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Concrete Slab Vibration and Structure-Borne Noise, Burj Dubai Case Study

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ABSTRACT

The Burj Dubai “Dubai Tower" is a skyscraper currently under construction in Dubai, United Arab Emirates. Concrete is being pumped to the top of the building using high-pressure hydraulic pumps. The hydraulic hammer action of the pumps, located on the buildings podium ground level, produces high levels of vibration. The vibration transmits to the lower basement levels and radiate as structure-borne noise. Noise and vibration measurements were conducted when concrete was pumped to level 140 at a height of 500m from the ground. The measurements were conducted at a number of points on the Concourse Level, Basement Level 1 and Basement Level 2. Reductions of vibration level as it transmitted away from the source and to other floors were measured. Structure-borne noise was estimated from measured vibration levels and compared to measured values where reasonable verification has been achieved.

INTRODUCTION

Usually ambiguity arises between structure-borne and airborne noise inside a building. It is often the case that the airborne noise transmitted through building elements (windows, walls, etc) exceed noise caused by structure-borne vibration. For noise control it becomes important to evaluate the contribution from structure-borne and airborne components to the total noise inside the building. Further complication arises when low frequency airborne sound induces building vibration in the frequency region below 100Hz.

To evaluate the sound radiated by a structure, considerable information about the vibration of the structure is required. The loudness of sound radiated from a structure depends on vibration amplitude as a function of frequency as well as the spatial distribution of vibration over the structure. This paper presents the results of predicted structure-borne noise from vibration measurements with the aim is to assess the accuracy of a simplified prediction method for structure-borne noise.

The measurements were conducted in Podium Levels of Burj Dubai, a skyscraper currently under construction in Dubai, United Arab Emirates. When it is completed in late 2008, it is predicted to be the tallest man-made structure in the world, as well as the tallest building by any measure (**Figure 1**). In all, some 300, 000m^3 of concrete will be used. A four-storey podium structure is connected to the foot of the tower.

Previously it was observed in Burj Dubai during concrete pumping that the noise level near the pumps on ground level was much lower than the noise level in Basement levels. This indicated that in podium levels the pumping noise is dominated by structure-borne noise component. Measurement of concrete pumping in Burj Dubai provided an opportunity to test the accuracy of predicting the structure-borne noise in a room using measured vibration levels in a simplified prediction procedure.

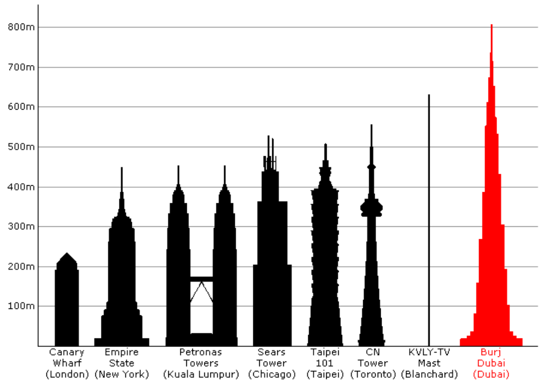

Figure 1 Burj Dubai compare to other tall buildings (CBS New)

Due to the height of the building and time restrictions, concrete is being pumped to the top of the building rather than being craned up in hoppits. Rotary pumps do not provide the required strength for such heights; instead high-pressure hydraulic pumps are relied upon. The rhythmic action of the pump provides a hydraulic impact every 5 to 7 seconds providing a pumping pressured of 190bar for every impact. (Frankfurter Allgemeine 2007)

The hydraulic impact action of the pump produced a reacting force in the pump that transmitted to the building. Once the concrete is started being pumped, it took the concrete around

30minutes to reach level 140. The pumping impact force steadily increased with the height of concrete column inside the pipe. The increased force input required for pumping a higher column of concrete was reflected in the level of pumping impact noise steadily increasing for 30minutes and then remaining constant. That is, once concrete reaches the top, the height of the column doesn't change and the pumping force required stabilizes.

