Toward Acoustic Landscapes: A Digital Design Workflow for Embedding Noise Reduction in Ground-forming

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Abstract: Noise pollution is considered the number two environmental health risk in Europe, and there is increasing global awareness of the health risks associated with noise exposure. As urbanization expands, a growing number of people are exposed to urban noise, to which airports and large urban infrastructure are significant contributors. Unlike indoor noise, which is extensively addressed using digital tools in architecture, there are limited parallel efforts in landscape architecture. In this context, mitigating outdoor noise through ground forming can replace the standard use of sound barriers and offer noise reduction means together with recreational use. The paper presents and demonstrates a digital workflow for designing acoustic grounds. The workflow links environmental noise data, parametric design, and acoustic simulation in a single design environment. A case study site adjacent to Munich Airport is used to demonstrate the workflow and comparatively examine the acoustic performance of different design patterns. The results indicate a possibility of reducing noise levels through ground forming.

Keywords: Performative grounds, noise mitigation, acoustic landscapes

1 Introduction: In Search of a Vast, Horizontal Acoustic Tile

In 2011, noise pollution was named the number two environmental health risk in Europe (WORLD HEALTH ORGANIZATION 2011). Since then, the World Health Organization (WHO) has constantly been updating the health risks associated with noise exposure (WORLD HEALTH ORGANIZATION 2022). As urban areas expand, the number of people exposed to urban noise grows. Airports and large urban infrastructure significantly contribute to this noise (BOUCSEIN et al. 2017). In addition, the propagation of noise caused by transport infrastructure has been shown to increase through poor urban design (MORILLAS et al. 2018). Existing methods for mitigating outdoor noise typically consist of prefabricated, vertical industrial acoustic walls. In contrast to acoustics in architecture, where digital tools are used to design and fabricate site-customized acoustic tiling, outdoor noise is not met with similar means. However, preliminary examples indicate that formed grounds could mitigate sound. Despite this potential, there is a lack of dedicated methods for creating acoustic grounds in landscape architecture. Mitigating noise through acoustic grounds could be beneficial for urban airports, which are typically bordered by buffering open spaces. In such areas, ground forming can provide noise mitigation as well as public recreational use.

1.1 Context and Objective

Digital tools enable the introduction of preciseness into landscape architecture design and making (CANTRELL & MEKIES 2018). Preciseness is defined here as the process of highly-articulate tailoring of a design for mitigating a natural phenomenon. In this context, the de-

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sign of acoustic grounds requires linking environmental data relating to noise to a landscape design aiming to mitigate it. The research seeks to promote noise mitigation through what can be viewed as the horizontal, ground-made, site-tailored version of an acoustic tile. To this end, the paper presents a digital design workflow for embedding noise reduction and simulating acoustic performance in landscape architecture. The workflow is based on a method for incorporating acoustic analysis in landscape architecture design developed by the authors (BAR-SINAI et al. 2023). This is demonstrated through a case study site in Hallbergmoos, adjacent to the Munich airport, which is amongst the ten busiest airports in Europe (BOUCSEIN et al. 2017). Currently, no physical noise reduction measures exist in the area (Figure 1).

