Engine test cell noise emission design with performance validation results

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Compatibility with existing land uses was a high priority when an industrial company began planning to relocate an existing industrial test facility from an urban location near a multi-lane highway to a semi-rural residential area near a small city. In the high ambient noise environment of the existing location, engine and hot gas test cell exhaust emission noise was benign. In the new low ambient noise location, the proposed facility could be disturbing to local residents. Executive management recognized the potential for community noise disturbance due to introduction of a new noise source. Controversy could negatively affect the company's image and possibly result in operational curbs, such as a potential curfew to reduce nighttime noise impacts. This article is a case study of the efforts undertaken to achieve the goal of community noise compatibility. It discusses the criteria or basis of acceptability, determination of noise emission levels and community's ambient sound environment, and the design process used to arrive at a solution.

The original facility was located in an industrial park, adjacent to a high-speed multi-lane divided highway, but residential communities were nearby. In spite of engine test cells and support equipment with loud noise emissions, few noise complaints had been received, because the test cell noise emissions were not much louder than the normal ambient sound level of traffic or other industrial noise sources. The proposed future site is near a two lane, moderate speed roadway. There was an existing industrial building on the new site. Environmental noise emissions from the existing building were moderate and insignificant. JEAcoustics was retained by the facility architect to determine the feasibility of achieving compatibility with the surrounding community. A consultant's confidentiality agreement with the owner prevents disclosure of the facility name, plant locations, discussion of plant processes or revelation of other proprietary information, but this article discusses why and how solutions were developed. Noise control designs and product applications are presented with results of post-construction noise validation measurements to show results.

Summary of project procedures

1. Measure and analyze sound levels and spectra of original facility test cell noise emissions
2. Visit the site and study aerial photos to identify sensitive receivers, such as residential structures and schools.
3. Measure and analyze ambient environmental noise characteristics in the community at sensitive receivers, including daytime and nighttime.
4. Compare building code and community ambient noise measurements to determine appropriate allowable noise levels at property boundaries.
5. Study preliminary architectural drawings to determine facility layout and identify test cell and support system noise sources.
6. Determine individual noise source attenuation amounts required to comply with criteria.
7. Develop and recommend specific architectural sound isolation and mechanical noise attenuation

measures, including selection and sizing of industrial mufflers.

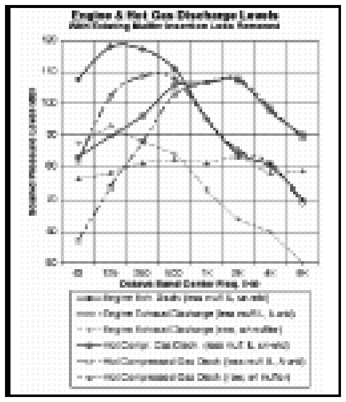
8. Assist architect and engineers with implementation of recommendations into construction drawing and specification documents.
9. Conduct post-construction validation measurements to confirm facility noise emissions comply with building code and achieve design intent.

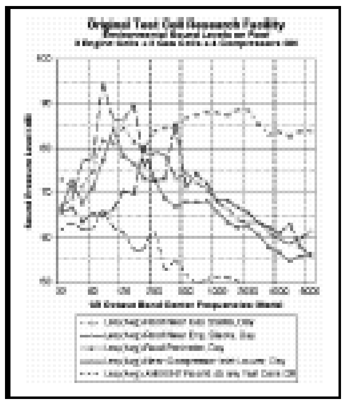
Noise control design issues

Community acceptance of the facility required that its environmental impact be minimal. Among other issues, the noise contribution to the environment could not be allowed to cause annoyance to residents in the area. In addition, compliance with the building code was required, including land use compatibility and noise regulations. To achieve these requirements, acoustical design criteria were required to satisfy all parameters.

