Noise and vibration design aspects for an indoor theme park

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Abstract

Doha Oasis theme park is a 25,000 sqm theme park located within a wider mixed use development comprising retail, residential, hotel and four basement carpark levels. The theme park has an elliptic footprint and is enclosed around the perimeter. The theme park is being constructed on a suspended reinforced concrete slab and as such the potential for rides exciting the structure was assessed with regard to both perceptible vibration and structure-borne noise. Airborne noise generated from ride mechanics and patrons was also assessed within the enclosed environment. This paper presents a review of the methods used and the treatment proposed to control noise and vibration within the theme park and from transferring to more sensitive environments adjoining the theme park.

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1. Introduction

Doha Oasis is a 25,000 sqm Theme Experience Centre (TEC) located within a wider mixed-use development (about 130,000 sqm) comprising retail, residential, hotel and four basement carpark levels. The theme park development will provide a vibrant microcosm of themed rides and entertainment attractions located in Doha, Qatar.

Figure 1: Artistic impression of the development as viewed from above (courtesy Gensler Architects)

The theme park occupies the central area of the podium at ground level and is covered by a steel dome ensuring a clear height of eighteen meters, supporting the landscape garden, and is penetrated by skylights. The theme park also expands well into the peripheral areas of the ground floor level to accommodate a total of twenty six or more different rides and attractions. Other areas of the Doha Oasis development include an extensive retail mall wrapped around the two top floors of the podium with uninterrupted views of the theme park, high end apartment buildings (9 floors), and a 7-star hotel consisting of a twenty eight floor glass tower. Noise and vibration assessment of elements within the theme park to provide an appropriate acoustic environment, along with impact from ride noise and vibration on the adjacent mall and residential structures was of critical importance in the design of the Doha Oasis development.

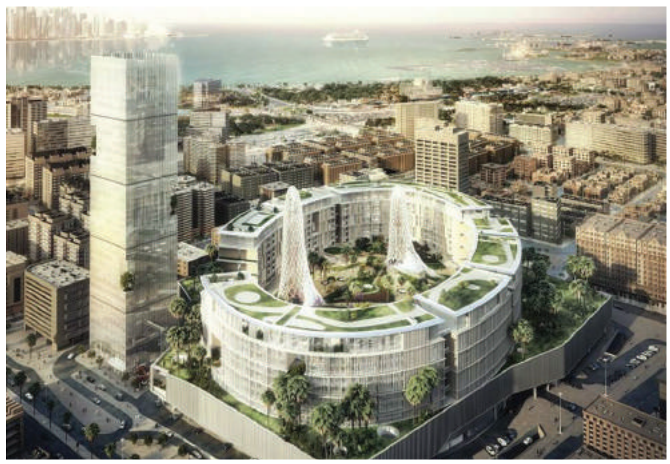

Figure 2: Artistic impression of the development as viewed from above (courtesy Nabil Golam Architects)

The theme park will house world-class attractions providing the latest in entertainment and themed experiences. The ride types to be implemented within the park include:

- Drop towers: These rides consist of a large central tower with ride occupants on a carriage which travels up and down the central tower. For the Doha Oasis theme park, these towers extend up past the roof structure, giving riders a birds-eye view of the gardens and luxury residential complex above the theme park.
- Rotating / rolling types: One or more passenger carriages which roll, rotate and spin around a number of axes.
- Swinging pendulum: A passenger carriage at the base of a large pendulum which swings about a central pivot point. The carriage can also rotate / spin about its central axes.
- Roller coasters: Roller coasters consist of one or more carriages which travel along a fixed rail path at various velocities / heights.

- Dark rides: Dark rides are themed attractions located within enclosed sections of the park to provide a secluded / stand-alone ride experience, involving a combination of hydraulically operated seats and an audio-visual experience. Some rides also feature a "4D" component where elements such as water mist or fan-forced air is directed at the ride occupants to coincide with the audio-visual component.