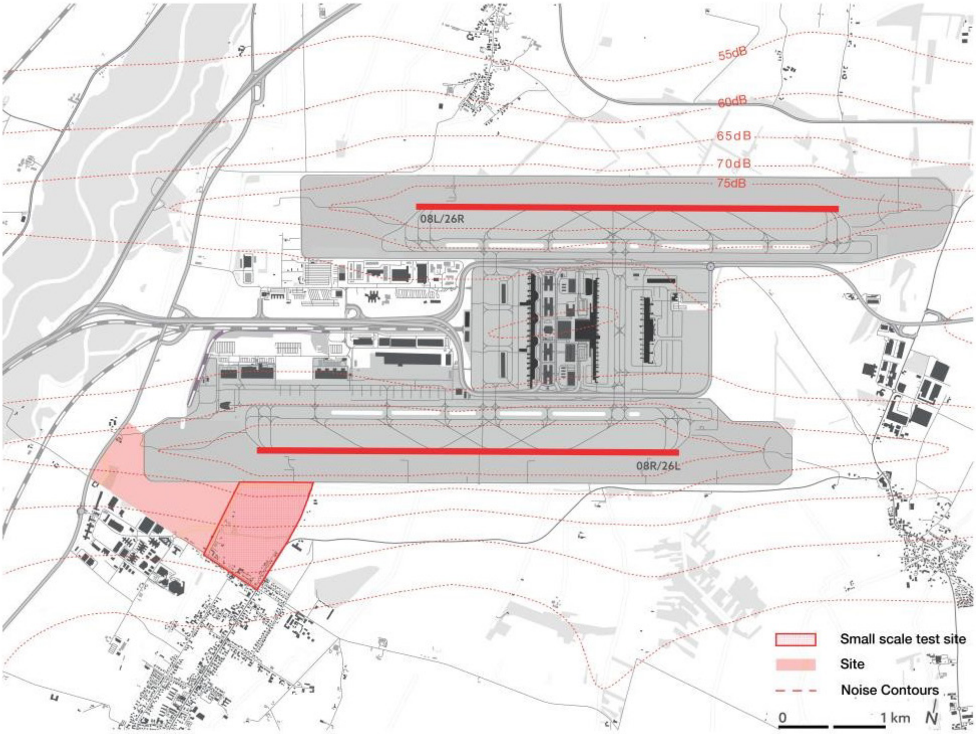

Fig. 1: The case study site in Hallbergmoos, adjacent to the Munich airport, overlaid with the average daily noise. Source of the noise levels: Bayerisches Landesamt für Umwelt (BAVARIAN MINISTRY OF ENVIRONMENT 2021)

1.2 State-of-the-art: Design and Simulation of Acoustic Grounds

There is a growing awareness of the need to protect from noise in outdoor spaces (SORVIG & THOMPSON 2018). In the context of airport noise, mitigation is addressed through three levels: (1) a primary level, which targets the noise source and is applied during the production of aircraft; (2) a secondary level, which adapts aircraft arrival and departure procedures; and (3) a tertiary level which includes measures by the local airport of aviation authority grounds (NETJASOV 2012).

Until recently, tertiary-level noise mitigation measures around airports did not include the formation of acoustic grounds. This possibility is beginning to be explored in landscape architecture projects, demonstrating a capacity to mitigate noise and vibrations through targeted ground forming. For example, Buitenschot Park demonstrates a reduction of the Schiphol airport noise through the construction of ground ridges and furrows. The park design distorts and disperses low-frequency noise waves, which have been reported to reduce the noise surrounding the airport by 10 dB (TASHAKKOR et al. 2020). A similar approach employed ground-forming for mitigating vibrations around a MAX Lab IV in Sweden

(WALLISS & RAHMANN 2016). These two examples challenge the standard practice of constructing absorbing sound barriers surrounding urban noise sources. However, there is still a lack of methods for performing noise mitigation through ground forming.

Acoustic simulation is often performed using stand-alone tools (SAKUMA et al. 2014), and as such, they do not readily support design iteration. While there are dedicated frameworks to integrate acoustic simulation in architectural design (PETERS 2015), there is a lack of similar methods for embedding noise reduction in landscape architecture design processes. Pachyderm, a recently developed open-source tool, performs ray tracing-based sound propagation simulation and visualization embedded in 3D design environments (VAN DER HARTEN 2013). However, despite the availability of Pachyderm, there is still a need for methods for applying it toward noise reduction in the design of open spaces. The lack of such methods currently limits the possibility of addressing noise in landscape architecture and urban design.

2 Acoustic Landscape Design Workflow

The paper addresses these gaps by developing a digital workflow that links noise, design, and simulation for embedding acoustic performance in landscapes. The workflow consolidates the design and simulation in a single digital environment. It consists of (1) noise data analysis, (2) the design of parametric ground formations, and (3) acoustic simulation and evaluation.