Sound levels at original installation

Noise measurements were conducted at the original facility to determine source levels and spectra. A Larson-Davis 2900 two channel real-time FFT spectrum analyzer with precision microphone and pre-amp (ANSI Type I, ±1 dB)[1] was used to acquire and analyze data. Outdoor measurements were made with a windscreen. Measurements were conducted within the building, on the roof, near test cell exhaust discharges, and adjacent to the compressor room air inlet. Since the existing facilities were intended to be replicated at the new site, these measurement results were considered very reliable indicators of future conditions. The engine exhaust and the hot gas test cell discharge pipes incorporated mufflers, whose insertion losses would have to be factored out of the raw data to determine the true source levels. Sound level measurements were normalized to 3m from the sound sources (exhaust terminations and inlet air louvers). Data was acquired in 1/3 octave bands over short durations, 30–60 seconds for continuous sources, and up to 3 minutes for varying level sources. The 1/3 octave Leq values (spectrum and overall Aweighted) were utilized as the reference source levels, with Lmin to Lmax values used to determine deviation





Noise Source, r = 3m (10′)	LAmin	LAeq	LAmax	ΔL	Dominant A-wt. Octave
Diesel Engine Test Cell*	83	84	86	3	250 – 500 Hz
Hot Compressor Gas Cell*	82	88	92	10	500 – 2000 Hz
Screw Air Compressors	71	76	78	9	Tones @200 & 400 Hz
Average on Roof Perimeter:					
3 Eng + 3 GS + 4 Compr	69	76	83	14	500 – 2000 Hz
Ambient: Roof – 9 am	58	61	65	7	250 – 500 Hz

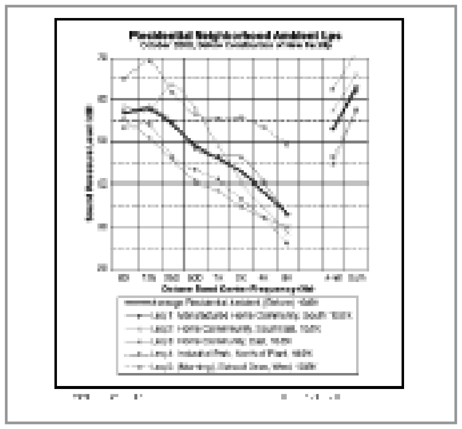
*Measurements of Engine and Hot Gas discharges included attenuation from existing mufflers, estimated >30 dBA.

from the integrated averages.

The noise spectra for various sources were analyzed for sound level, balanced spectrum, variability (difference between Lmin and max), and tonality. Sideband differentials of 6 dB or more between 1/3 octaves are considered tonal[2]. In addition, the A-weighted octave spectra were studied to determine principal contributing frequencies to overall A-weighted level. In other words, the octave levels, decreased by A-weighting factors, were plotted on level versus frequency charts to determine which frequencies contributed the most to dBA levels or audibility. For example, the engine noise, above, is greatest in the 125 Hz octave, but with A-weighting, the 250–500 Hz frequency span contributes the most to the A-weighted sum. The 1/3 octave spectra were then reviewed for tonality (large sideband differentials) and peak frequencies, such as the 200 Hz and 400 Hz helical screw compressor tones in the chart above.

Allowable noise criteria

Noise measurements were conducted during late evening and morning hours in the community surrounding the proposed relocation site, for the purpose of establishing acceptable noise levels. Measured ambient sound levels included



contributions from the existing plant facility. Noise reinforcing effects due to weather[3] were taken into consideration. Ambient nighttime noise spectra for five locations were acoustically averaged (logarithmically) to create a representative ambient sound spectrum beyond the property boundary of the plant. The A-weighted summation was 53 dBA. After accounting for weather and other site conditions, 50 dBA was determined to be the maximum allowable plant noise level at the property boundary that would be compatible with community conditions.

