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ACOUSTIC EMISSION OF INTERNAL DRAINAGE IN MULTI-STOREY BUILDINGS

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ABSTRACT

The number of multi-story buildings continues to increase around the world, and as a result, the quality of life for those people living in these buildings requires ongoing evaluation. Many residents of multi-story buildings complain about noise disturbances from internal drainage systems, mostly from toilets flushing in the upper levels. This paper seeks to establish whether or not the noise from internal drainage systems in multi-story buildings affects daily human activity and sleep patterns. A survey was undertaken on a 6-storey building and used a sound level meter to measure noise levels on different floors in the building. The results showed that the building height does not influence the noise, nor does the noise affect human activity and sleep patterns, principally because the noise does not last longer than a few seconds, with a typical duration of 15 seconds or less.

Keywords: Multi-storey building; Acoustics Emissions; Drainage; Flow.

INTRODUCTION

Multi-story buildings have seen a significant rise in number in recent years. Starting from around the middle of the 20th Century, the growth rate in their numbers has been considerable, particularly in cities in Asia and Europe. In developed cities across the globe, multi-story buildings are often the main feature of urbanisation[1]. Multi-story buildings also bring economic implications as they often increase the cost of buying land. In addition, they can also add aesthetic value and can influence the lifestyle of people living in and around these developments[2].

However, modern structures must offer their residents comfort, of which curbing sound emissions is one significant aspect [3]. Unfortunately, sound emissions can be found in buildings where proper provisions have not been made to tackle such problems. Sound emissions in multi-storey buildings can come from, for example, floor impact noise, neighbours, and electronic and elevator equipment. In addition, it is not uncommon that emissions in new buildings arise from the plumbing systems. And while noise from sanitary facilities is not peculiar to multi-storey buildings, it is essential to tackle this problem as multi-story buildings are home to a large number of residents. Over time, occupants living with plumbing noise problems realise that such noises can be irritating during the day and can interfere with sleep at night[4].

In the construction industry, there is a range of materials that possess high sound insulation properties; in particular, studies show that multiple walled pipes can significantly reduce sound emissions[5]. Another method of reducing noise in pipes involves using sound insulation materials.

Although these different materials can be tested and the material properties compared [6], there is no evidence that noise emissions have been completely eliminated in most buildings.

The research reported herein has reported the acoustic emissions generated from internal drainage systems in multi-floor occupancy buildings. In addition, a questionnaire has been circulated to understand the effects, if any, of noise from drainage on sleep behaviour and premature awakening and to gather subjective responses from residents. This study is an experimental one, looking at a 5-story building and focusing on the effect of sound transmission on occupants. Acoustic measurements were made to gain an understanding of the extent of transmission that might affect occupants' well-being. Thus, the work has been done so as to help propose a systematic approach to reducing sound emissions during the design and installation stages. Hence the goal is to ascertain the level of sound emissions from multi-storey building sanitary facilities and how best to properly mitigate any adverse effects by identifying suitable sound-insulation material. Information on methods and materials are presented along with detail on data collection techniques, followed by the main results and recommendations for future research.

REVIEW OF THE LITERATURE

From the beginning of civilisation, tall structures have fascinated humankind. This dates back to 2600 BC, when the Egyptian pyramids were constructed and are still regarded as one of the seven wonders of the ancient world [7]. Currently, the tallest building in the world is the Burj Khalifa, located in Dubai in the United Arab Emirates, standing at 828m tall [8].

However, multi-storey buildings require modern technology to aid their function, part of which is the provision of sanitary facilities for the removal of wastewater.

Sound emission from drainage

Sound is generated in pipes due to solid, gaseous, and liquid waste transport. Sound waves can travel through elastic mediums and liquid and various solid materials [9,10]. The majority of audible frequencies range between 20 and 20,000 Hz. Humans hear sound best between 1,000 and 5,000 Hz [11].

Audible ranges are divided into 10-octave bands, representing specific frequency spectrums. These range from 16,000 Hz to 31.5 Hz and sometimes are separated into third-octave bands for accuracy. If 500 Hz is taken as a medium frequency, its low and high frequencies will range between 300 Hz and 750 Hz, respectively. Hence, the knowledge of the third-octave bands aids the overall calculation of sound level[12].

