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AMBIENT VIBRATION ANALYSIS OF HERITAGE UNREINFORCED MASONRY BUILDINGS IN BANGLADESH

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Abstract

Most of the historical unreinforced masonry structures were built in Bangladesh during Mughal period and British rules. This type of structures is seismically vulnerable and need to strengthen for preserving its historical and cultural heritage value. This study was conducted to collect preliminary information on dynamic properties of old historical unreinforced masonry buildings located in Bangladesh. A series of ambient vibration tests (microtremor records) were performed to evaluate structural dynamic properties (damping ratio, fundamental natural frequency, etc) of three old unreinforced masonry buildings including mosque and educational use occupancy. Microtermor record was taken for 30 minutes for each building. After obtaining microtremor records, random discrete technique was performed to estimate transfer function and relevant characteristics. This paper describes the buildings tested, applied methodologies, equipment used and test results. Based on experimental information, variations of dynamic properties with preliminary influence factors are discussed.

Keywords: unreinforced masonry; microtremor; dynamic property; direct shear test.

1. Introduction

Bangladesh is located in a seismically moderately region in Global Seismic Map prepared by Global Seismic Hazard Assessment Program (GSHAP, 1992). Although no major earthquakes occur in this country in the last few decades. During the past few earthquakes and also in the time of recent earthquakes, the masonry structure of Bangladesh shows poor structural behavior. Ancient masonry structures are particularly less vulnerable to dynamic actions, especially seismic actions.

Unreinforced masonry was a very common practice and used technology. Those heritage unreinforced masonry structures have been named according to their extent of Bengali civilization, cultures and religions. Few of those are- Pala Buddhist architecture, Islamic and Mughul architecture, Terracotta temple architecture, Common Bungalow style architecture, Indo-Saracenic revival architecture etc.. Later on the British colonial age predominantly represent the buildings of the Indo-European style developed, which is mainly a mixture of Indian European and Central Asian components. The more prominent works amongst them are Ahsan Manzil in Dhaka and Tajhat Palace in Rangpur City. All of them are mostly masonry, sometimes in combination with stones and other local materials [1].

The remains of the ancient archaeological sited bear ample testimony to the fact that are the art of building was practiced in Bengal from early period of her history. A satisfactory reconstruction of the history of architecture in ancient Bengal has been found from the evidence of the disappeared materials. The structures were rudimentary wattle and dub construction with beaten earth flooring. The early period of the history has witnessed the spouting of a number of urban centers at sites like Mahasthan at Bogra City in Bangladesh and in west Bengal at Bangarh at Dinajpur City, Chandraketugarh at 24 Paraganas district, Mangalkot at Burdwan district, Pokharana and Dihar. Traces of mud ramparts, noticed at several of these sites suggested that an early Bengal City often contained an acropolis.

In addition mud, bamboo and timber and occasionally burnt bricks were used for building houses. Terracotta drainpipes and ring wells were also found. But later after, during the succeeding periods, represented by sites like Banarh and Mahasthan, the houses became more and more complex, with a simultaneous increase in the use of burnt bricks [2].

Mosque architecture (1205-1765) was introduced by the Muslims to ritual needs of their religion, Islam after the establishment of Muslim rule in Bengal. For this consequence numerous mosque were built during the five and a half centuries of the Muslim period before the British colonial period. Most the building were constructed with burnt bricks and stones. Bricks an easily manufactured material form the abundantly available clay of the delta, has been the traditional building material of Bengal from the ancient times, as seen in the ruined but monumental Mainamati and Paharpur, monasteries in Bangladesh.

Although rooted in the 15th century architectural traditions of Bengal, their stark, unadorned exteriors, circular engaged corner towers and massive appearance shows the considerable influence from Tughluq architecture of Delhi. The most important of this approach is the Shatgumbad Mosque in Bagerhat district of Bangladesh. The mosque has eleven bays and seven aisles, with the largest bay in the center. This central bay is divided into seven independent, rectangular bays that are covered by the chau-chalas; this being the earliest use of the form in Bengal. The interiors of the miniature chau-chalas have thin, raised bands of brick that imitate the rafters and purlins of bamboo hut frames. There are seven entrances each on the north and south sides. It seems that the stone pillar once had brick casings, because there are traces of brickwork around some of their bases.

