ISOLATION OF PERFORMANCE HALLS FROM GROUND VIBRATION

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Abstract

One of the inherent characteristics of transportation systems, especially steel wheel and rail systems, is that vehicles running on the roadway or trackway generate vibration which transmits through the ground into nearby buildings. As our urban areas build up or are redeveloped, it is frequently desired for a variety of reasons to place a concert hall or theater in a location which is in close proximity to or over a rail system or roadway. In such cases, the application of building isolation design, either to the performance hall within a building or to an entire building, can be used to allow placement in a location which would otherwise be unacceptable because of the noise, and possibly vibration, generated within the building due to the nearby transportation facility. Recently there have been several instances where the desired location in a central city area, or in proximity to other arts facilities, resulted in major concert halls being located near rail system subway tunnels. Structural design configurations were developed to accomplish noise and vibration isolation of the performance hall box within the building to eliminate the groundborne noise and vibration as a potential intrusion within the performance halls. In most cases the design criterion was that the noise from outside sources should not exceed the threshold of hearing. Design procedures, configurations and materials to successfully achieve this criterion are presented.

Introduction

Steel wheels rolling on rails or rubber tires rolling on pavement or guideway result in ground or structure vibration due to forces generated at the rolling interface. With steel wheel and rail systems, the frequency range of the vibration can include frequencies from 12-15 Hz up to 300-400 Hz and result in audible noise radiated to the interior of buildings located near the rail facility. Rubber tired vehicles tend to generate lower frequency vibration which can and does result in feelable vibration in nearby buildings. Perhaps the most critical type of occupancy for buildings near a railway or other transportation corridor is a performing arts facility with concert, opera or theater halls where very low background noise is necessary as a component of the appropriate acoustical environment. Residential buildings located near rail facilities or subways are also a type of occupancy where the structure-borne noise radiated within the building can be objectionable. However, the criteria for acceptability are generally higher sound levels than for a performance hall.

There are criteria unrelated to the potential for good overall acoustics which dictate the location or placement of many new concert halls and theaters. Therefore, rather than selecting a quiet site, demands for proximity to other cultural venues such as art museums, other concert halls or theaters, or location within a large multi-purpose building, are the overriding criteria and result in placement at sites which have high exterior airborne and groundborne noises which can adversely affect the ambient noise within the completed hall. Provision of structural vibration isolation of either the entire building or of the performance hall within the building, creating a box-in-box type of structure, is the procedure that can achieve acceptability at such noise and vibration impacted sites.

Recent examples of such circumstances in the United States include: the new Benaroya Concert Hall in Seattle, located directly over a mainline railroad tunnel and adjacent to a bus and future rail transit tunnel; Verizon Hall at the Kimmel Centre in Philadelphia, located adjacent to a rail transit subway; and the Jazz@Lincoln Center Concert Theater in New York, located within a large multi-purpose building directly adjacent to two rail subway lines. Other examples include the Sangnam Hall at the LG Arts Centre in Seoul, Korea, also located within a large multi-purpose building directly adjacent to a rail subway, and The Esplanade Concert Hall and Opera/Ballet House in Singapore, located near four rail transit subway lines and adjacent to a ship channel. At The Esplanade site the diesel engines in passing ships and boats generate groundborne noise which is comparable to the groundborne noise from rail facilities.

When it is suspected that a new performing arts facility (or residential building) is located near enough to a rail or other transportation corridor that there may be groundborne noise and vibration sufficient to cause excess interior noise, the general design process includes: (1) a groundborne noise and vibration survey at the site to determine the amplitudes of noise and vibration at the foundation levels for the new building, (2) projection of the expected structure-borne noise in the performance hall(s) or residence, considering the type of foundation and structure proposed for the buildings, and (3) comparison of the expected structure-borne noise radiated into the new facility with the criteria for acceptable noise from exterior sources. When this process results in identification of the potential for excess noise, then the design process continues with the next steps consisting of: (4) development of appropriate structural modifications, and (5) designing an isolation configuration to control the structure-borne noise and vibration so that it will not exceed the design criteria for the project.

Site Evaluations

The amplitude and propagation characteristics of groundborne noise and vibration are highly variable due to the large variations in geological strata at different sites and due to different types of ground at the building foundation and at the subway, roadway or guideway. Conditions vary from very soft soil layers with low propagation but high levels of vibration at the source, to very stiff rock with low vibration level but very high transmission or propagation. Therefore, to determine the expected level of structure-borne noise at a new building site, vibration measurements on the site provide the best base data for estimating the effect on the new building facilities. Groundborne noise and vibration can be projected using data from prior measurements in various types of geological strata. However, such estimates are subject to at least a 10 dB range of uncertainty added to the range of uncertainty regarding the new building characteristics.

