T30 results are investigated a smoother distribution can be observed in DEM results versus ray-tracing. Reverberation time is also a critical parameter and is the primary indicator in room acoustics design, and well defined in terms of its optimum ranges by codes and regulations. From both figures it can be clearly stated that there is an under estimation of ray-tracing regarding to sound attenuation in these case structures. T30 results of DEM at some positions are still higher than field tests, the reason of which should be further investigated.



	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
BAG_DEM	1,92	1,94	2,02	2,09	2,14	2,17	2,21	2,04	2,48	2,40	2,41	2,43	2,47	2,51
BAG_RAY TRACING	2,59	2,51	2,51	3,82	2,47	3,48	2,96	2,55	2,43	2,23	3,10	3,10	4,87	3,87
BAG_MEAS	1,20	1,42	2,00	2,00	2,10	2,10	1,90	1,80	2,10	1,50	2,00	2,00	2,00	2,50



	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
USK_DEM	1,60	1,72	1,76	1,90	1,91	1,84	1,62	1,70	1,78	1,81	1,86	1,89
USK_RAY TRACING	2,32	2,22	2,73	2,45	3,27	2,93	2,56	2,73	2,32	4,49	2,42	2,55

Figure 5. Comparison of field test, DEM and ray-tracing results of T30 (s) in station BAG (above) and station USK (below) for different receiver (R) positions for 1 kHz

4. Conclusion

The optimization of acoustical material application is highly important in subway station acoustics. The criteria for sound pressure levels and reverberation times are well set in codes and regulations. As some recent findings out of field tests imply that there is a certain amount of overdesign when classical ray-tracing estimations are applied, alternative methods are investigated in this study.

Diffusion equation model has been recently used in room acoustics. This new method is also searched for its reliability in long rooms as well as in rooms with some sound absorptive surfaces. In this paper, the DEM is applied on two case stations and compared to field tests and ray-tracing simulations. Results indicate that ray-tracing underestimates the sound attenuation and results in higher reverberation times in comparison to DEM solution. DEM is more coherent with field test results, while there is still a variation for specific receiver positions. The reasons of deviations per receiver positions will be further investigated in a future study.

Considering the computational load, the efficiency of the DEM is also proved. The time dependent solutions of case stations with DEM lasts within 10 to 15 minutes on a computer with Intel(R) Xeon(R) E5-1650 CPU, @ 3,60 GHz processor. This solution not only provides results on specified receiver positions but for the whole volume. Its capability of providing spatial energy distributions and energy flow vector analysis are other advantages of DEM, which are not included in this paper for briefness. The DEM application in this study has proven to be a practical and reliable method that can accelerate room acoustics analyses and support the acoustical design process of subway stations.

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