The Chhota Sona Mosque in Gaur dated by inscription to the reign of sultan Alauddin Husain shah (1494-1519), and was built by a high official in the royal court. This rectangular mosque is completely faced with stone in the exterior, while inside there is stone up to the springing of arches. Pillars, pilasters and the platform in the northwest corner are of stone. There is abundant stone craving in low relief in the exterior and ornamental niches within rectangular panels, rosette and pot motifs that are used repeatedly.

The Chatmohar mosque in Pabna district dated 989 AH (1581-82) and the Kherua mosque in Sherpur district dated 989 AH (1582). These mosques used the single aisle, three bayed plan which was to become the paln par excellence for Mughal mosques in Bengal from the 17th century onwards. In elevation the octagonal corner towers, the curved cornices. Low drum less domes, brick surface and pointed arches link them to the Sultanate style.

A refined Mughal provincial style was developed in the capital city Dhaka in the 17th century. The Lalbagh Fort Mosque in Dhaka dated 1059 AH (1649) and 1194 AH (1780) conforms to the typical Mughal mosque plan which was mostly masonry [3]. Kantanagar Temple, commonly known as the Kantaijiu Temple is a late-medieval Hindu temple in Dinajpur district of Bangladesh. The Kantajew Temple is one of the most magnificent religious edifices belonging to the 18th century. The temple was built by Maharaja Pran Nath, its construction started on 1704 CE and ended in the region of his son Raja Ramnath on 1722 CE. It boasted one of the greatest example on terracotta architecture in Bangladesh and once had nine spires, but all were destroyed during the great Indian Earthquake that look place on 1897 [4].

One of the most vulnerable forms of construction to damage in construction is unreinforced masonry. The 1989 Newcastle, Australia, earthquake was a recent event that demonstrated this vulnerability. The majority of damage in Newcastle was to older load bearing masonry construction or nonstructural masonry. Also a large number of small and large masonry performed well during the earthquake [5].

Historical structures have been built without accounting for the seismic actions and are vulnerable even to moderate events but, due to their historical importance and to the daily presence of tourists, their seismic rehabilitation is quite delicate, aiming at the protection of both human life and cultural heritage. Seismic preservation should be based on a good knowledge of the dynamic characteristics of the structure and a suitable choice of the intervention, if necessary. The first step is very important in order to assess, also by means of a suitable numerical model, the possible dynamic behavior of the structure during strong events. But it is not easy for several reasons: the structural size of the various elements (walls, floors, etc.) cannot be evaluated with the needed accuracy; the material characteristics, such as the tension-strain relationship, the strength, etc., are not known; structure and materials often exhibit inelastic behavior; horizontal structures are not effective in joining the vertical ones; the depth of the foundations is often variable as well as their geometry and material properties, including the soil characteristics; buildings are often connected to other constructions, so that their behavior is very complicated. For such kind of structures the experimental analysis is often the only way to improve our understanding about their dynamic behavior [6, 7, 8, 9 & 10].

2. Methodology

2.1 Study Design

Masonry is the building of structures from individual units laid in and bound together by mortar; the term masonry can also refer to the units themselves. The common materials of masonry construction are brick, building stone such as marble, granite, travertine, and limestone, cast stone, concrete block, glass block, and cob. Masonry is generally a highly durable form of construction. However, the materials used, the quality of the mortar and workmanship, and the pattern in which the units are assembled can significantly affect the durability of the overall masonry construction.

This research was initiated to collect preliminary information for heritage unreinforced masonry buildings in the Dhaka City. The purpose of conducting ambient vibration testing in general is to obtain the dynamic characteristics of a structure, its natural frequencies, corresponding mode shapes and damping estimates. The structure is assumed to be excited by wind, traffic and human activity. The measurements, typically accelerations, are taken for a long duration to ensure that all the modes of interest are sufficiently excited. Microtremor measurements were carried out to characterize the site dynamics. Five sensors were used for the measurement. The buildings are typically two storied with some part three storied. Three sensors were placed at different three stories on the line of stiffness of every floor. Other two sensors were placed on the ground to record the soil dynamics.