The propagation of vibration in the building away from the source and from floor to floor was also assessed. The propagation of vibration through a building structure is very complex. The vibration transmits from a source to a building component and quickly transmitted to almost all parts of the structure. In multi-storey buildings a common value for the attenuation of vibration from floor-to-floor is approximately 3dB (Nelson 1987). The measurement also provided and opportunity to verify this number.

MEASUREMENT METHOD

Noise and vibration levels were measured in Burj Dubai Building from concrete being pumped to 140th floor of the building. The concrete pump was located on Ground Level podium with the concrete pipe attached to building core.

Noise levels were measured using an LA 5570 Ono Sokki Precision Sound Level Meter (SLM). Vibration measurement was carried out using the same SLM where the microphone was replaced with an Ono Sokki piezoelectric accelerometer. The accelerometer was attached to the SLM through specialized connecting device.

Figure 2 shows the measurement locations that are in Level Basement 2 (B02), Level Basement 1 (B01), Concourse Level (Con), and Ground Level (Gnd). At the Ground Level, floor vibration was measured directly underneath the Concrete Pump at the soffit in Level Con.

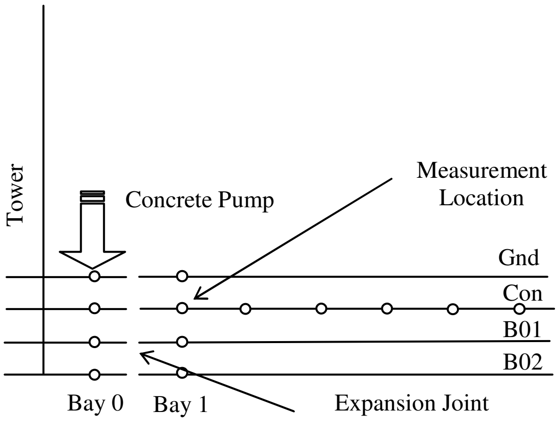

Figure 2 measurement location

Noise levels were measured at measurement locations in Level Con, B01, and B02 at 1.5m above floor using a tripod. For vibration level the accelerometer was attached to the floor or soffit using hot glue.

For vibration, measurement locations were selected at the middle of floor bays, equidistant to the nearest columns, as these floor locations have the least stiffness to vibration.

To investigate the variation of floor vibration with distance from the source, the measurements were then repeated at the mid-bay of next seven floor bays of Concourse Level. To investigate the variation of vibration level with floor levels, the measurements were repeated directly underneath the first point on the floor of the Concourse Level, Level Basement 1, and Level Basement 2.

RESULTS AND DISCUSSION

Once the concrete is started being pumped, it took the concrete around 30 minutes to reach the highest level. The pumping impact force increased with the height of concrete. Each measurement is an average of 3 to 4 strokes of the pump that lasts 15 to 20s in total duration.

Pumping Concrete

As can be seen from **Figure 3** the vertical vibration level [dB Ref 10^{-6} m/s^2] (z-axis) measured, progressively increased with time. This reflects the increased force input required for pumping a higher column of concrete inside the pipe. Once concrete reaches the top, the height of the column doesn't change and the pumping force stabilizes.

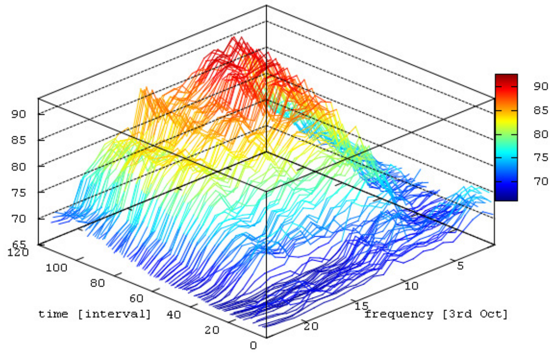

Figure 3 Increase in vibration level with pumping force.