The preferred procedure for evaluation of groundborne noise and vibration is a survey with measurements in boreholes with depth equivalent to the proposed new building foundation level. An alternate or supplementary procedure is measurements within existing buildings at or adjacent to the site. Measurements in existing buildings do require consideration of adjustment or corrections to the type of foundation and structure planned for the new building.

It is important to recognize that the primary source of groundborne vibration and noise is at the invert or trackway for trains in subway, whether in rock or soil strata. The main propagation of groundborne noise and vibration is via shear waves through the geologic media with some conversion to Rayleigh waves at the surface if the building is at a sufficient distance from the subway. For surface rail or roadway facilities, the primary wave propagation is surface Rayleigh waves, which allows vibration assessment measurements to be made at the surface only unless there are layers with differing characteristics between the surface and the foundation level of the building.

Figure 1 is a photograph showing a plastic pipe lined borehole and the accelerometer waterproof casing devised to make measurements of groundborne noise and vibration. An air bladder is used to secure the accelerometer carrier to the borehole at the measurement depths included in the survey. Digital tape recording of the data from the three orthogonal oriented accelerometers provides data which can be used to determine the levels in the undisturbed soil and to calculate the vector sum of the energy which will be imposed on the new building foundations. The photo also shows a surface-mounted accelerometer for measuring vertical vibration at the surface.

From the groundborne noise and vibration survey results, the typical maximum levels from passing transit trains or other vehicles can be determined to define the structure-borne noise and vibration coupled or transmitted into the foundation. These data are then used to project the level of structure-borne noise expected to be transmitted up through the building structure and re-radiated from the floors and walls of the performance halls. These projections include estimating the coupling of the groundborne noise and vibration to the foundation or base levels of the building. For example, with a heavy reinforced concrete structure a coupling loss of 10 to 15 dB can be expected. For a relatively light weight steel frame composite concrete floor building, coupling loss at the foundation may be only 5 dB. Conversely, a reinforced concrete frame and column structure has relatively little attenuation of the structure-borne noise that propagates up through the building, whereas, a steel frame composite concrete floor building will result in 2 to 3 dB attenuation per floor. It is important in such projections to base the calculation on a line source or to use data from line source measurements as the calculation basis because the structure-borne noise from a line source or long dimension source attenuates at a much lower rate through the building structure than for a point or small dimension source.

Figure 1 Groundborne noise and vibration survey borehole and measurement equipment

The criterion for acceptable noise from exterior sources in performance halls is frequently the threshold of hearing, sometimes denoted the N1 criterion. For theaters and residences a less restrictive noise criterion of NR-20 or -25 (NC-20 or -25) may be specified by the acoustical designer.

After the projected structure-borne noise levels have been compared with the design criterion for the building or spaces of concern, the degree of reduction required from building isolation can then be determined. Sometimes the result of the site evaluation will indicate that increasing the coupling loss by use of very heavy foundation elements and heavy structure in the basement levels will be sufficient. Use of floating floors and isolated walls is another type of intermediate reduction which may be adequate. In other cases, it has been found that an effective vibration isolation system placed between the basement or garage levels and the upper part of the building is necessary to achieve the noise reduction needed. In the most critical cases, use of a heavy basement and foundation structure to increase coupling loss in combination with a relatively low natural frequency structural isolation system is necessary in order to achieve sufficient reduction of the structure-borne noise.

Isolation System Design

For a performance hall with low level noise criterion the most important design parameters are:

(1) A high acoustical impedance foundation and structure at the basement levels or building structure below the isolation plane. This is generally accomplished through the use of heavy reinforced concrete foundation and basement or lower level structure.

(2) A high acoustical impedance relatively rigid structure for the performance hall, particularly for the first one or two levels above the isolation plane. This is also accomplished through the use of heavy reinforced concrete structure or concrete encased steel structure.

(3) Very low acoustical impedance resilient mounts for isolation with vertical natural frequency selected to give adequate vibration isolation at the lowest frequencies of significance, as determined from the site survey, and with low acoustical impedance in the audible frequency range present in most situations where there is significant groundborne noise.

It is important that the structure above be stiff in order to increase the natural frequencies or modes of the structure to the highest possible frequencies. This is because as the dynamic motion and flexing or bending of the structure occurs, the effective mass load on the springs decreases with increasing frequency, even with a very stiff but light weight structure. The natural modes of the structure can result in very significant loss of isolator efficiency due to the effective mass loading becoming a very small local part of the structure at higher frequencies. This effect is why many building isolation projects, and even floating floor installations, have turned out much less effective than expected by the designers.