2. Previous work and key design issues

Preliminary concept design for the theme park was undertaken based on a review of previous theme park designs and installations, which were used to inform the design and expected acoustic performance requirements for the new Doha Oasis development. Measurements reported by Kaiser and Rohde (2013) summarised below in Figure 3 for an open air theme park show similar average noise levels between 65-85 dB L_{Aeq} (with an average of approximately 75 dB) are possible with appropriate treatment. The key difference between noise measurements undertaken in the open air theme park compared to Doha Oasis are that impact from reverberant noise build-up had only a minimal impact (distinct from the enclosed Doha Oasis theme park, where control of reverberation will be more crucial).

Figure 3: Summary of noise levels at Universal's Islands of Adventure park (Kaiser and Rohde, 2013)

Sound level data in Menge, C W (1999) '*Noise from amusement park attractions: Sound level data and abatement strategies*' which includes noise measurements of roller coaster events at 15 metres, free-fall events at 15 metres, water ride events at 15 metres, and coaster screaming at 15 metres were also referenced for the preliminary acoustic modelling (and later comparison against the benchmarking survey). Figure 4 shows a time history of noise levels within the theme park, in a ride's "pre-show" area, and on the ride, with an average noise level of typically 85 dB L_{Aeq} close to the ride, and maximum noise levels of up to 100 dB experienced by patrons on the ride.

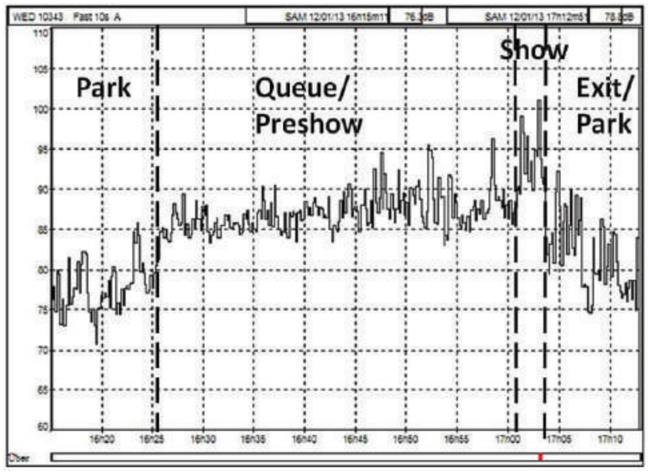

Figure 4: Time trace of a ride including "pre-show" queue and on the ride (Kaiser & Rohde, 2013)

It is considered that a percentile level is more representative of maximum noise levels relative to average noise levels given varying distances from rides, patrons, audio, etc.

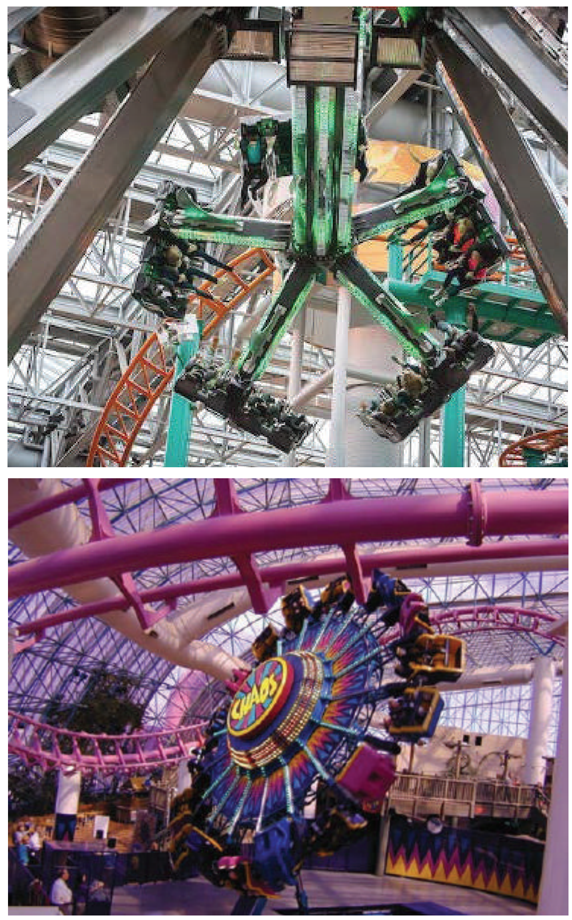

Figure 5: Typical examples of roller coaster (orange/pink tracks on Top/Bottom image), swinging (Monster Mash at Mall of America– Top) and rotating rides (Chaos at Adventure-Dome-Left)

It was therefore considered that a difference of 15 dB between the maximum noise level (L_{Amax}) and continuous equivalent level (L_{Aeq}) be allowed for in the design of sound insulation measures. Further details on L_{Amax} and L_{Aeq} differences are discussed in the following benchmarking survey sections.