The present state of knowledge concerning shear strength and shear load-displacement behavior of masonry is far less advanced than that concerning masonry behavior in compression, even though shear failure is an important, often governing mode of failure in many masonry buildings [14]. This lack of understanding is reflected by the low values of shear resistance allowed by present U.S. building codes (ASCE 31 02). Information on the post-peak behavior and on the deformations associated with pre-peak and post-peak responses are also lacking. Only recently, the terms softening and dilatancy were introduced in the research community [15]. Knowledge of such behavior is essential if adequate analytical models are to be developed to describe the in-plane behavior of masonry walls. Most of the research conducted to date regarding the masonry shear behavior has been limited to determining the peak shear stress and affecting parameters.

Lime mortar was used as the bonding material in all the three study buildings. It was required to check the shear stress of the bonding mortar of masonry. Direct shear test has been carried out to find the best result for mortar strength at one building (Old academic Building of BUET) as identical as all the three buildings are similar in bonding material. This paper describes the buildings tested, the tests and results, and the methodologies and equipment used.

2.2 Study Area Selection

The tests were performed on and around three buildings of Dhaka City. Figure 1A shows the map of Dhaka City and figure 1B shows the locations of the three buildings tested in the Dhaka City. The buildings were the Curzon Hall Musa Khan Mosque Building, shown as Point A, the Aambour Shah Shahi Mosque, shown as Point B, and the Old Academic Building of Bangladesh University of Engineering and Technology (BUET), shown as Point C. The points were taken for the microtremor measurements. The three buildings feature similar structural systems, with unreinforced masonry load bearing walls at the sides of the buildings with a mix combination of wood and I-Joist steel diaphragm floors connecting them.

Figure 1A: Dhaka City Map (source: Dhaka Map of RAJUK website)

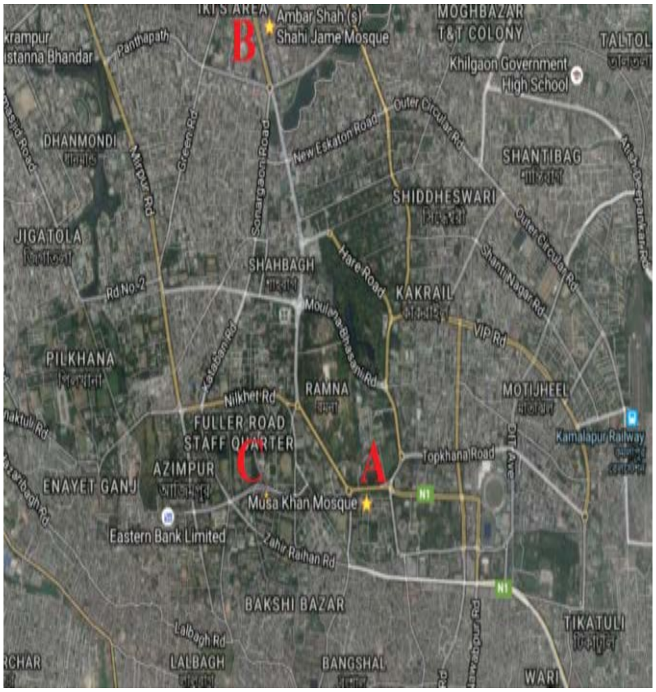

Figure 1B: Location of Study Area (source: Google map)

2.3 Description of Buildings

2.3.1 Musa Khan Mosque at Curzon Hall

This mosque is located at Curzon hall in Dhaka University at latitude 23°43'38.5"N and longitude 90°24'06.9"E. The Musa khan mosque (Figure 2) belongs to oblong shaped plan measuring 15.17 m by 7.54 m externally with a 1.52 m thick surrounding brick wall. The prayer hall is entered from the eastern side by three archways and the other two side walls have one pointed-arch openings each. To articulate the main mihrab niche from outside, the kibla wall is projected in the centre towards the west. The whole length of the rectangular hall is divided into three unequal bays by means of two 1.06 m wide arches springing from the east and west walls. The side bays are rectangular in shape and smaller in width, but the central one is bigger and square. With the help of brick pendentives the square central bay is transformed into an octagonal area. By introducing a series of sequences the octagonal area is transformed into a circular supporting area, upon which the dome supports. The two smaller rectangular side bays are converted into square supporting areas for the dome by using two half domed vault springing from the eastern and western walls. Plan and front elevation of the mosque are shown in Figure 3 and Figure 4 respectively.