Figure 2 is a schematic diagram showing the essential elements of a high efficiency structure-borne noise and vibration isolation system. Included are:

(1) Heavy concrete footings or columns with continuous slab, or at least heavy grade beams, between footings or columns. Similarly, for piling or caissons, heavy caisson caps with heavy grade beams or continuous floor slab for coupling in the horizontal direction.

(2) The vertical gravity load and horizontal restraint isolation bearings designed as long service life structural elements.

(3) Heavy concrete beams and continuous relatively thick floor directly above the isolation bearings.

(4) Concrete shear walls of 250 to 350 mm thickness, coupling the isolation floor to the structure above.

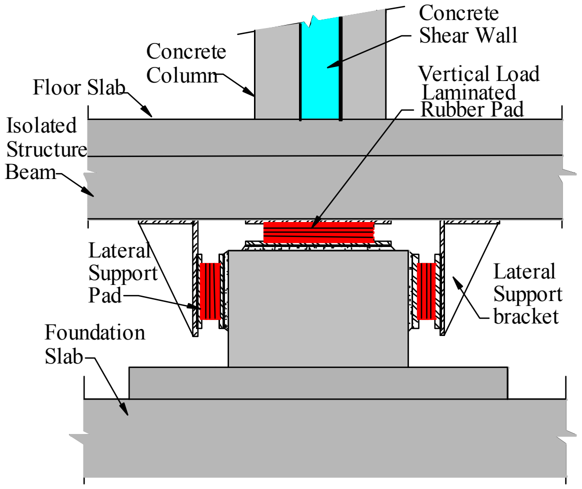

Figure 2 Essential elements for a high noise reduction isolation design

The concrete shear walls are a part of the dynamic stiffening to maximize the effective mass load on the bearings. The horizontal restraint bearings must be located in equal and opposite pairs and preloaded so that they remain in compression when there is any lateral deflection due to seismic events. They also provide for mechanical stability of the overall isolated box structure.

Because of the relatively wide frequency range which must be attenuated, typically 12-15 Hz to 250-300 Hz, an elastomeric isolation pad with appropriate stiffness and other properties is the most effective type of isolator spring to achieve a high degree of noise and vibration reduction. From the various elastomer materials available, natural rubber provides the best characteristics for building isolation applications, a low ratio of dynamic-to-static stiffness, a very low creep rate under compression load and very long service life without deterioration or stiffening of the elastomer material. Most synthetic materials have limited service life, particularly under constant compression load. Also, the ratio of dynamic-to-static stiffness is significantly higher with synthetic elastomers. This results in higher static strain in the elastomer for the same basic natural frequency of the isolation system.

There are numerous instances of natural rubber installations reviewed or removed after 50 to 90 years service with no deterioration and full retention of the load support capability and resilience. Thus, the isolation designs do not require provision for maintenance and replacement of the rubber pads, although in most instances the designs are arranged to provide access for checking the condition in the future.

Using natural rubber as the elastomer results in designs with a 120 mm to 190 mm total thickness of the rubber for isolation of concert halls and other projects requiring a high degree of noise reduction. For projects with a lower or intermediate noise reduction requirement, a total rubber thickness of 75 to 125 mm is generally sufficient.

With the 120-190 mm thickness pads for concert hall applications, the typical stiffness is designed for 9 to 12 mm deflection under the static gravity load or dead load of the isolated hall. This results in calculated natural frequency in the range of 5 to 7 Hz, which achieves good isolation for the entire frequency range, including any feelable vibration components from the transportation facility. This degree of deflection also limits the static strain to the range of 5% to 8%, which assures low load stress and long service life for the elastomer. For applications requiring a lesser degree of noise reduction, the designs are arranged to have a static deflection of 6 to 9 mm and natural frequencies in the range of 7 to 10 Hz, which is low enough to provide isolation for the frequency range from typical transportation facilities and for structure-borne noise and vibration from building services equipment.

Example Isolated Structures

Figures 3 and 4 show typical examples of concert hall projects where the foundation and lower level structure is the very heavy reinforced poured-in-place concrete for achieving high mechanical and acoustical impedance below the isolation plane. The photographs also show the heavy concrete construction above the isolation plane, the complementary part of the design which is necessary to maximize the effectiveness of the isolation springs.

Figure 3 Benaroya Hall typical arrangement of concrete beams and bearing pads

Figure 3 is representative of the isolation design at the Benaroya Concert Hall in Seattle. The floor below the isolation plane is 250 mm concrete and the 1.0 m x 1.5 m beams are upstands above the floor with the parking garage below. All columns through the two parking levels are heavy reinforced concrete. The beams above the isolation for the concert hall floor are similar size with vertical offsets to accommodate the lateral restraint bearings. The floor above is 300 mm concrete with metal deck forming. The overall design for the system has a calculated natural frequency of 4.5 - 5.0 Hz. There are a total of 308 gravity load vertical support bearings, 400 x 400 mm plan size, and 224 lateral restraint bearings of 530 x 530 mm plan size.