Typical enclosed theme and amusement parks include Mall of the Emirates (UAE), Adventure-Dome (Las Vegas, Nevada, USA), Mall of America (Bloomington, Minneapolis, USA) and Galaxy-Land (West Edmonton Mall, Alberta, Canada). Noise levels within enclosed theme parks will depend upon the proximity of patrons to rides (to control direct sound pressure levels), and the volume and finishes within the theme park (to control reverberant noise build-up).

Based on the literature review, the key design considerations for the Doha Oasis project were ensuring an appropriate acoustic environment within the theme park, and control of noise and vibration into the sensitive retail mall and residential/hotel components of the mixed-use development. These design issues were investigated using a combination of benchmarking surveys and noise and vibration modelling to determine appropriate treatment and control methods for all areas.

3. Sources of noise and vibration

Undertaking a vibro-acoustic assessment of the theme park development required a detailed understanding of all noise and vibration sources within the theme park (including individual ride types, specifications and configurations):

- Noise and vibration from rides such as wheel / rail noise interactions, hydraulics, structure-borne regenerated noise from supports, walls, ceilings and other building elements, and screams / yelling from people on the rides. Noise from the rides will also depend on the ride cycle times including passenger loading/unloading times and ride duration, the total number of ride occupants (and the percentage of people screaming).
- Noise from operation of mechanical services plant including duct-borne noise, breakout noise, noise from plant rooms, and casing radiated noise from units.
- Background and theme music played through dedicated speakers as part of the themed rides, in queuing areas, in eating / dining spaces, and in the dark rides (as part of the audio-visual experience).

The primary noise sources throughout the theme park will be noise from rides and associated screaming/yelling, which will generally be dominant over operation of the mechanical services / HVAC systems, and in any areas without music being played.

4. Performance criteria

Noise and vibration design targets were developed based on a combination of ASHRAE and ANSI (noise due to operation of building services plant and equipment), the World Health Organisation (WHO) guidelines for noise in dwellings (for residential components) and public spaces (also referencing the limits reported by Thorburn (1992) for Mall of America), and the ISO 10137 vibration curves. Table 1 presents a summary of the noise and vibration design criteria deemed appropriate for the Doha Oasis project.

Table 1: Summary of noise and vibration criteria for the Doha Oasis theme park

Design element	Theme park noise limit dB L_{Aeq}	Building services noise limit dB L_{Aeq}	Vibration response factor
Theme park open areas	75-80	45-50	8
Theme park food and beverage spaces	70-75	40-45	8
Theme park retail areas	50-55	40-45	8
Theme park offices	40-45	35-40	8
Adjacent retail mall	35-40		8
Hotel residential areas	30		VC-A

5. Benchmarking

To confirm noise sources, appropriate design targets, and determine practical noise and vibration control treatment for an enclosed theme park environment, Aurecon undertook a detailed acoustic survey of several USA theme parks and rides including Adventure-Dome (Las Vegas, Nevada) and Nickelodeon Universe (Mall of America, Minneapolis). Key findings and observations from the benchmarking survey are detailed in the following sections.

5.1 Screaming and Ride Noise Observations

The primary noise sources throughout the theme park will be noise from rides and associated screaming yelling, which will generally be dominant over operation of the mechanical services / HVAC systems, and in any areas without music being played. Control of noise from rides and screaming within the Doha Oasis theme park will therefore be vital in ensuring an appropriate acoustic environment and promoting an enjoyable experience for all patrons.

- The Adventure-Dome consists of a glass dome with limited acoustic absorption to any of the internal surfaces. The ride supports are also fixed directly to the raised concrete slab, and the ride guides appear to be primarily hollow steel channels. The highly reverberant environment combined with increased radiated noise from the hollow steel channels (and potentially re-radiated structure-borne noise from the slab) combine to produce a very noisy environment which was considered unpleasant and borderline distressing, with continuous noise levels of 80 to 85 dB L_{Aeq} measured throughout the park. These noise levels made communication difficult (raised voices / straining to hear).