Burk et al. (2011)[13] stated that an A-weighting is applied to sound measurements that consider the relative sound perceived by the human ear, recognising the ear's sensitivity to low audio frequencies, particularly below 1,000 Hz, with B-, C- and Z-weightings used to measure very low, medium and very high frequencies. Ray (2010) [14] also noted that a minor change in the decibel reading leads to a significant change in the sound produced, which has an impact on what the person hears. The NIH (2014) [15] pointed out that the duration of exposure to certain sounds is a significant factor in the amount of pleasure or discomfort experienced by the listener. Thus, humans should limit their exposure time to certain sounds beyond 85 dB, and for every 3 dB beyond 85 dB, the exposure time should be cut by half to avoid permanent hearing damage.

The average sound level in dwellings is typically around 25 dB, with 60 dB being the norm for offices, depending on the activity and overall quality. This results in noise rating (NR) curves for background noise evaluation as reported by Ref. [16].

Causes of noise in the drainage system

Causes of noise in drainage systems include water hammers, impact noises on bends and tees, flow noises, and falling solid matter noise. When the water closet, WC, is flushed, noise emissions are typically transmitted via connected structures. While a degree of noise within the room housing the sanitary facility is usually deemed acceptable, consequent sound in surrounding apartments is undesirable, and measures should be taken to prevent this[11]. In addition, water hammers can lead to the unwanted movement of improperly attached pipes, causing vibrations, noise and, in some cases, the loosening of joints and fittings [17]. Flow impact on bends and tees designed can also lead to noise, horizontal movement of sewage leads to flow noise as vertical movement leads to falling noise[18].

Transmission of noise in the building

Sound is transmitted through a building by air and solid-borne pathways. Structure-borne transmission involves sound emissions through solid materials and is regarded as the main noise path. Noise can also convert from one form to another, e.g. from structure-borne to airborne and vice versa. According to BS 8233: 2014[19], two stages of plumbing noise should be considered during the design and construction stages. Porous materials tend to absorb the sound of middle to high frequencies based on their thickness. Typical materials are:

- Hard finish: Plaster on a solid backing,
- Porous absorber: 50 mm mineral fibre 50 kg/m³,
- Panel absorber: 9 mm ply, 50 mm cavity containing 25 mm mineral fibre,
- Perforated panel: 14% perforations, 25 mm cavity containing mineral fibre,
- Perforated gypsum tiles/board, 16% perforations, suspended with 200 mm plenum.

METHODOLOGY

The two major pieces of equipment required for this analysis are the Nor140 sound analyser and the calibrator. The Nor140 sound analyser is a precision handheld device used to record sound and monitor building acoustics in real-time. The calibrator is inserted within the microphone cartridge of the sound level meter.

Acoustic emission measurements

Measurements were collected from a 6-storey student residence with modern engineering design and technology. Each floor has the same layout from top to bottom, with each room having a toilet with a bathtub, WC and a washbasin. Care was taken to ensure that the faucets in the bathtub and washbasins were turned off, and there was no ongoing plumbing activity in the building before the test was carried out.

The Nor140 sound analysing device was placed on the ground floor, and the water closet was flushed on the 5th, 4th, 3rd, 2nd and 1st floors in turn and the results were recorded on the ground floor. This was repeated for each floor. The sound pressure level measurements were made using 1/3 octave bands because this produces more precise results. These were then converted to octave bands so as to make comparisons with required standards. Equation 1 aids in calculating the sound pressure level for different octave [20].

$$L_p = 10 \log (10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + 10^{\frac{L_3}{10}} + \dots + 10^{\frac{L_n}{10}}) \quad (1)$$

Questionnaire

A series of questions were drafted for the purpose of understanding the effect of noise emissions from the drainage system on the sleep pattern and daily activities of the residents of the multi-storey building. The questionnaire was developed and delivered

online and deployed a scaling system to assist respondents (aged 15-35 years). The questionnaire was designed in accordance with ISO (2003)[21] recommendations and uses a direct question method. The procedure used to choose the words for the questionnaire scale was done in a way that is consistent with its position on a numerical scale of 1 to 5 for most of the questions. The questionnaire was used to answer the following questions:

1. Have you lived or currently live in a multi-story building?
2. Are you satisfied or dissatisfied with the noise from your water closet as a result of flushing?
3. Are you satisfied or dissatisfied with the noise from your building drainage system?
4. Does the noise from your water closet as a result of flushing affect your daily activities?
5. How heavy or high do you sleep?
6. Does the noise from the flushing of the water closet from the upper floors affect your sleep?
7. Does the noise from the flushing of the water closet from your adjacent neighbour affect your sleep?