Figure 2: Musa Khan Mosque

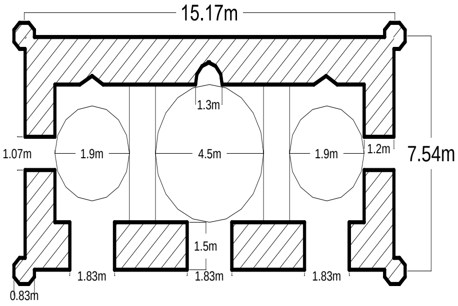

Figure 3: Plan of Musa Khan Mosque

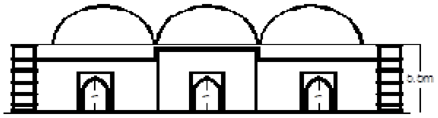

Figure 4: Front Elevation of Musa Khan Mosque

2.3.2 Aambour Shah Shahi Mosque at Karwanbazar

One of the most well preserved mosque complex of Dhaka city belonging to the 17th century is the Aambour Shah Shahi Mosque (Figure 5). It is located at Karwran bazaar in Dhaka City at latitude 23°45'11.6"N and longitude 90°23'35.0"E). The mosque proper has the usual oblong shaped plan measuring 13.41m by 7.30m externally with a 1.2m thick along east-west direction and 1.6m thick along north-south direction brick wall. The prayer hall is entered from the eastern side by three archways and the other two side walls have also one arch opening each. Corresponding to the three frontal openings, the kibla wall is niched with three mihrabs. The rectangular shaped prayer room is divided into three square bays by two wide transverse corbelled cusped arches supported by twin brick pilasters embedded in the east and west walls. With the help of half domed squinch at each corner, each square area is transformed into a circular supporting area, upon which the dome supports. All the three domes, with a very low shouldered dome on a cylindrical drum, are crowned with lotus and kalasa finial. The central one is slightly higher than the flanking ones. Plan and front elevation of the mosque are shown in Figure 6 and Figure 7 respectively.

Figure 5: Aambour Shah Shahi Mosque

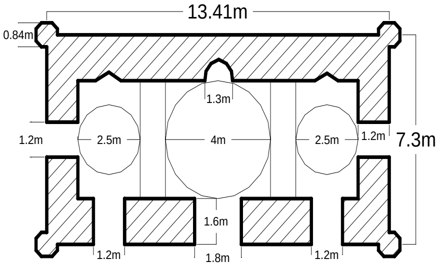

Figure 6: Plan of Aambour Shah Shahi Mosque

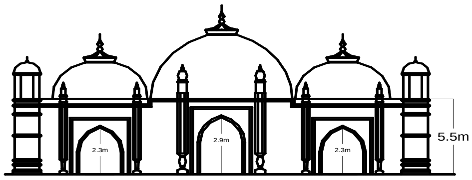

Figure 7: Front Elevation of Aambour Shah Shahi Mosque

2.3.3 Old Academic Building (OAB) of BUET

The Old Academic Building of Bangladesh University of Engineering and Technology (BUET) at latitude 23°43'39.0"N and longitude 90°23'34.2"E was built on the early 1900’s (Figure 8).Some parts of the building is two stories and some parts is three storied. The OAB building has a mixed used of office cum academic. The OAB’s proper has plan measuring 70.5m by 48m externally with a 1.1m thick brick wall every direction. It is Unreinforced Masonry Bearing Walls with Stiff Diaphragms (Building Type 15 according to ASCE/SEI 31-03) [13]. First floor (2nd story) is slab supported on masonry wall, Ground floor (1st story) is slab on grade. It is mainly unreinforced burnt clay brick masonry with lime mortar. Plan of the OAB is shown in Figure 9.