- Nickelodeon Universe (Mall of America) has a significant portion of the upper perimeter walls covered with acoustic absorption (a spray-on adhesive insulation product), and appears to have all ride rail and guides filled solid to control re-radiated noise. These acoustic treatments combine to provide a much more pleasant acoustic environment within the theme park with an overall noise level of approximately 75 to 80 dB L_{Aeq} in worst-case locations, and a lower level of 70 to 75 dB within the food and beverage spaces which were setback from the rides. It is noted that Nickelodeon Universe did not feature any noticeable or significant noise barriers or baffles to directly shield noise from the rides (or otherwise block direct line-of-sight to the rides), and instead relied upon acoustic absorption and source treatment of the ride guides to control overall noise levels and reverberant noise build-up.
- The difference between measured average continuous equivalent noise levels (L_{Aeq}) and maximum intermittent noise levels (L_{Amax}) was greatest at locations closest to the rides, with the difference much smaller at locations further from the rides (in general public / food and beverage spaces). It is noted that the L_{Amax} noise levels on the Adventure-Dome rollercoasters (El Loco and Canyon Blaster) were greater than those at Nickelodeon Universe (Orange Streak and Rock Bottom Plunge) by at least 10 dB, which is likely due to rumbling / rattling of the unfilled ride guides (and potentially structure-borne radiated noise from the suspended slab of the Adventure-Dome).
- Screaming noise was most noticeable from the rollercoasters and the drop-tower type rides, with significantly reduced screaming / yelling from the rolling and rotating type rides. Screaming noise generally occurred during fast accelerations / drops / roller coaster loops, and is dependent upon the number of ride passengers (as well as age demographic). Generally the screaming was of short duration and while it was noticeable, it was not overly intrusive in the public areas, particularly at Nickelodeon Universe where a combination of general public noise / conversations and music masked a lot of the ride noise and screaming.

5.1 Rail ride design observations

Based on the benchmarking noise survey and site inspection, the following key ride design differences between the Adventure-Dome and Nickelodeon Universe were identified:

- Ride guides / rails at the Adventure-Dome were hollow, whereas at Nickelodeon Universe they were core-filled to provide a more highly-damped structure. The addition of dampening material to the ride guides (such as sand / foam / pellets) resulted in significantly

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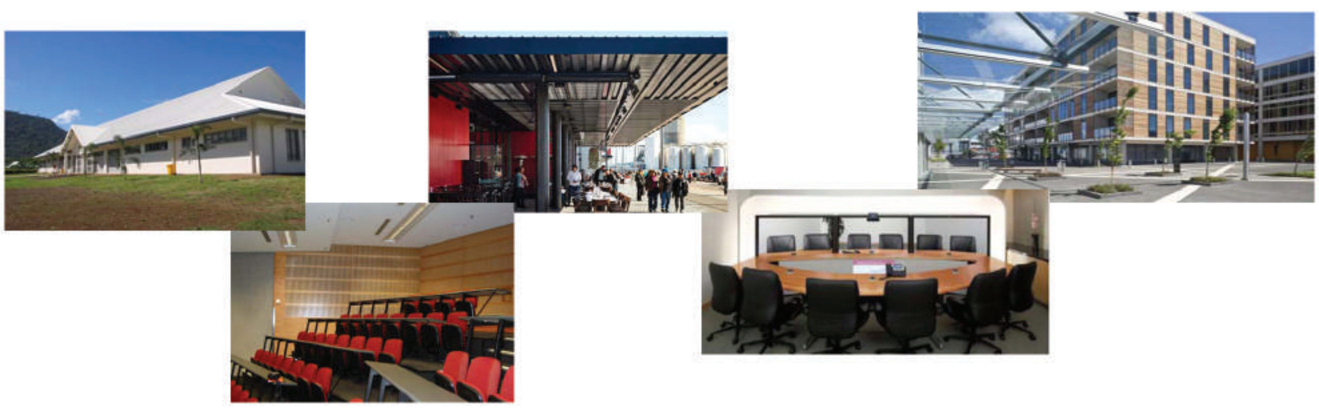