Figure 4 The Esplanade Concert Hall concrete structure at the isolation level

Figure 4 is a photograph from The Esplanade Concert Hall in Singapore. In this case the bearings were just above a foundation level 1.0 m thickness slab with no basement or garage levels below. Isolation pad sizes varied depending on column loading and included sizes up to 600 x 600 mm. Even though the subway tunnels were predominantly in rock, resulting in higher frequencies for the groundborne noise, the design natural frequency was 7-8 Hz to be sure of including all frequencies from the marine traffic on the adjacent ship channel and the low frequency vibration from building services equipment.

Figure 5 is a photograph from a different type of structure; the Jazz@Lincoln Center Concert Theater located in a steel frame multi-purpose building. To achieve the high impedance below the isolation all of the steel columns directly supporting the isolated hall were encased in concrete. Also, a thick concrete slab at the floor below the isolators and full concrete encasement of the theater structure above the isolators were provided. Figure 5 is of one of the perimeter columns with both vertical gravity load bearing pads and lateral restraint pads. There are 98 vertical isolation pads of 550 mm square or 600 mm square configuration. A total of 48 lateral restraint pads are provided primarily for mechanical stability because the location is an area not requiring seismic protection. To assist in balancing the lower acoustical impedance of the concrete encased steel structure the bearing pads are 190 mm rubber thickness.

Figure 5 Jazz@Lincoln Center photo showing concrete encased steel beams and isolation bearing pads

Figure 6 is a photograph from a non-performing arts type of application, a 12-story condominium building in Toronto, Canada, located directly adjacent to a double track subway. In this case, the isolation was provided at the top of columns in the parking level below the building. The entire building was isolated via a heavy concrete transfer slab poured directly above the isolation bearing pads. Because the noise criterion was less restrictive than for a concert hall, there are no lateral beams or continuous floor slab located directly below the isolation bearings for lateral stiffening. Also in this case the 120 mm thickness of the rubber pads is less than typical for the concert hall applications.

Figure 6 Town & Country condominium building isolation at top of garage level

Noise Reduction Results

Each of the designs presented as examples had significantly different structural design. Developing the overall structural modifications to accommodate the isolation, and developing the design of the rubber bearing pad, involved a large amount of coordination work with the structural engineers for each project. The overall result at the concert hall projects has been achievement of the goal of reducing the railroad or rail transit system noise to the threshold of hearing. Benaroya Hall in Seattle, opened in September 1998, Verizon Hall in Philadelphia, opened in December 2001, The Esplanade Concert Hall and Opera/Ballet House opened in October 2002, and Sangnam Hall in Seoul, Korea opened in March 2000, all have structures similar to the schematic design in Figure 2 with natural rubber pads of total thickness of 120 mm to 156 mm, depending on the structural design requirements. For each of these halls the result was maximum interior noise levels at or below the threshold of hearing for groundborne noise from train passbys. At the time of this writing, the Jazz@Lincoln Center in New York has not yet opened.

Other successful projects include the Town & Country Condominium in Toronto with total rubber pad thickness of 120 mm and noise levels less than NC-25 in the condominium units. The Goodman Theaters in Chicago are directly over a shallow-depth rail rapid transit tunnel and with 127 mm thickness pads and intermediate weight structure for the main theater the PNC-20 criterion was achieved. The Burnham Plaza Theater in Chicago, located 1.0 m from a rail transit elevated structure and supported at grade level on 100 mm rubber pads, achieved the NC-25 design criterion.

The overall conclusion is that with appropriate consideration of the structural configuration, of the isolation system design natural frequency and of the acoustical impedance mismatch between the rubber pads and the structure both below and above the isolation bearings, it is possible to achieve even the most restrictive design criteria for interior radiated noise. The overall design procedure and requirements which have been developed make it possible to successfully build noise-critical spaces such as concert halls in locations where there is severe impact due to groundborne noise from transportation facilities.

Summary

The purpose of the information and examples presented is to demonstrate that the technology and design procedures are readily available, and that there is a history of successful application indicating that structural isolation can be used to accommodate site locations which would otherwise be unacceptable due to groundborne noise from transportation vehicle sources. There are now several examples around the world of concert halls and other performance halls located in close proximity to rail transit subways or railroad facilities where background noise level at or below the threshold of hearing has been achieved through application of appropriate structural design combined with isolation via elastomeric materials. By using natural rubber as the resilient material it has been possible to develop the isolation pads as structural elements with life expectancy similar to that of the buildings.

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