2.1 Noise Data Analysis: Combining Online and On-Site Measurements

Airport noise consists of ground-level noise as well as noise produced by aircraft during takeoff, landing, taxiing, and idling stages. The Munich Airport tracks noise in real-time through monitoring stations and provides publicly available data (MUNICH AIRPORT 2022). However, only one of the monitoring stations is positioned on the perimeter of the site. In addition, the monitoring stations are situated 4 m above ground. This height is determined by the Environmental Noise Directive (END) (EUROPEAN COMMISSION 2002), as it is where reflections from the ground stop playing a major role. Measurements performed above 4 m, therefore, allow the official comparison of different contexts. This calculation method is also the basis for all the noise abatement measures. However, measurements at the height of 4 m limit the possibility of understanding the noise as it is perceived by a listener on-site.

To sense the noise as it is felt on-site, the study combined online data with on-site noise sampling using mobile phones. The use of mobile devices has become an increasingly prevalent method for collecting environmental data (MURPHY & KING 2016). The noise sampling was conducted using five different devices. The devices simultaneously recorded the noise levels during takeoff and landing on five points on-site for 90 consecutive seconds (Fig. 2).

Despite their limited accuracy, and while at this point of the research, no identifiable relationship between the official and on-site sampling could be specified, the mobile phone measurements provided a picture of the felt noise levels on the ground. This noise, therefore, also includes the ground effect which the official measurement stations exclude. While the official averaged noise contour (BAVARIAN MINISTRY OF ENVIRONMENT 2021) is limited to the runway areas (Figure 1), the on-site noise sampling recorded peaks of 75 dB and above beyond the airport fence and within Hallbergmoos, underscoring the need for noise abatement in the area notwithstanding the averaged noise levels.