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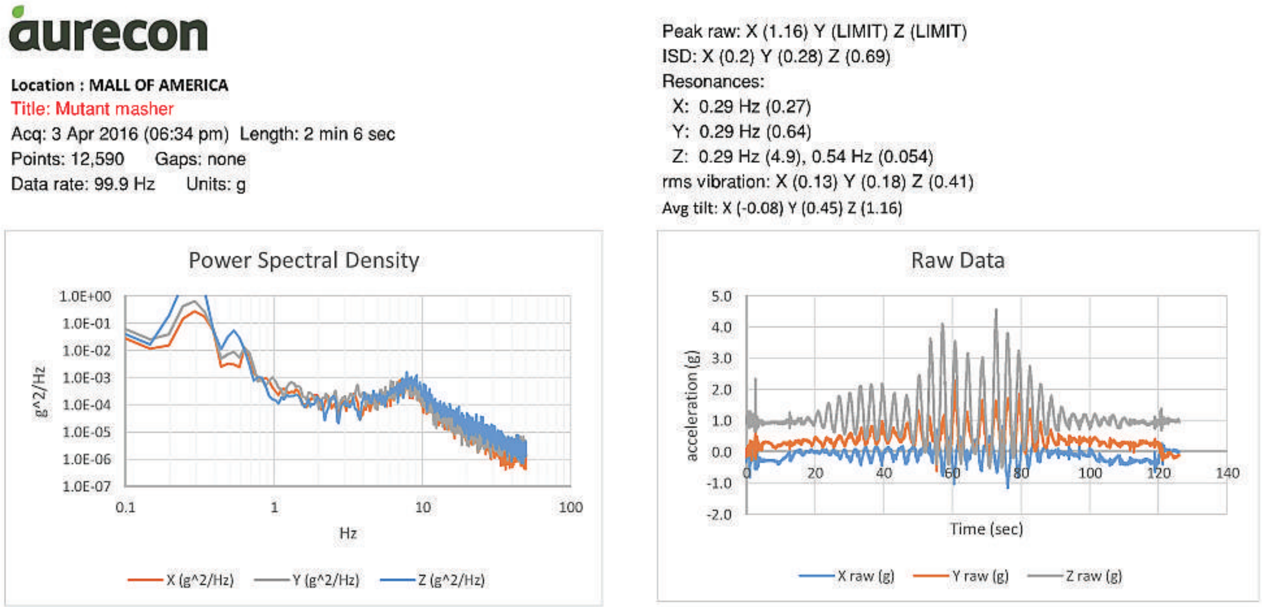

Figure 6: Results of vibration monitoring using the VibSensor App (on the "Mutant Masher" ride - Figure 5)

reduced maximum noise levels due to less rattling / shacking, and reduced structure-borne noise re-radiated from the rails.

- Rides at the Adventure-Dome were directly fixed to the suspended slab resulting in low-frequency reradiated 'rumbling' noise audible within the space. The Nickelodeon Universe rides were mounted on significant plinths / inertia bases with the main slab on grade which assisted in reducing any structure-borne noise.

The above points highlight the importance of the ride guide design (ie filling the guides with sand / foam), and proper vibration support, isolation and damping.

5.3 Vibration measurements

The VibSensor (version 1.3.3) iPhone App developed by Now Instruments and Software, Inc (2015) was used to undertake vibration benchmarking analysis of rides, ride supports and floor slabs throughout each of the theme parks. The VibSensor App uses the iPhone's in-built accelerometers to measure and log acceleration in three-directions, and is able to output Power Spectral Density (PSD) graphs and time-history data (as shown in Figure 6). The App and accelerometer were calibrated using a SoundBook MK2 fitted with a 100 mV/g accelerometer to ensure accuracy of the result.

Based on the vibration survey data acquired using the VibSensor App, the dynamic loads of each ride were measured along with accelerations on the various support and slab arrangements (eg the suspended slab of the Adventure-Dome). Each measurement captured detailed frequency data which was invaluable in calibrating the vibration and structure-borne noise finite element model, and determining vibration isolation and damping requirements for the Doha Oasis theme park.