The findings were compared with the building code to determine a single noise criterion that would satisfy all requirements. In this region of the United States, the Southern Building Code is in common usage (individual municipalities adopt the model building

noise notes

Rollercoaster

Patrons, ticket-sellers and ride attendants were exposed to excessive noise at last year's Brisbane Ekka, a government investigation has found. The noise from the rollercoaster ride peaked at almost 150 decibels. Inspectors from Workplace Health and Safety chose Brisbane's sideshow alley for their first check of noise exposure at Queensland carnivals. During the August 2003 audit of more than 50 locations, they found ticket-sellers, ride attendants and patrons were exposed to excessive noise, with the average between 85–100dB. "The above-exposure situation is made worse when considering that almost without exception workers at the show work a 10-hour shift and 10 days straight," the report says. The report said the rollercoaster was the loudest, where noise exceeded the 140dB limit – and workers with unprotected ears should not have been subjected to this volume. The quietest ride tested was the dodgem cars at 105dB, but all other rides ranged from 106–138dB. "Ride owners did not fulfil their obligations to prevent risk to workers from exposure to excessive noise," it said.

Reference	Day	Night	Factor	Allowable
SBCCI Standard for Sound Control[4]		*Tonality*		
SSTD 8-87, Table 303, Residential (R1)	60 dBA	–5 dBA	–5 dBA	50 dBA
Average Measured Community Ambient Noise,		*Weather*		
Evening (assume = nighttime)	–	53 dBA	–3 dBA	50 dBA
DESIGN CRITERION: Property Boundary (night)		50 dBA (55 dBA if non tonal)		

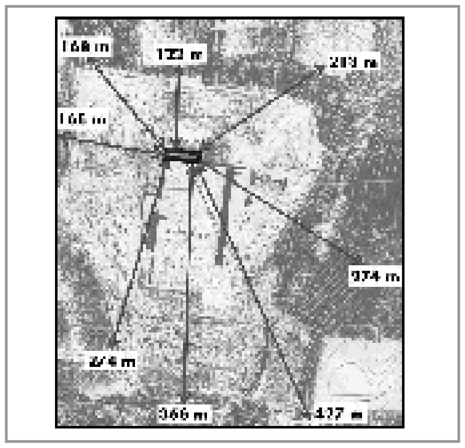
code). This code permits 60 dBA noise at residential property boundaries, with a 5 dB reduction for nighttime and a 5 dB penalty reduction if noise emissions are tonal. The tonality penalty could apply to this site. Therefore, the code requirement would be 50 dBA allowable, which coincided with the findings of the community ambient noise measurements. The Design Criterion of 50 dBA at the property boundary was recommended by the consultant and accepted by the Client.

Noise sources to be mitigated

The noise sources to be relocated included test cell exhaust discharges from diesel engines that might vary in size from 500 to 2000 horsepower. Depending on the testing requirements, engines might operate continuously at a constant speed, or operate over a range of rpm's. Other test cells contain apparata that discharge hot compressed gas (cannot describe in detail due to confidentiality agreement). A group of (very tonal)helical screw air compressors provided process air for the test facility. A fabrication and support machine shop inside the building could produce transient impact and machine noise. Anticipated sources also included building air handling and exhaust fans, which were to be roof mounted.

Proposed site

The facility property boundaries are at least 60 m in any direction from the proposed site. At least 27 dB of distance loss could be expected, unless the sound is reinforced by large reflecting surfaces or atmospheric conditions. The existing building at the relocation site is larger and taller than the proposed test facility, and



consequently, reinforces sound in one direction, but also acts as a barrier[5] to noise propagation in another direction. To be conservative, 25 dB of distance loss was assumed to be "worst case." *Given a 50 dBA allowable at the property boundary plus 25 dB of distance loss, noise sources on the site in excess of 75 dBA require attenuation to assure compliance with the building code and the design criterion.*

Noise attenuation design concepts

A multifaceted design approach was developed to address the various types of noise sources, and to achieve low noise levels with smooth, balanced spectra. Each type of noise source had distinct spectral, temporal and directional characteristics. Design concepts were developed to match attenuation frequency responses to noise source spectra, and to reduce tonal and intermittent (temporal) sources below the ambient levels at sensitive receivers.