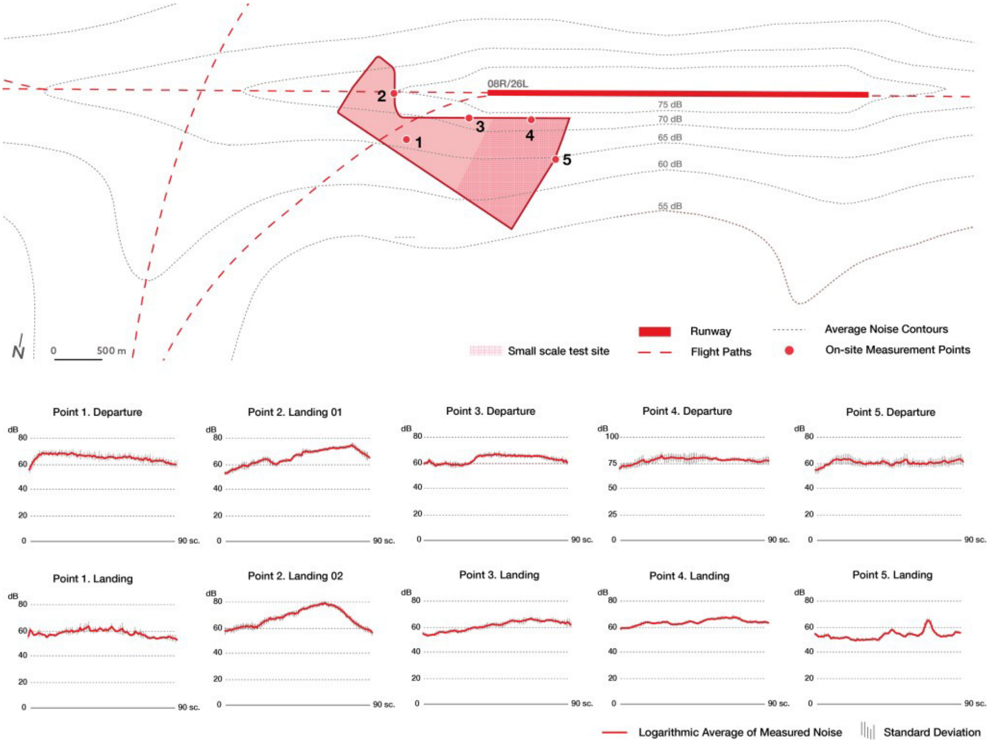

Fig. 2: On-site measurements of noise levels around the Munich Airport

2.2 Design: Parametric Ground Formations

The design first proposed a basic layout for the park and coupled the desired noise mitigation strategy with urban design considerations. The plan defined the movement paths, program, and areas dedicated to acoustic ground-forming (Figure 3). In these areas, the research tested formations consisting of mounds with public paths located between them. Four design patterns were tested at three heights: 2.5 m, 5 m, and 7.5 m. These included: high-to-low (HL), undulating mounds in gradually decreasing heights (7.5/5/2.5 m – 0.5 m); low-to-high (LH), undulating mounds in gradually increasing heights (0.5 m -2.5/5/7.5 m); constant height mounds (CM), featuring uniformly sized undulating mounds (tested in 2.5/5/7.5 m); and constant heigh solid ground (CS), an elevated ground without any undulation mounds (tested in 2.5/5/7.5 m). The width of the mounds was set to 21 m to provide an inclination and slope that allow public accessibility even in the higher-mound instances (Figure 3).

2.3 Acoustic Simulation and Evaluation

The simulation process includes several aspects:

1) **A base model** – the base model aimed to reproduce the on-site conditions and noise levels as measured before any ground modification. In construction, base models are often referred to as 'digital twins,' a digital environment that simulates the existing condition in the physical environment (BOSCHERT & ROSEN 2016). The topography and the built fabric were created using Blender with imported layers derived from Shuttle Radar Topography Mission (SRTM) data, a GIS data source with a 9-16 m accuracy. The model was then placed in a bounding box to support the acoustic simulations.
2) **Noise source (emitter)** – the noise source was introduced into the model and situated on takeoff lane 08R/26L at a level of 75 dB. The simulation works as a transfer path that disperses the noise. The transfer path holds a noise spectrum with several frequencies. However, simulations, including the presented ones, rarely include all frequencies.
3) **Simulation tool** – for simulating sound propagation, the research employed Pachyderm RC 26, an open-source tool that integrates acoustic simulation and visualization in a 3D design environment (VAN DER HARTEN 2013). Pachyderm provided a ray tracing-based method and was integrated into Grasshopper and then linked to the base model. This integration allowed performing the design and the simulations in the same digital environment. The research employed an i7 processor, 32GB of RAM, and an Nvidia Quadro 1000 graphics card which could not perform a full-site acoustic simulation due to insufficient processing power, memory, and graphic processing.
4) **Noise sampling grid and points (receivers)** – to address the simulation challenge, the study developed a method for sampling the acoustic performance using a grid with 20/20m size cells. Within this grid, three listener points were positioned as noise receivers at a height of 1.65 m (Figure 4). Point 1 was closest to the airport runway, point 2 was in the middle of the site, and point 3 was in the residential area of Hallbergmoos.

Evaluation – while the simulation calculated noise levels, the evaluation focused on the relative reduction in the noise levels as measured in the model before and after the design intervention and reformed grounds. The focus on the reduction levels allowed us to analyze noise reduction as a trend and compare the acoustic performance of the different design scenarios.

3 Results

The results of the simulations, summarized in the table (Table 1) and graph (Figure 5), can be viewed through three aspects: listener points, design, and height. Each scenario is referred to according to the initials of the design pattern, followed by the height in m (i. e., CS2.5).

3.1 Performance by Listener Point

Point 1: The best noise mitigation was achieved here with HL5 (28.4 dB reduction) followed by CS2.5 (27.5 dB reduction), C7.5, and CS7.5 (27.4 dB reduction). Last ranked the LH 2.5 (1.3 dB reduction).

Table 1: A summary of the acoustic simulation results

Mound pattern	Noise Point 1 (dB)	Point 1 Reduction (dB)	Noise point 2 (dB)	Point 2 Reduction (dB)	Noise point 3 (dB)	Point 3 Reduction (dB)
Empty site	81.32		78.57		75.09	
HL 2.5	59.31	22.01	59.36	19.21	58.09	17
HL 5.0	52.91	28.41	54.25	24.32	56.16	18.93
HL 7.5	55.05	26.27	55.38	23.19	54.64	20.45
LH 2.5	80.04	1.28	77.27	1.3	57.94	17.15
LH 5.0	54.72	26.6	56.13	22.4	54.82	20.27
LH 7.5	56.79	24.53	53.69	24.88	56.82	18.27
C 2.5	53.78	27.54	52.95	25.62	54.15	20.94
C 5.0	57.03	24.29	52.2	26.37	53.44	21.65
C 7.5	53.93	27.39	52.86	25.71	53.99	21.1
CS 2.5	57.39	23.93	56.69	21.88	58.87	16.22
CS 5.0	54.23	27.09	54.47	24.1	54.55	20.54
CS 7.5	53.91	27.41	56.24	22.33	53.2	21.89

Point 2: The best noise mitigation was achieved with C5 (26.4 dB), poorest performance with LH2.5 (1.3 dB reduction).