Figure 8: Old Academic Building of BUET

Figure 9: Plan of Old Academic Building

2.4 Data Collection Using Microtremor

The purpose of conducting Microtremor measurements is to obtain an estimation of site response for a particular location. Three approaches are commonly used to analyze microtremor data; power spectral densities obtained directly from the Fourier amplitudes, spectral ratios relative to a reference site, and Nakamura’s technique [12], which is defined as the spectral ratio of horizontal components to vertical components recorded at the same site

(H/V ratio). It is common to perform tests over a period of time to observe the stability of the measured site response, in order to provide a reliable prediction of the period of potential earthquake motion at that site.

Nakamura's technique describes the microtremors as Rayleigh waves propagating in a single layer over a half-space, and assumes that the microtremor motion is due to local sources such as traffic and human and construction activity nearby. It further assumes that the vertical component of ground motion is not amplified by the soil layer. Hence, the spectral ratio of the horizontal to the vertical components at the surface (H/V ratio) gives an estimate of the period at which it peaks, corresponding to the site period.

The equipment used for the microtremor testing system consists of five velocity transducers; two horizontal and one vertical, an amplifier and a laptop computer used for data acquisition. For the selection of the test location, care is taken to avoid heavy traffic, manholes, foundation sand other underground structures. The sensors are placed so that the two horizontal sensors are orthogonal, preferably facing North and East. The analysis is carried out using Nakamura's method, plotting the H/V spectral ratios that are the result of taking the RMS of the east and North spectral ratios. The most significant peak of the H/V spectral ratio is taken to be the dominant frequency of the site.

Methods to get geophysical information from the microtremor measurement were 1) obtaining the phase velocity by array observation of microtremor and 2) obtaining H/V spectrum by using 3 component sensors. After obtaining the phase velocity or H/V spectrum, S-wave velocity profiles should be interpreted by applying an inverse analysis. All 5 sensors were placed in a single row with the distance of 15m and 30 min data was taken.

Soil characteristics can be assessed by Microtremor measurement. Hard soil gives high frequency and soft soil gives low frequency. A structure may experience a vibration period at which it oscillates in the earthquake vibration motion and will tend to respond that. Natural frequency is obtained based on the spectral ratio of horizontal component of the structure to that of ground. Wave propagation mechanism of Microtremor and its relation with ground vibration characteristics were studied from the beginning of Microtremor studies [11]. Figure 10 shows the microtremor testing equipment.

Equipment arrangement Microtremor Sensor

Figure 10: Microtremor Equipment

2.5 Data Collection Using Direct Shear Test

The direct shear test to measure the shear stress due of mortar bond of Old Academic Building of BUET has been performed by using Hi-Force Hydraulic Jack. Figure 11 shows the testing activity of direct shear test.

Figure 11: Direct Shear Test

3. Data Processing and Analysis

The analysis has performed using the GeoSiG software and D-Plot software. For microtremor observation at the selected buildings, initially the sensors were deployed. Three sensors were fixed on the different stories of the building and another one on the free field near the surface. After taking the observation with the help of microtremor, the time domain velocity data was converted into to frequency domain data and natural frequency if the structures are determined.

3.1 Curzon Hall Musa Khan Mosque

The intention of the tests described in this research was to provide some preliminary information about the dynamic behavior. The Microtremor analysis of Curzon Hall Musa Khan Mosque has been illustrated as below in figure 12 and figure 13.