Beginning within the building, absorption was specified to reduce build-up of reverberant sound within test cells and support equipment spaces. Wall, door, window and roof assemblies were designed to contain sound within the building, including vibration isolation and decoupling of elements to reduce exterior surface radiated noise. Silencers were selected for air inlets, engine exhausts and hot compressed gas discharges. Based on known locations of residential, commercial, and light industrial zoning, the direction of least sensitivity was determined, so that exhaust pipe terminations could be pointed that way. A roof parapet wall was designed to surround the other three more sensitive sides of the loudest noise sources (the open end of the roof parapet permitted a draft to dilute exhaust fumes). With all of these concepts combined, in addition to the estimated 25 dBA of distance noise reduction, the design approach included:(a) room acoustics attenuation, (b) barrier attenuation, (c) building noise containment, and (d) inlet/exhaust silencing.

For each noise source group, the silencer and muffler applications were developed and recommended. Typical and well-known architectural noise control techniques utilized to achieve the containment and absorption of noise within the facility are not discussed in greater detail here, but generic muffler performance characteristics and discussions of our applications recommendations are presented in "Test Cell Muffler Concepts," below. Engine Test Cells: Diesel engines produce broadband noise. With A-weighting applied, dominant octaves are in the 250–500 Hz octave bands. Attenuation requirement: >40 dBA.

> Barrier Attenuation: Exhaust pipe terminations on roof point in the direction of least sensitivity (towards fewer, more distant homes). Parapet wall taller than exhaust pipe terminations on the three, more sensitive sides of roof exhaust discharges.
> Silencers: Straight perforated pipe silencer (with acoustically absorptive fiber filler in body), within test cell, in series with 3-chamber reactive muffler located in mezzanine above. Combined insertion loss is greatest over 250–1000 Hz frequency span, matching maximum A-weighted engine exhaust octaves (see "Test Cell Muffler Concepts" below).

Hot Gas Cells: Hot compressed gas discharge produces a broad tonal noise. Dominant Aweighted octaves are in the 500–2000 Hz bands. Attenuation requirement: >43 dBA.

> Barrier Attenuation: Exhaust pipe terminations and parapet wall enclosure as above. Silencers: Straight perforated pipe silencer (with acoustically absorptive filler in body), within test cell, in series with larger absorptive muffler with "bullet"insert, located in mezzanine above. Combined insertion loss is greatest over 1000 -2000 Hz frequency span, matching maximum A-weighted hot gas exhaust octaves (see "Test Cell Muffler Concepts "below).

Air Compressor Room: Helical screw compressors produce strong tones. For this installation, peak tones are at 200 and 400 Hz octave bands. Attenuation requirement: Minimum >1 dBA overall, but to assure tonality is reduced below ambient, >6 dBA.

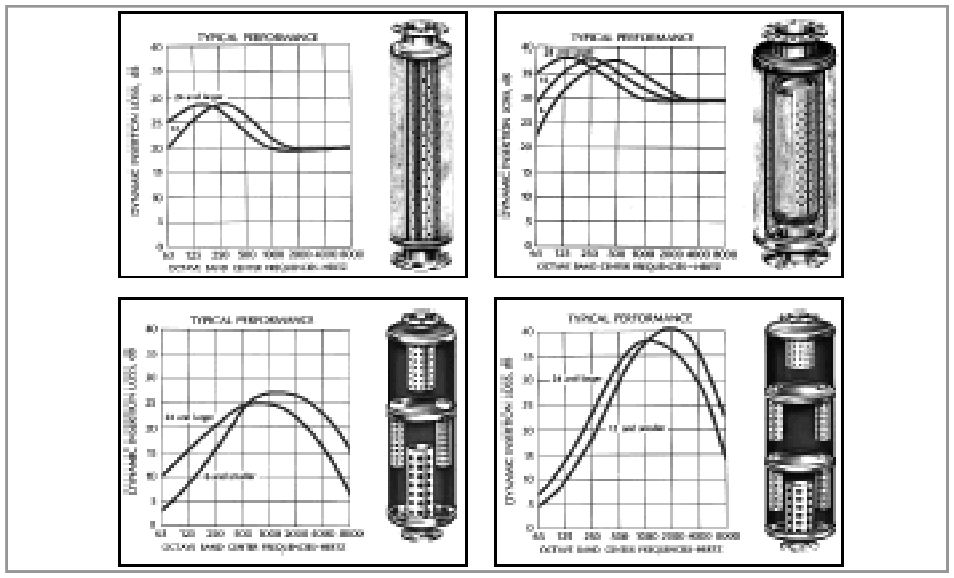
> Silencers: Acoustical louver in exterior wall air inlet, selected for >7 dB at 500 Hz.