Point 3: The best mitigation is achieved with CS7.5 (21.9 dB reduction), followed by C5 (21.6 dB), then CS5 and HL7.5 with a similar noise reduction (20.5 dB reduction). The poorest performance was CS2.5 (16.2 dB).

3.2 Performance by Design Pattern

High-to-low (HL): This design showed the most effective noise reduction levels at point 1 for all heights. The best performance was achieved with 5 m mounds which showed an average reduction of 23.9 dB across the three points.

Low-to-high (LH): In this design, there was a significant difference in effectivity between the lower mound patterns (2.5 m) and the 5 and 7 m high ones. The best average reduction across the three points was attained by the 5 m high mounds (23.1 dB).

Constant mounds (C): This design demonstrated highly effective noise reduction levels. The highest effectivity was attained by the CM2.5 (24.7 dB), followed by CS7.5 (24.7 dB), and CS5 (24.1 dB).

Constant solid height (CS): This design demonstrated that CS**5** performed better than CS2.5 (4.3 – 2.2 dB difference), CS 7.5 performed better than CS5 at point 1, but CS5 performed better than CS 7.5 m at points 2 and 3. The average reduction of CS5 and 7.5 m was equal.

3.3 Performance by Height

2.5 m: Constant mounds perform best at all points, followed by the constant solid. LH showed the poorest performance at points 1 and 2 and then a significant increase in performance once height was reached toward point 3. At point 3, HL and LH performed with a negligible difference.

5 m: At this height, the HL pattern demonstrated the best performance at point 1. In average performance, however, constant mounds outperformed HL with an average reduction of 24.1 dB compared to 23.8 dB by HL. CS followed with an average reduction of 20.67 dB.

7.5 m: At this height, HL, C, and CS all lost effectiveness with distance. The LH section performed marginally better at point 2 than at point 1 (0.4 dB). All the designs at this height showed the lowest noise reduction at point 3.

4 Discussion

4.1 Acoustic Performance Trends

In line with existing works, the results indicate a possibility of reducing noise levels through ground forming. A few noteworthy trends can be summarized based on the acoustic performance results:

1) **Higher does not equal better –** while we would expect the highest mounds to perform better, the simulations showed that performance is impacted more by design than by height. The best-performed mitigation, HL5, was not achieved by the highest design. The lowest height, C2.5, outperformed other designs and showed an equal performance to C7.5. In addition, in comparing the same design at different heights, such as in the HL pattern, the best performance was shown at 5m rather than 7.5 m.
2) **The benefit of patterns –** the results indicate the benefit of the constant mounds (CM) pattern in relation to constant solid ground (CS) for mitigating noise. This trend can be clearly seen by comparing the CS2.5 m to the other patterns, as well as in the high average performance of CM in relation to the CS 5 pattern.
3) **High-to-low outperforms low-to-high mound patterns**– overall, the patterns that ranged from high to low performed better than the designs ranging from low to high. A significant difference was seen with the LH2.5 pattern, which had the lowest performance (1.3 dB reduction) compared to the other results. An exception is LH 7.5, with slightly better performance than HL7.5 at point 2. This trend may indicate that patterns increasing in height in the direction of the noise dispersion provide less effective mitigation unless they are high enough to form a barrier adjacent to the noise source, which explains the improved performance of LH5 and LH7.5.
4) **Constant height outperforms inclined, high-to-low slopes** – constant mounds (CM) show great effectivity regardless of their height, and mounds as low as 2.5 m can yield significant noise reduction. This result aligns with the effectivity demonstrated around the Schiphol airport, where constant-height ridges and furrows were used and reportedly reduced the noise levels by 10 dB (TASHAKKOR et al. 2020). However, in comparison to ridges, mounds can offer more accessible and versatile public use throughout the park, not limiting public activity to the furrows.