5.4 Noise measurements

Noise measurements were undertaken using the SoundMeter (version 8.3) iPhone App developed by Faber Acoustical, LLC, utilising an external condenser microphone which was calibrated using an external calibrator. This arrangement allowed for on-ride noise measurements to be undertaken including third-octave band analysis and waterfall plots to be generated (as shown in Figure 8), including calculation of ride sound power levels, without relying on bulky hand-held instruments and mitigating the risk of damaged or dangerous equipment in the ride environment.

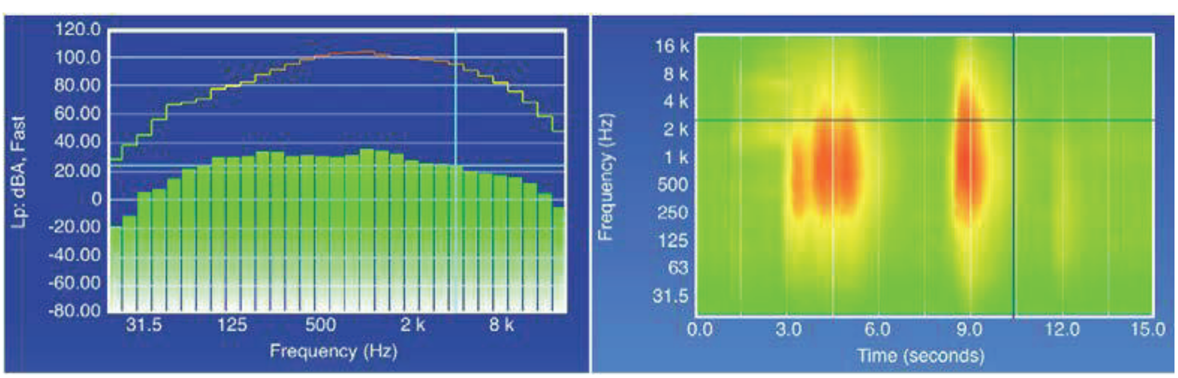

Figure 7: Results of noise measurement using the SoundMeter app (on the pink track rollercoaster - Figure 5)

6 Modelling

To assess the acoustic conditions within the Doha Oasis theme park including noise levels at food and beverage seating areas, noise mapping at various levels within the park, noise impact on the theme park envelope walls (including impact on the adjacent areas such as the retail mall), and vibration impact from the rides, a combination of room acoustics modelling and vibration analysis was undertaken as described in the following sections.

6.1 Airborne noise

To assess airborne noise throughout the theme park an acoustic model of the theme park including noise sources such as rides, screaming and EWIS speakers was developed using the EASE (Enhanced Acoustic Simulator for Engineers) software suite with an example of the noise mapping output shown in Figure 8. Based on the noise source data from the literature review and benchmarking survey, an inventory of all noise sources was developed. For each noise source a continuous equivalent noise level was calculated (taking into account intermittent screaming for the rides), and for the large rides which traverse a significant area (eg. the roller coasters), the noise source was distributed evenly over the expected path to account for the instantaneous change in noise source location.

A number of acoustic absorptive treatment options were implemented within the model to assess the sensitivity of overall noise levels within the park to the extent of treatment (including insulation to the underside of the ceiling, combined with various baffles, screens and walls). Based on the modelling it was determined that a fully acoustically absorptive ceiling (NRC 1.0) would reduce noise levels by between 3 to 6 dB L_{Aeq} compared to an acoustically reflective ceiling, depending upon proximity to the rides and other noise sources.

Modelling indicated that further reductions in reverberant noise level of approximately 3 dB L_{Aeq} can be achieved through strategic implementation of acoustic absorptive baffles and screens localised around sensitive dining and respite areas.