In **Figure 3** the numbers along the Time-axis indicated the number of time-intervals with the first interval denoted by zero. The numbers along the frequency-axis indicate the number of one-third octave bands with the 20Hz band denoted by zero.

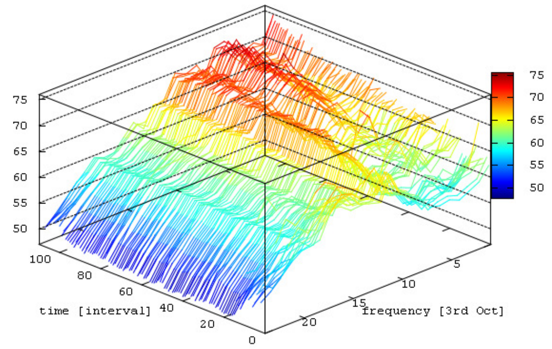

Figure 4 Increase in noise level with pumping force.

As can be seen from **Figure 4** noise measurements conducted concurrently reflect the same behaviour. **Figure 4** have similar Time and Frequency axes as **Figure 3**.

The measurements reported in this paper are all measured after the stabilization event.

Vibration Transmission

Table 1 shows the measured reduction in vibration level each bay compared to the next, progressively moving away from the tower. Also between bay 0 and 1 there is an expansion joint in the building that prevents direct transmission of vibration between the bays.

Table 1 Reduction in vibration level [dB] at different floor bays (Level Concourse)

	Frequency [Hz]						
Bay	32.5	63	125	250	500	1k	2k
0 to 1	-1	-8	-10	1	0	-7	-8
1 to 2	-2	-1	-4	0	-7	0	2
2 to 3	-3	-3	0	-10	-3	-6	-4
3 to 4	1	-1	0	2	-4	0	0
4 to 5	-2	-2	-1	-3	0	0	0

Note that the vibration levels progressively decrease away from building core. The reduction to Bay 1 is significant as there is an expansion joint between Bay 1 and Bay 0. The progressive reduction for other Bays are generally 0 to 4 dB, except for some frequencies that show significantly higher reductions and some time increase of 1-2dB.

There is a significant reduction in vibration levels transmitted to further out floor bays. However the reduction is not constant from bay to bay, but change depending on frequency.

The podium levels are reverberant spaces and the noise level across these levels do not changing significantly, despite the reduction in vibration level away from the vibration source (see Figure 5).

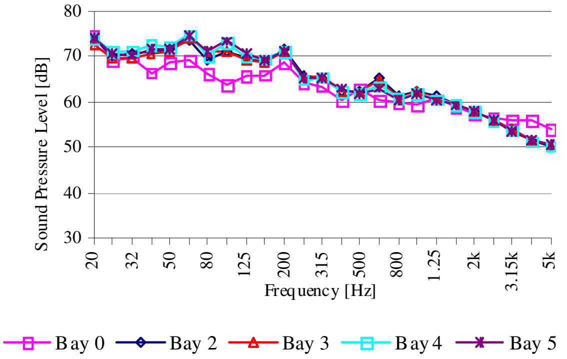

Figure 5 Noise level at Level Concourse

Table 2 shows vibration transmission to Level Concourse, and Level Basement 1 at Bay 0 and Bay 1. As can be seen, the transmissions do not reflect the 3dB reduction quoted in the literature (Ishi and Tachibana 1978). Vibration transmission to Level Basement 2 is not shown, as the level is significantly lower being slab on ground.