Roof Mounted Air Handler and Exhaust Fans: Radiated noise levels at perimeter of roof were estimated to be less than 75 dBA, and therefore required no additional attenuation.

Test cell muffler concepts

Dissipative versus reactive mufflers

A silencer design approach was selected



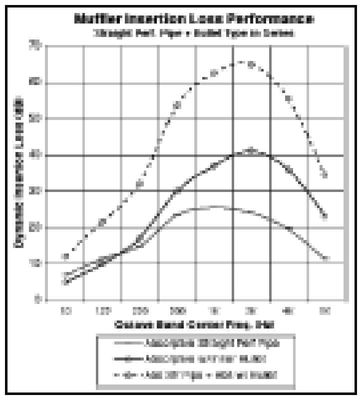
(Illustrations courtesy of Burgess Manning[6])

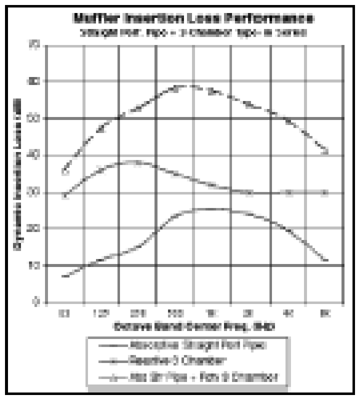
to match attenuation spectrum with source spectrum, i.e., maximum silencer insertion loss in the maximum A-weighted noise source octave. In the cases where a single silencer could not achieve compliance with the allowable noise criterion, two silencers were applied in series. In those cases, the silencer types were selected based on composite insertion loss spectrum. Two primary types of silencers are common for engine exhaust, dissipative (absorptive), and reactive. It is not the intent of this article to discuss the “how” and “why” of silencer physics, but instead, to discuss the applications.

Dissipative silencers are double wall vessels with perforated inner walls. The annular space is usually filled with acoustically absorptive fibers. Some attenuation occurs from Helmholtz resonance, but most of the broadband attenuation is from the acoustic filler. The most simple designs have a straight perforated pipe as the inner wall, and have virtually no pressure drop. Others have a greater diameter inner wall, with a perforated “bullet”insert inside the pipe. These can have somewhat greater attenuation, but at the cost of slightly greater pressure drop. Both variations have good mid-to high-frequency attenuation, but poor low frequency attenuation.

Reactive silencers are vessels that attenuate noise by the expansion chamber principle[7]. Reactive mufflers generally have at least two chambers, connected by small pipes. The pipes may be perforated to diffuse airflow. The frequency response and amount of attenuation is proportional to the volume and number of chambers. Reactive mufflers have good low frequency attenuation (peak frequency depending on length and diameter), but typically have much greater pressure drop than dissipative silencers.