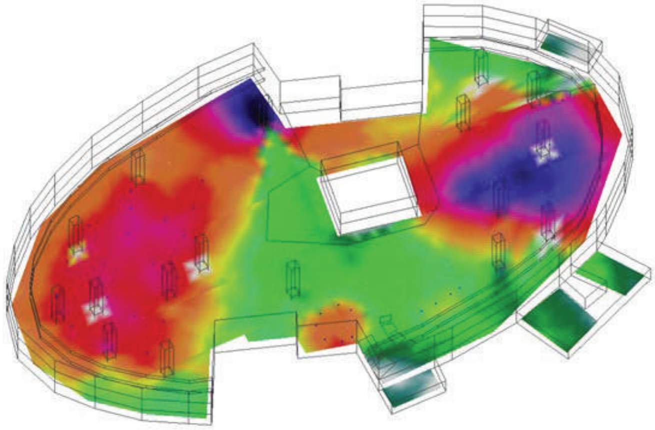

Figure 8: Noise mapping of the Doha Oasis theme park using EASE software

6.2 Vibration and structrue-borne noise

The 3D finite element model was built using Strand7 Finite Element Analysis (FEA) software. The structure includes a section of the retail mall and residential tower, and a section of the carpark basement, as shown in Figure 9 below. The structure consists typically of a base building slab, 600 mm thick generally with edge thickening to 1,200 mm thick and an edge beam 1,000 mm deep interfacing with a perimeter slab nominally 350 mm thick. Ride foundations up to 1,500 mm thick are located directly on the base building slab, with sand surrounding the ride foundations which is constrained beneath a floating concrete slab, providing significant damping.

Dynamic loads (in terms of linear transient or harmonic) for each ride were provided by ride suppliers, calculated from kinematic equations of motion and calibrated/verified with measurements during the benchmarking exercise. Vibration time histories and spectra were obtained from the finite element model and compared with the design criteria to assess compliance and determine appropriate mitigation measures (damping, isolation, structural modification).

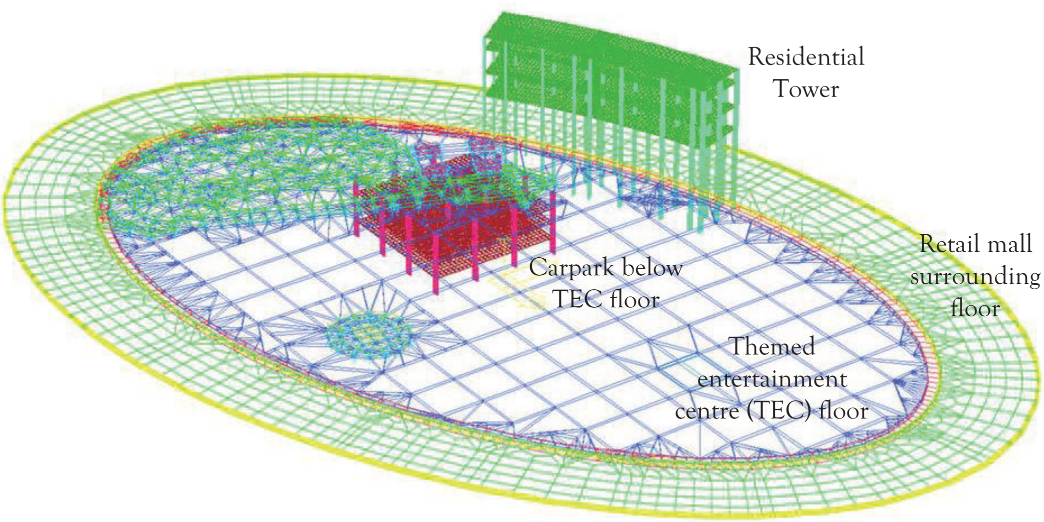

Figure 9: 3D finite element model of showing the components of the development

7 Design Recommendations

7.1 Airborne noise

There are numerous noise producers within the enclosed theme park (including the guests themselves) and for the majority of these it is not possible or practical to control such noise at source, particularly when screaming is an integral part of the guest experience for many visitors. As such, it is important to introduce acoustically-absorptive materials to control the reverberation and build-up of such noise sources.