RESULTS AND DISCUSSION

Acoustic results

Using Equation 1, all the measurements were calculated in octave bands and plotted as shown in Figure 1. The frequencies analysed were for audible frequencies only, ranging from 16 Hz to 8 kHz, and

Table 1. The sound level from flushing at different levels in a building.

Location of measurement	LAeq, dBA
Background noise	26.0
Ground floor measurement from flush at 1st floor	42.0
Ground floor measurement from flush at 2nd floor	39.0
Ground floor measurement from flush at 3rd floor	41.6
Ground floor measurement from flush at 4th floor	40.9
Ground floor measurement from flush at 5th floor	42.2

Figure 2 shows the same measurements as in Table 2, but with octave bands, the result of the tests represented graphically for integrated average sound pressure levels. The results illustrated in Figure 2 show the corresponding values for the tests carried out. The green curve depicts the NR curve of 30. From the Figure, the sound measurements at frequencies just above 250 Hz to 4.0 KHz clearly fall above the acceptable values for dwellings. As a result, there is a need to further analyse the noise levels to ascertain the noise level that needs to be reduced in A-weighting frequency.

From the graph above, it can be seen that the noise from each floor is similar throughout; from the moment the toilet is flushed from any level, it follows the same pattern, with little difference, which may be

compared with the NR curve. NR curves for dwellings are 25 and 30. The NR curve is used to ascertain where the SPL level exceeds standards by comparing the sound pressure level lines measured with the NR curve, representing typical sound pressure level values with respect to octave bands.

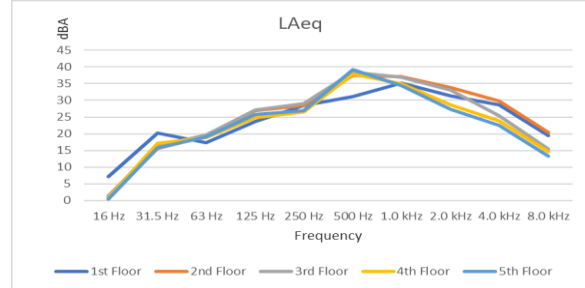


Figure 1: Integrated average sound pressure level dBA.

Table 1 illustrates the results obtained from a series of noise tests run with the aid of a sound level meter on different levels of the multi-story building. The results show that the sound level from the five floors tested is similar, which means that when the toilet is flushed, irrespective of the level it is flushed from, the sound is transmitted through the pipes equally down the building. This means that the height of the building does not influence sound transmission through the internal drainage system of a multi-story building. The results in Table 1 show the average value of the results presented graphically in Figure 3.

caused by the speed of the sound takes from the source to arrive at the point of collection with the sound level meter. The noise peaked at a frequency of 500 Hz and 39.2 dBA, which is well within the limit of 45 dBA for toilet flushing noise within a residential building.

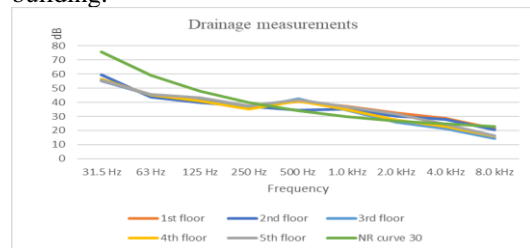


Figure 2. Drainage measurement results.

Table 2 shows that only noise of frequencies ranging from 500 Hz to 4 kHz needs reduction with all sound pressure levels not exceeding 10 dB; this indicates that the acoustic emissions are not so high but can

result in discomfort for residents. As such, it is pertinent that more insulation should be added to reduce the noise emissions in the drainage system.

Table 2: Loudest SPL octave band measurement analysis.

Frequency	31.5	63	125	250	500	1.0	2.0	4.0	8.0
Drainage measurement SPL, dB	57.7	45.8	43.7	37.7	42.4	37	32.6	28.8	21.5
NR 30 curve	75.8	59.2	48.1	39.9	34	30	26.9	24.7	22.9
Reduction needed	-18.1	-13.4	-4.4	-2.2	8.4	7	5.7	4.1	-1.4
A-weighting correction factor	-39.4	-26.2	-16.1	-8.6	-3.2	0	1.2	1	-1.1
Reduction needed in A-weighting	-	-	-	-	5.2	7	6.9	5.1	-

Questionnaire results

Results are presented in percentages illustrating the survey responses from 90 participants to understand their perception of noise from the flushing of WCs in the multi-storey building under consideration. Key findings are presented below, and graphical results are available in Appendix 1.