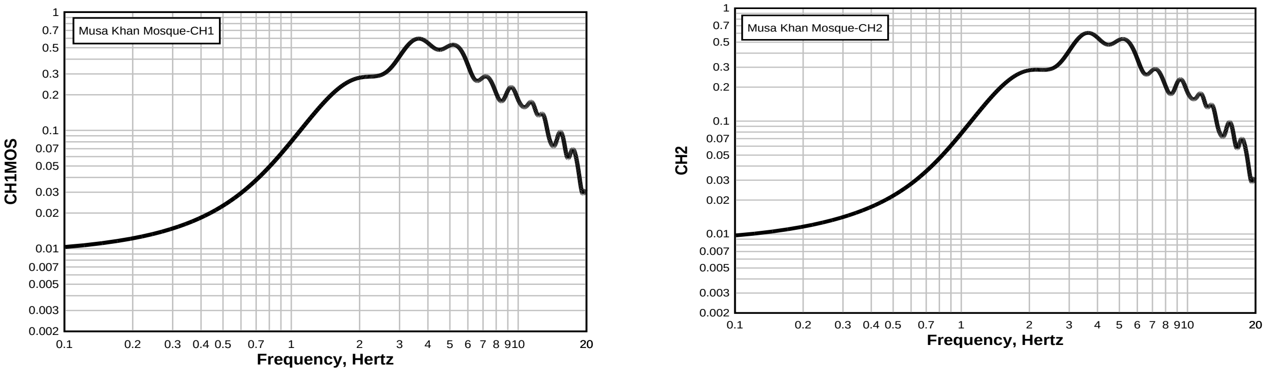

Figure 12: The corresponding FFT of recorded time series of the Curzon Hall Musa Khan Mosque

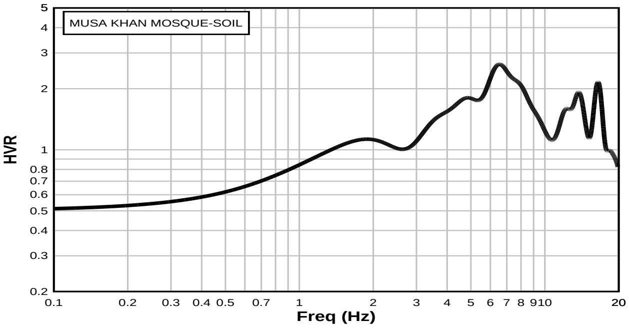

Figure 13: The corresponding H/V ratio of the Curzon Hall Musa Khan Mosque

3.2 Aambour Shah Shahi Mosque

Observation of microtremors can give useful information on dynamic properties of the site such as predominant period and amplitude. Microtremor observations are easy to perform, inexpensive and can be applied to places with low seismicity as well. The Microtremor analysis of Aambour Shah Shahi Mosque has been depicted as below in Figure 14 and Figure 15.

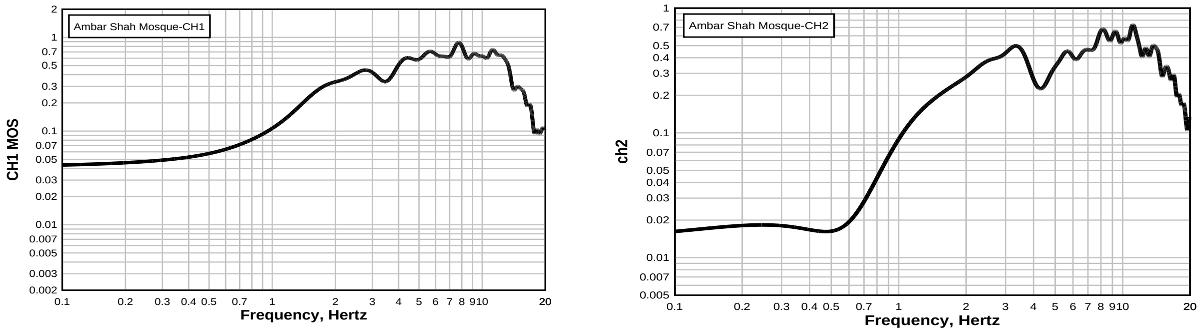

Figure 14: The corresponding FFT of recorded time series of the Aambour Shah Shahi Mosque