- Roof soffit: The underside of the roof structure has been identified as the primary location of such treatment. This treatment may be located directly on the underside of the roof or alternatively at the underside of the roof trusses, consisting of 50 mm thick fiberglass batt panels with a suitable facing (most cost effective is a black woven fibreglass cloth) that does not degrade the acoustical properties of the fiberglass. Ideally the insulation should be offset from the roof soffit by 50 mm by way of battens or similar to enhance sound absorption at low frequencies. It is noted that dynamic LED video content will played across the theme park ceiling and rear wall over a 70% open area screen (required for air distribution), however this will not affect the performance of the roof soffit sound absorption (due to the large open area making the screen effectively acoustically transparent).
- Column cladding and "*theme*" cladding: To supplement acoustic lining to the roof soffit, a stretched micro-perforated acoustic membrane which will allow dissipation of acoustic energy is proposed for the columns and selected wall areas. This can be back-lit as required to incorporate lighting effects. Alternatively perforated metal cladding with woven (high flow-resistive) fabric backing for individual rides and other attractions should be implemented.
- "*Rock wall*" cladding: Spray-on acoustic plaster which has a degree of porosity and therefore a good level of mid-to-high frequency sound absorption can be implemented to themed rock wall type surfaces to provide additional acoustic absorption (for example, adjacent roller coasters).
- Suspended Baffles: Suspended acoustic baffles or similar are proposed over noise-sensitive patron seating areas.
- Acoustic Ceilings: Ceilings to the underside of the mall balconies will be sound absorptive, either as a standard mineral fibre ceiling tile, perforated plasterboard ceiling, plaster acoustic tile, or as a more decorative finish such as a perforated metal/timber feature ceiling.
- Sound Insulation: Appropriate level of glazing between the TEC and external elements such as the retail mall concourse, roof plaza, retail spaces (including

cinemas) and surrounding residential towers.

7.1.1 Dark rides

Dark rides located within the enclosed areas of the theme park (similar to a cinematic experience) will have an associated loud sound track with typical noise levels noted by Pelton (2000) of up to 100-110 dB L_{Aeq}. The retail mall floor structure will be 300 mm thick post-tensioned concrete, with a sound insulation rating of approximately Rw 60. For general theme park noise this will be sufficient, however for dark rides directly under the floor with high sound levels (including low-frequency characteristics), a resiliently suspended ceiling under the floor is proposed, along with 100 mm black tissue faced fiberglass or similar insulation to at least 50% of the interior surface area to control reverberation.

7.1.2 Public Address and background music

While there will not be individual soundtracks for various rides and themes, there will be background music being played at moderate volume throughout the park. Typically the loudspeakers used for the background music/paging system should be located near to the park visitors, which is acoustically preferred so as to diminish the overall loudspeaker noise level, and thus the reverberant noise level build-up within the park.

7.1.2 Vibration and structure-borne noise

In addition to the acoustic treatment outlined above, it is vital that the ride guide tracks and rails be filled with damping material (sand/pellets/foam) and wheel rims be hard plastic such as nylon or similar to ensure suitable control of airborne noise from the guide tracks. The use of sand surrounding the ride foundations, which is constrained beneath a floating concrete slab, will also be vital as it provides significant damping of transient vibrations radiated from the theme park floor.

8. Conclusions

This paper has outlined the key acoustic issues associated with design of an enclosed theme park to promote a suitable acoustic environment and achieve a balance of excitement from a combination of screaming, yelling, and background music, along with quieter respite areas for dining, conversation and rest. Also considered is the noise and vibration impact (including structure-borne regenerated noise) on adjacent noise-sensitive mall and shopping areas which are separate from the theme park, but share several walls and floor slabs.

Benchmarking of similar existing theme parks was undertaken to determine appropriate internal design sound levels within the park, and identification of noise control measures. These investigations highlighted the differences in subjective perception of two different theme parks, varying from pleasant and 'enlivened' within a well-designed theme park, through to a noisy and unpleasant acoustic environment where only minimal acoustic treatment had been implemented.

Key acoustic design considerations for the theme park were identified including damping of ride rails through implementation of filled-rails (sand or similar), isolation of ride mounts (vibration mounts / plinths), analysis of the theme park slab for vibration response (Finite Element Analysis), strategic placement of acoustic absorption to control reverberant noise build-up, design of sound insulating envelope elements (eg slabs, ceilings, walls, glazing), and appropriate design of theme park music and public address systems.

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