- a) The tolerance level of respondents to noise from the flushing of the water closet: This aspect reflects how satisfied or dissatisfied respondents are about the noise emission from their water closet when flushed. The range was 'very dissatisfied' to 'very satisfied'. 33.3% of respondents were neither satisfied nor dissatisfied, followed by 31.1% who said they were satisfied, 26.6% who were dissatisfied, 5.5% very dissatisfied, and 3.3% very satisfied. This shows that most respondents are either indifferent about the noise from the flushing of the water closet or satisfied with it.
- b) Respondents' satisfaction with noise insulation: This question aims to understand the overall satisfaction level of respondents with noise insulation in their building of residence. Out of the 90 respondents that participated in the survey, 35.5% were satisfied with the insulation level of their building, 27.7% were dissatisfied, 26.6% were neither satisfied nor dissatisfied, 6.6% were very satisfied, and just 3.3% were very dissatisfied. This shows that most of the respondents were either satisfied or indifferent.
- c) Impact of water closet flushing noise on daily human activity: This question was drafted to understand if toilet flushing affects daily human activities such as reading, working, or watching a movie. 51.1% disagreed that noise from the flushing of the water closet affected their daily activity, 21.1% neither agreed nor disagreed, 14.4% agreed, 8.8% strongly disagreed, and 4.4% strongly agreed. This shows that most respondents are not affected by noise from toilet flushing, and others are indifferent, leaving just the small number who believe it bothers them. Those may be individuals who are more intolerant to the noise

of any kind.

- d) Impact of water closet flushing noise from upper floors on sleep: Ninety respondents gave their verdict on the impact of flushing water closets from upper floors on their sleep pattern. 46.6% of respondents noted that noise from the flushing of water closets from upper floors does not affect their sleep pattern, 21.1% agree, 17.7% neither agree nor disagree, 13.3% strongly disagree, and just 1.1% strongly agree. This shows that the majority of respondents are of the opinion that water closet flushing from upper floors has no impact on their sleep patterns. Those who felt their sleep was disturbed may be light sleepers whose sleep patterns can easily be interrupted by the mildest of sounds.
- e) Impact of water closet flushing noise from a next-door neighbour on sleep: This survey showed that noise generated from the flushing of the water closets from the adjacent neighbours on the same floor has no impact on sleep patterns. Of the 90 respondents, 44.4% disagreed, 22.2% strongly disagreed, 16.6% agreed, 14.4% neither disagreed nor agreed, and only 2.2% strongly agreed. This is an indication that sleep is not affected by noise from the flushing of the toilet from a neighbour's residence on the same floor.

From the analysis carried out, it is observed that while most respondents claim that the noise from flushing water closets does not disrupt their daily activity and sleep pattern, others believe it does. This finding is confirmed from the acoustic emissions levels presented herein. The analyses also show that there is a need for further insulation. Hence, the pipes should be insulated further to reduce noise emissions.

CONCLUSION

The tests carried out as reported herein lead to the conclusion that noise from the internal drainage system from flushing WCs at different levels in a multi-story building does not change with height. The test was run on a 6-storey residential building, and the average noise levels obtained were 42, 39, 41.6, 40.9

and 42.2 dBs, respectively. The variability in this range is negligible, showing that the noise difference is unchanged throughout the different levels. The questionnaire also provides results that show that noise from the water closet's flushing, although loud enough to be heard by its residents, whose ages range from 15 to 35 years, does not pose a major problem because it does not occur beyond 10 seconds. The noise does not disturb sleep patterns but can be problematic if it becomes continuous. Since the noise to be reduced is between the mid to high-level frequency, pipes should be covered thoroughly by insulation and placed behind a perforated gypsum board, 16% perforations, suspended with 200 mm plenum as recommended in BS 8233:2014. These results can be used to improve human health, comfort and general wellbeing. Furthermore, this article will aid better sound insulation in buildings, knowledge of the best materials for sound insulations and a proper understanding of what humans perceive as tolerable and intolerable noise levels.

RECOMMENDATION

To further reduce the noise level within a multi-story building, it is pertinent to run further tests to confirm the best materials to protect residents from unwanted noise. In addition, it is pertinent to analyse the acoustic emissions generated from the hydraulic jumps that occur at junctions between vertical and horizontal stacks and determine optimum places to create bends and velocity breaks, hence decreasing the acoustic emissions.

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Results of the survey