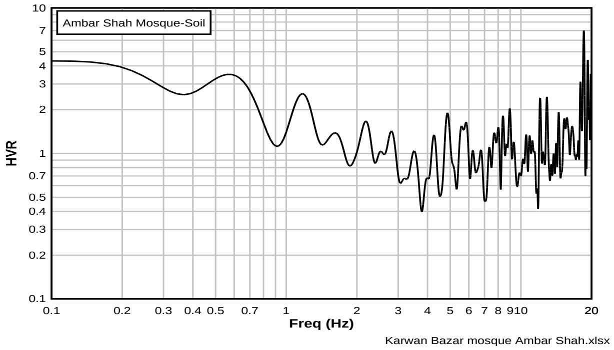

Figure 15: The corresponding H/V ratio of the Aambour Shah Shahi Mosque

3.3 Old Academic Building (OAB) of BUET

Seismic noise is relevant to any discipline that depends on seismology, such as geology, earthquake engineering and structural engineering. It is often called ambient wave field or ambient vibrations.

The Microtremor analysis of Old Academic Building of BUET has been shown as below in figure 16 and Figure 17.

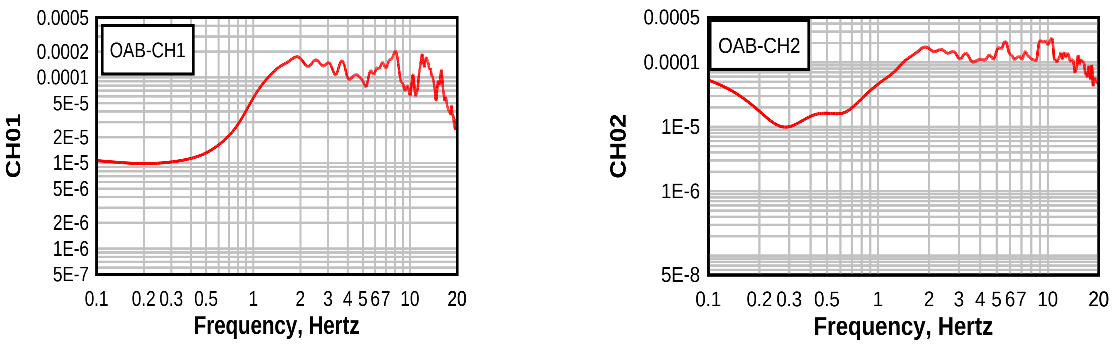

Figure 16: The corresponding FFT of recorded time series of the OAB

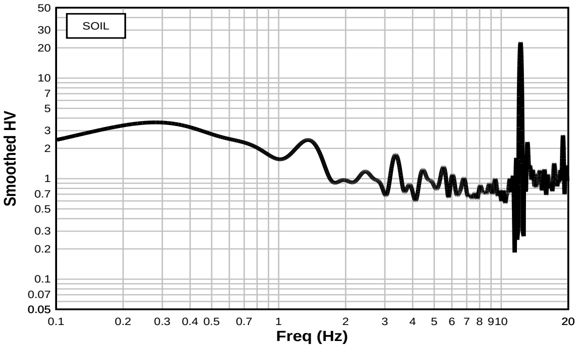

Figure 17: H/V ratio of recorded time series of the OAB

3.4 Direct Shear Test of Old Academic Building (OAB) of BUET

Shear failure is the dominant mode of failure observed in many masonry buildings subjected to lateral loading due to earthquakes, wind (in tall and slender structures), support settlements, or unsymmetrical vertical loading. Lateral loading can produce both diagonal cracking failures and shear failures of the horizontal joints. Joint resistance is of particular concern in the analysis of the load-bearing unreinforced masonry structures that are rather common among older buildings in many countries in the world. The shear generally acts in combination with compression caused by the self-weight and floor loads. Confinement by, for instance, structural frames to in-fill walls may also lead to shear compression.

The in-place shear test, also known as the push test, pro-vides a direct measurement of the shear resistance of mortar joints in masonry. The test is suitable for masonry that has relatively strong units and weak mortar so that shear cracks form in the typical stair step pattern along mortar joints and the units remain uncracked. In this type of construction, the shear strength of the mortar joints limits the shear strength of the masonry wall [16].