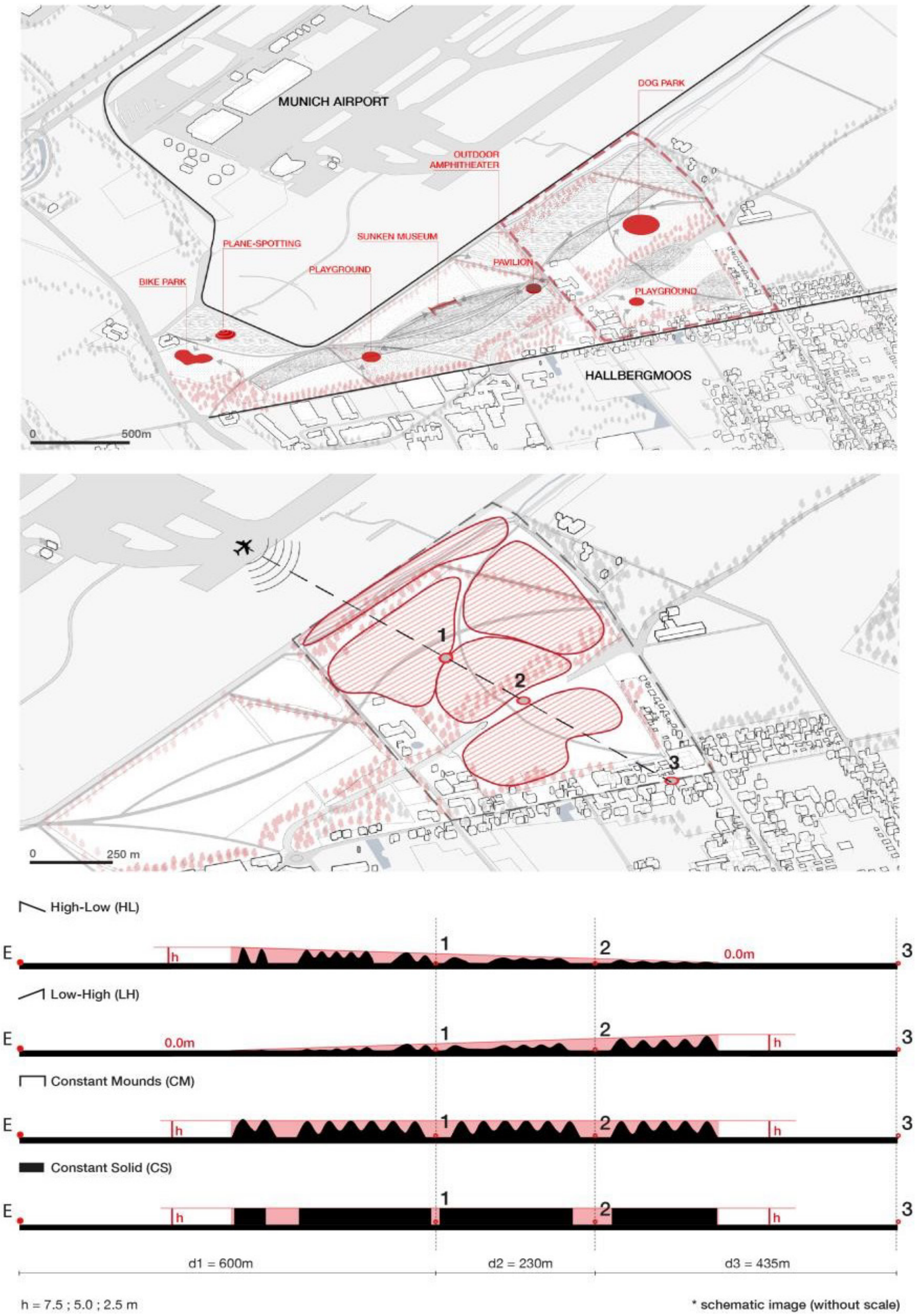

Fig. 3: (Top) A program and layout for a noise-mitigating park in Hallbergmoos; (Middle) The selected intervention area with parametric undulating mounds; (Bottom) Four different design patterns, tested at three different heights: 2.5 m, 5 m, and 7.5 m.