For this project’s extraordinary attenuation requirements, two mufflers in series were recommended for hot gas exhausts and for test cell exhaust discharges, but the pressure drop implications had to be considered. The hot compressed gas discharge could not accommodate much pressure drop, so pairs of absorptive silencers were selected for moderate pressure drop; one straight pipe and one bullet insert type, which produced an insertion loss frequency span with peak insertion loss near the center of the audible spectrum. The engine exhausts could tolerate moderately high-pressure drop, so reactive mufflers were specified in concert with straight pipe absorptive types, which produced broadband insertion loss, with good low frequency





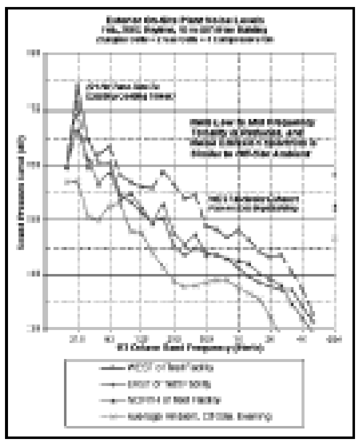
attenuation. In both cases, the dual silencer in-series performance was specified to match source noise spectra.

Design implementation and results

The facility architect and engineers implemented the primary noise control recommendations for room acoustics, sound containment, air inlet and exhaust pipe silencers and roof parapet. The building noise containment designs, including interior test cell acoustical measures perform as planned. Inlet attenuation for the air compressors and exhaust attenuation for the engine and hot gas test cells exceed expectations. Environmental noise emissions have relatively smooth spectrum shapes (tonality is suppressed), and low noise emission levels compared to surrounding environment. The results provide improved working conditions for technicians in the support shop and operators at the test cell control consoles, with interior sound levels 6–9 dBA less than the levels at the older facility. Exterior sound levels from building wall radiation, compressor inlet air louver, and the various test cell exhaust discharges are very moderate. Actual performance validation measurement results are shown below.

Validation measurements to confirm results

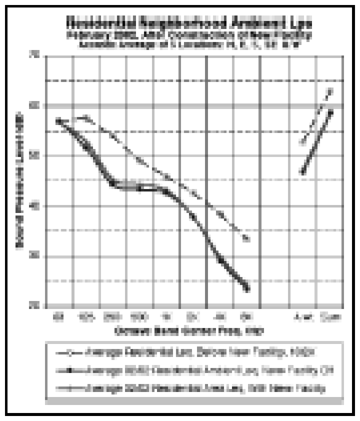
JEAcoustics returned to the new plant facility in February 2002, to conduct performance validation measurements. Sound levels and spectra were measured within the compressor room, representative operational test cells, control console areas adjacent to test cells, support mezzanine, on the roof, and around the perimeter of the building. All sound levels due to test cell operations, including the screw air compressors, met or exceed design projections. a tonal peak on the site in the 31 Hz 1/3 octave band (see chart), which is believed to be from a cooling tower or another industrial source, because it exists in the ambient measurements when the test cells are not in operation. Neither the noise source measurements at the original installation, nor measurements near the exhaust terminations at the new facility exhibited the 31 Hz tone. On the west side of the new facility, broadband sound levels were somewhat greater than on north and east sides, but by observation, exhaust fan noise from the pre-existing building on the relocation site contributed to sound levels. With those exceptions, the outdoor noise levels and spectra on site were

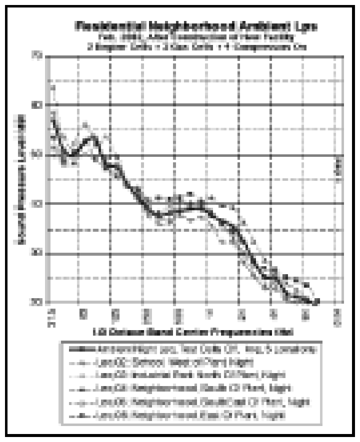


Source: 2 Eng +2 GS +4 Compr Measured: r = 15 m (50 ft) Projected: r = >60 m (200 ft)	LAeq	Projected to Prop. Line
North of Building	53	<40 dBA
East of Building	55	<42 dBA
West of Building	58	<45 dBA
South (Existing Plant Bldg. acts as noise barrier)	N/A	N/A
allowable Lp @Prop. Line	–	50 dBA

neither loud nor tonal.