Table 2 Reduction in vibration level [dB] at different floor Levels

	Frequency [Hz]						
Floor-Floor	33	63	125	250	500	1k	2k
Bay 0							
Gnd to Con	-3	-3	-5	-5	0	-3	-13
Con to B01	1	1	0	3	-7	-2	0
Bay 1							
Gnd to Con	-2	1	1	-3	-5	-11	-24
Con to B01	-1	-8	-5	-3	-7	-5	-5

Figure 6 Shows the noise level at Level Concourse, Level Basement 1, and Level Basement 2. The noise level in Level Basement 1 and 2 are similar while the noise at Level Concourse has higher levels of noise at frequencies above 500Hz. This is due to significant noise from the Concrete Pumps and Concrete Delivery Trucks transmitted to Level Concourse through the expansion joint, especially at high frequency.

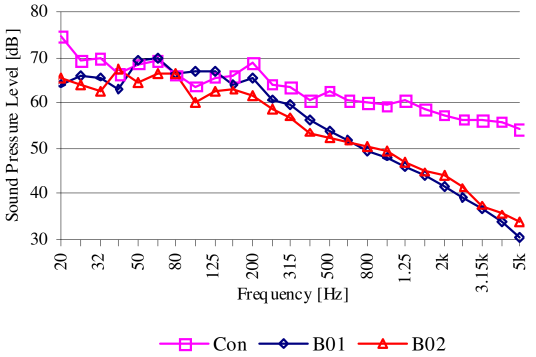

Figure 6 Noise level at Bay 0 of three podium levels

Prediction

One can measure the sound power level L_w radiated from an object by placing it in a reverberant room of known absorption area *A* where L_p is the sound pressure level in the room.

$$L_W \approx L_P + 10\log\left(\frac{A}{4}\right) \quad \text{Equation 1}$$

However it is generally desirable to relate the radiated power with the structural vibration. The relationship is described in terms of the so-called radiation efficiency. The radiated sound power *W* from a surface area *S* is related to the vibration velocity by the equation shown below (Cremer et al., 1973)

$$W = \rho c \sigma S \left\langle u^2 \right\rangle \qquad \text{Equation 2}$$

where u is the root mean square velocity of the radiating surface, ρ the density of air [kg/m^3], c is the speed of sound in air, and σ is the radiation efficiency of the radiating surface.

Therefore, if radiation efficiency of a vibrating surface is known, the average sound pressure level (L_p) it produces in a reverberant environment of known absorption can be estimated from the measured vibration levels. The absorption of the room α was calculated using the absorption coefficient of room surface finishes (mainly concrete) and associated surface areas. Room constant was used to calculate the reverberant noise inside the room.

Note that the entire podium plan of a level forms a 'triangle' shape around the central tower area, at each level. To calculate the reverberant noise, only the area from one side of the 'triangle' was used to estimate the room size, which made a concrete box of 160mx65mx6m dimension. However this room had a number of openings to other sections, to the outside, and to other floor levels. To incorporate this into the calculation, a 15% open area for the floor and ceiling was included in the room absorption calculation. The calculation with the open area resulted in reverberation time reasonably close to the on-site estimated reverberation time of approximately 2s at 500Hz.

Note that the height of the room is considerably lower that the length and width of the room. Therefore the structure-borne noise contributions from walls can be ignored without significantly impacting the overall noise level.

The sound power levels L_w of structure-borne noise were calculated from measured vibration levels according to Equation 2. The calculated power levels L_w were used to estimate the reverberant sound pressure levels L_p at the podium levels (Equation 1).

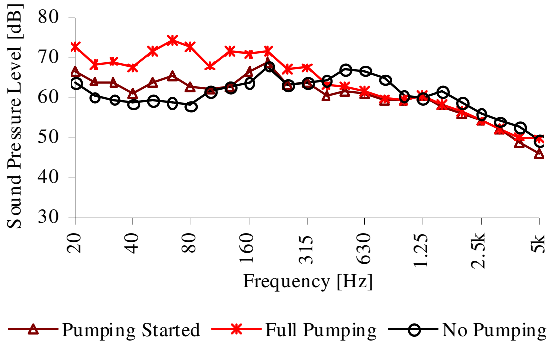

Figure 7 Noise comparison

Figure 7 takes three noise spectra from **Figure 4** that show the noise level before the concrete pumping started, when the concrete was somewhere halfway to the top, and when it reached the top. As can be seen, the structure-borne noise is clearly dominant over background noise only at frequencies below 500Hz. Even when the concrete reaches the top, the noise levels above 500Hz do not exceed the background noise. Therefore for comparison of predicted structure-borne noise to measured only frequency below 500Hz were used.