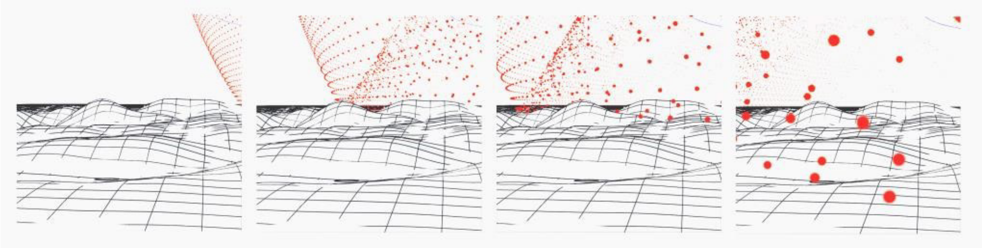

Fig. 4: The acoustic simulation of the noise propagation

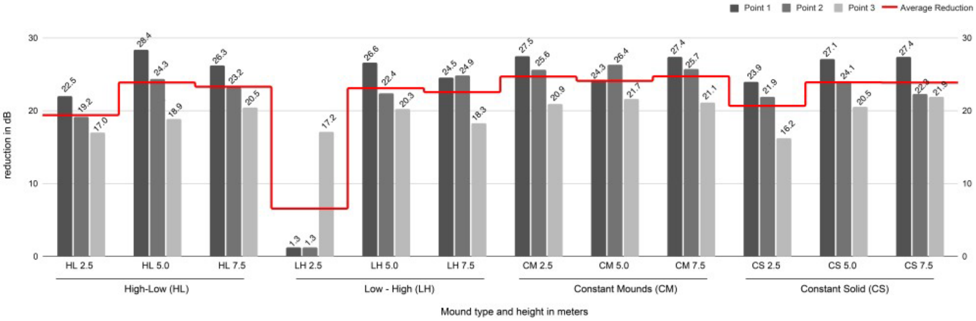

Fig. 5: A graph showing the reduction levels in dB for all the designs, in different heights, and the average performance of each design across the three listener points

4.2 Contribution and Current Limitations

The paper contributed a novel digital workflow for designing acoustic grounds. The workflow provides and demonstrates a step-by-step guide for parametrically designing, prototyping, simulating, and evaluating noise mitigation through ground forming. The digital workflow includes several steps – noise analysis, parametric design, and acoustic simulations, and allows for comparatively evaluating ground formations to understand their noise mitigation effectivity.

The workflow was demonstrated in a site adjacent to the Munich airport. The parametric designs featured three patterns of undulating mounds and one constant-height solid ground at three different heights. The acoustic evaluation was performed by comparing the noise levels before and after the ground modification in selected points within the simulation model. The results indicate the benefit of using constant height, undulating mounds rather than inclined patterns of higher flat elevated grounds as a noise mitigation strategy.

Due to the complexity of the task at hand, the study faced several limitations, which will be addressed in future work. First, the complexity of acoustic simulations increases significantly with the size of the tested area and, along with them, the computing time. This complexity is a current obstacle in using such tools in landscape architecture. In the future, this can be addressed with improved processing power, memory, and graphics processing capabilities. Alternatively, a different simulation method with a lower sampling rate could be used. The site could also be divided into smaller parts, simulated separately before their results are combined. Second, the research focused on noise propagation and did not look at: the frequency aspect; the effects of weather, a factor known to influence noise; and the effect of noise absorption on the ground surface and the way different ground covers may contribute to reducing noise transmission. Finally, future work will also look at additional design patterns, varying heights, and regularity vs. irregularity and consider these factors in relation to multiple noise emitters in various locations.

5 Conclusion and Outlook

The presented workflow allowed us to comparatively assess the acoustic performance of different landscape designs and discern trends associated with their design features. This contributes to the capacity to embed acoustic performance in landscape architecture and mitigate noise pollution through ground forming. The digital workflow can be used for addressing noise around other airports as well as around other sources of urban noise or large transportation infrastructure. As such, the workflow also promotes a broader endeavor – the development of dedicated methods which link environmental data and parametric design toward forming performative grounds in response to environmental challenges.

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