Equivalent levels (Leq)measured 15 m (50 ft)from the new test facility varied from 53–58 dBA on the north, east and west sides of the facility (the existing building south of the test facility does not permit a nearby measurement in that direction). When the 15 m (50 ft) measurements are projected out at least 60 m (200 ft)in any direction to property boundaries, sound levels due to test facility operations are only 40 –45 dBA. Nighttime ambient sound levels in surrounding neighborhoods average 47 dBA (energy average of A-weighted levels at five locations). The Southern Building Code permissible nighttime sound level at the property boundary, after accounting for tonality is 50 dBA (55 dBA for non-tonal noise)in residential areas. The (projected) 40–45 dBA noise emissions at the property boundary could increase the 47 dBA ambient 1–2 dB ((by addition). Those levels are within the project design criteria and comply with the building code.





Sound levels measured in neighborhoods in the vicinity of the test facility show a 1–2 dB increase in the 125–500 Hz octave bands, when compared with ambients (both are energy averages of Leqs at five locations surrounding the facility). Individual 1/3 octave spectra from the five community locations surrounding the plant show very little tonality (re: side band differentials >6 dB), and have spectrum

noise notes

Sydney airport

Australia's Federal government predicts a tripling of passengers through Sydney's airport in the next 20 years. So, according to NSW Department of Infrastructure, 5230 more homes will have to be insulated as the footprint of suburbs heavily affected by noise from planes increases. To insulate all those homes, at about $50,000 (AS) each would cost $300 million, or $15 million a year But while federal funding was $9.9M in 2003/4, by 2005/6 it is down to a mere $600,000 and 2006/7 falls to just $100,000.

shapes very similar to the average ambient 1/3 octave community spectrum.

Conclusion

It is possible to design and construct an industrial test facility within a semi-rural community with very quiet ambient noise environment with very little noise impact. The design approach of matching attenuation spectrum to noise spectrum proved successful at reducing environmental noise emissions to acceptable levels and preventing community annoyance due to perceptible tonality. The project complied with the Southern Building Code Standard for Sound Control and met all acoustical design criteria.

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noise notes

Shanghai subway

One of Shanghai's top seismology experts is pushing the local government to take immediate action to reduce the amount of noise generated by Shanghai's subway lines. "When a subway train races by at high speed, it will cause neighbouring constructions, including their floors, walls and pillars, to quiver and produce noise," Zhu Yuanqing, deputy director of the Shanghai Seismological Bureau, said yesterday. In January, Zhu submitted a proposal to the city government during the annual plenary session of the Shanghai People's Congress. Zhu noted in his proposal that a noise test conducted by the bureau in an underground area close to the People's Square metro station last year measured vibration level as high as 94 decibels – China's environmental policies recommend a ceiling of 65 decibels for noises in urban areas. "Normally, the subway noise can affect an area of some 30-50 meters around the subway facilities," he said. "Those noises will disturb people and cause them to feel uncomfortable." Zhu has suggested the city take steps to reduce the amount of vibration caused by passing trains, especially near preserved buildings. He noted the cities of Shenzhen and Guangzhou in Guangdong Province have both been successful in curbing subway noise. In Shenzhen, subway constructors installed vibration-separating springs and rubber boards inside subway tunnels to reduce noise. In a telephone interview, Wu Yi, general manager of Shanghai Metro Construction Corporation, said: "Our company has already decided to use various noise-reduction facilities in future metro construction." He said the company is considering installing vibration-reducing boards below subway tracks to cut down on noise. According to the company, the city will have built nine subway lines stretching 250 kilometres by the end of next year. By that time, the city's subway system will be capable of handling 3.2 million passengers every day. The city has announced plans to build 12 new metro lines by 2020 to augment its current five lines.