The Uniform Code for Building Conservation (UCBC) provides an empirical relationship that relates the mortar joint shear strength to the masonry wall shear strength, assuming that wall shear strength is limited by the shear of the mortar joints rather than shear through the units. The method is not applicable for determining shear strength of modern masonry with high strength mortars [17].

A calculation on direct shear test of lime mortar as bonding material of Old Academic building has been made. The calculation is given below-

Direct Shear Test of Old Academic Building of BUET	
Jack diameter	35 mm
Area	962.12 mm^2
Brick Size	254 mm (Length); 114.3 mm (Width)
Contact Area	77419.2 mm^2
Dial Gauge Reading	650(Kg/cm^2); 89846.22 (N)
Shear Strength of the Sample, τ	1.161 N/mm^2
Nos. of bricks above testing brick	100 Nos.
Height of wall above testing brick	9.15 m
Unit weight of wall	19 KN/m^3

Vertical Pre-stress on testing brick, σ	173.85 KN/mm^2
$\sigma * \mu$	0.174 N/mm^2
Shear Stress due to mortar bond only	$\tau - \sigma * \mu = 0.987$ N/mm^2

Reliable information on shear resistance is needed when performing retrofits and seismic upgrades of masonry buildings. While shear strength of a masonry wall is difficult to measure without resorting to large-scale testing, less destructive in-place tests of single masonry units provide a comparative figure that can be correlated to full-scale wall behavior. This less destructive alternative is more economical than large-scale testing and is desirable when a building's historic integrity must be maintained.

4. Results and Discussions

For the three buildings described earlier in this paper, both vertical and horizontal measurements were recorded, with a sampling rate of 200Hz and duration of 30 minutes for each. From the analysis of the normalized H/V ratio plots and FFT of the three buildings, the pertinent information obtained is presented in Table 1.

Table 1: Comparison of Microtremor Result of Soil (H/V ratio) and Building (FFT)

Test points	Predominant Frequency of Soil (HVR)	Structural Predominant Frequency	Remarks
Curzon Hall Musa Khan Mosque	1.8 Hz	3.6 Hz	Possibility of no seismic resonance
Aambour Shah Shahi Mosque	1.2 Hz	2.6 Hz	Possibility of no seismic resonance
Old Academic Building of BUET	1.6 Hz	1.9 Hz	Possibility of seismic resonance

The predominant frequency of the building of the Curzon Hall Musa Khan Mosque has found 3.6 Hz which is different from the predominant frequency of the site soil (1.8 Hz). So there's no possibility of soil strucrutre interaction during any severe earthquake. It is also similar in case of the Aambour Shah Shahi Mosque. But the predominant frequency of building of the Old Academic Building of BUET is in the range of the peak frequency of the soil. This value is close to the range of the higher modes of vibration for the buildings measured as shown in the figure 16 and figure 17. This raises the possibility of soil-structure interaction.

The direct shear test was done to find the mortar strength. From the analysis the shear stress due to mortar bond only was found about 0.987 N/mm^2 which is below the standard value. The direct shear test result suggested that as the mortar bond was not strong enough, the OAB building will be unable to resist lateral forces due to an strong earthquake. A detailed assessment has been done by following the guidelines of Arya (1986)[18]. Retrofitting of the masonry wall is mandatory. Currently, the OAB is being retrofitted.

5. Conclusions

The intention of the tests described in this paper was to provide some preliminary information about the dynamic behavior and the dynamic site conditions for three masonry buildings in Dhaka City. The Curzon Hall Musa Khan Mosque, Aambour Shah Shahi Mosque and the Old Academic Building (OAB) of BUET were each tested by researchers of BUET. Among the three historical buildings, from the dynamic analysis it has found that two buildings (Curzon Hall Musa Khan Mosque, Aambour Shah Shahi Mosque) are safe from seismic resonance whereas the Old Academic Building of BUET has the strong probability of severe seismic resonance. Also the direct shear test result on brick mortar of OAB shows that the mortar strength is below the standard value which indicates that the load bearing masonry wall is unable to withstand the lateral seismic force. This means the

OAB needs to be retrofitted. In this case, the earthquake resistant guidelines for non-engineered construction of Arya (1986) have been followed to retrofit the OAB.

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