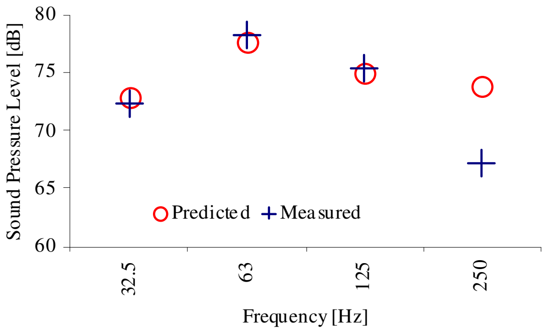

Figure 8 Structure-borne noise, Level Con, Bay 0.

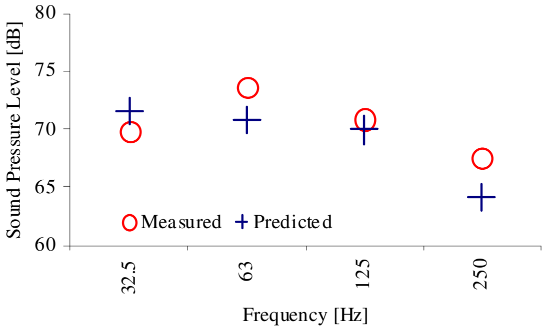

Figure 9 Structure-borne noise, Level B01, Bay 0.

Figure 8, **Figure 9**, and **Figure 10** show the calculated structure-borne noise levels compared to the measured noise levels, showing good correlation. Note that the effect of high frequency noise transmitted through the expansion joint at the 250Hz is evident as we go up to Level Concourse.

Note that for Level Basement 2, the floor is concrete slab supported on the ground. Vibration level from the floor is significantly lower than vibration of the ceiling (Floor of Basement 1). Therefore in the calculation for L_w, the vibration from floor of Level Basement 1 was used. Similarly, the vibration levels at locations further out from the building tower are lower, and calculations result in noise level lower than the measured levels. Therefore, in the prediction the vibration levels measured in Bay 0 were used.

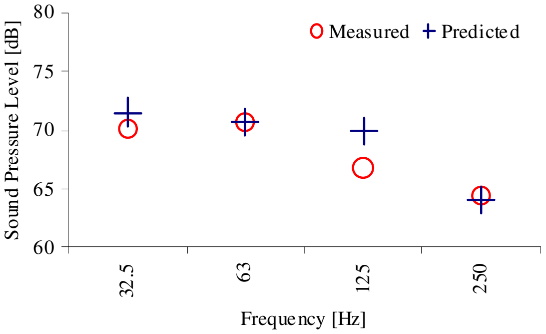

Figure 10 Structure-borne noise, Level B02, Bay 0.

CONCLUSIONS

This paper reports the noise and vibration measurements conducted in Burj Dubai from impacts of concrete being pump to a height of 500m. The measured vibration levels were used to calculate the structure-borne noise in the building.

Based on the assumptions detailed in previous section, the structure-borne noise levels were calculated and compared to the measured noise levels. Two important parameters for the calculation of structure-borne noise are, the vibration levels from correct location should be used in the calculation (especially for large rooms), and attention to the interior absorption properties of the room should be paid.

Also reported are vibration levels at different locations in a floor and at different floors demonstrating the transmission of vibration in the building. With the source on Ground Level, the reduction of vibration to Concourse Level is greater than expected.

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