Natural Frequencies Evaluation on Partially Damaged Building using Ambient Vibration Technique

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Abstract. Severe damages observed on the school blocks, roads, retaining walls and drainage within the compound of SMK Kundasang Sabah possibly due to the ground movements triggered by the Ranau earthquake in 1991. Ambient vibration measurements were carried on the remaining demolished 3-storey building which partially damaged in order to measure the predominant building frequencies using tri-axial 1 Hz seismometer sensors. Popular methods of Horizontal-to-vertical spectral ratios (HVSR) and Fourier amplitude spectra (FAS) were used to compute the ambient vibration wave fields of each building axes (Transverse or North-South (NS), Longitudinal or East-West (EW) and vertical) into Fourier spectra. Two main modes of translation and torsion were observed from the peaks frequencies obtained at 2.99 to 3.10 Hz (1st mode), 4.85 Hz (2nd mode) and 5.63 to 5.85 Hz (3rd mode). The building experiencing translation modes of bending and shear in the NS and EW directions. It could be seen when the amplitudes tends to increase when the floor are increased. Meanwhile, the torsional bending mode is expected to occur when the deformation amplitudes are found to be increasing horizontally, when moving into partially structural damaged section located on the East wing of building.

1. Introduction

Geophysical methods can provide excellent resolution of spatial variability across a site with several advantages such as non-destructive, non-invasive nature and relative speed of assessment [1]. The application of seismic instruments such as geophones, seismometer and accelerometer are widely accepted as a powerful tool to investigate the dynamic characteristics of site or structure whether in laboratory or on-site such as ambient vibration testing. Ambient vibration or ambient noise can be simply described as all natural and artificial sources of noise generated near the surface of the earth in the vicinity of the recording instrument [2]. Comparable definition given by microtremor which defined by a very weak ground motion which produced by a variety of excitations such as wind, traffics, etc. that is recorded at ground surface [3].

Appropriate monitoring and re-evaluation mechanism without much destruction can be engaged to secure the integrity of the existing structure and stability of ground condition [4]. According to [5], the application of ambient vibration able to identify the presence of soil-structure interaction and also to
detect structural damage by determining the frequency shift of the buildings. In addition, lack of structural design information, difficulties and constraints of destructive testing and requirement of quick experimental method and analysis gives additional advantages of using ambient noise method [6]. Besides, this ambient vibration investigation is also applicable to existing structures in low to high seismic regions, or also to new structures which nowadays more focusing to new construction technologies and innovation such as lightweight, renewable materials, rapid constructions techniques etc. [7,8,9,10].

Dynamic characteristics and resonance effects of the damaged site and 3-storey building of SMK Kundasang was performed by using ambient vibration method. SMK Kundasang was constructed in 1984 and became formal two years later. It is located on a flattened sloping ridge at 1250 m above the sea level, flanked by two basins. In 1991, an earthquake struck from Mensaban fault in Ranau at a magnitude of 5.1 on a Richter scale, generating tremors in Kundasang region and causing severe damage to some structures, roads (see figure 1) and infrastructures including those within the compound of SMK Kundasang. Structured interview of some local residents drew a consistent observation that one of the parallel adjacent buildings of similar configurations to a 3-storey reinforced concrete buildings of nineteen bays and approximate length of 57 meters connected by open stories of sheltered corridors on each level fractured a few years after the earthquake event due to progressive ground subsidence. Half of the building had to be demolished while the remaining neighbouring structure maintained a monitoring system put in place by the local authorities to monitor progressive structural and non-structural deterioration. In this study, the simplest and classical method of Fourier Amplitude Spectra (FAS) was used to identify the modal frequencies of the building from the ambient vibration time series collected. Meanwhile, Horizontal to Vertical Spectral Ratio (HVSR) method was executed for ground fundamental frequencies.

![Figure 1](image1.png)

**Figure 1.** Structural and nonstructural damages of SMK Kundasang site and building

2. Methodology

Microtremor measurements were taken using three units of Lennartz portable tri-axial seismometer sensors, (S), with 1 Hz eigenfrequency, CityShark II data logger and 1 GB memory card (see figure 2). The measurements were performed on ground surface and building. Two measurements have been conducted on ground, as shown in figure 3(a) and Table 1. The position of each sensor was shown by
orange and pink dots. Meanwhile, three measurements were carried out on building using similar instruments. In building measurements, the sensors are lying along the school corridor and placed closer to the structure main frame joints. The arrangements of sensors were made in two conditions, by horizontally and vertically. The horizontal sensors’ alignment is defined when all sensors are placed simultaneously on the same floor at several columns, such on the 2nd floor (refer to blue dots) and 1st floor (refer to red dots) at column 1, column 10 and column 20 as illustrated in figure 3(b) and tabulated in Table 2. The vertical sensor’s alignment is made at one column from top to bottom, such represented by green dots.

In order to get good signal quality and enough windows during analyzing stage, all noise disturbances especially transient and bad weather conditions were strictly avoided as recommended in [11]. Sampling rate of 100 Hz was used, at the maximum of gain level reached up to 512. A 15-minute recording length of microtremor was performed on the ground and building discounting all frequencies below 1 Hz [12]. The ambient vibration signals were recorded in the vertical direction (UD) as well as North-South (NS) and Earth-West (EW) horizontal directions. All sensors were aligned to the reference axis as a benchmarking which parallel to the NS direction, in the weaker building axis, for both the building and site microtremor measurements.

![Figure 2. Schematic connection of microtremor apparatus](image)

![Figure 3. (a) Building layout plan and sensor positions on the ground and (b) Front elevation and sensor alignments of the studied 3-storey or partially damaged building](image)
Table 1. Ambient vibration measurements breakdown on ground (refer to figure 3(a))

| Measurement lines & File Index (FL No.) | Sensor 1 (S1)         | Sensor 2 (S2)                   | Sensor 3 (S3)                   |
|----------------------------------------|-----------------------|---------------------------------|---------------------------------|
| In front to building:                  | Close to West wing    | Close to the center of building | Close to East wing              |
| FL 461 (orange dots)                   |                       |                                 |                                 |
| At the back of building:               | Close to West wing    | Close to the center of building | Close to East wing              |
| FL 469 (pink dots)                    |                       |                                 |                                 |

Table 2. Ambient measurements breakdown on building (refer to figure 3 (b))

| Sensor Alignments | Position of Sensors | Sensor 3 (S3) | Sensor 1 (S1) | Sensor 2 (S2) |
|-------------------|---------------------|---------------|---------------|---------------|
| Horizontal        | Upper floor (2nd floor) | C1            | C10           | C20           |
|                   | 1st floor           | C1            | C10           | C20           |
| Vertical          | At column 10        | 2nd floor, L2 | 1st floor, L1 | Ground floor, LG |

In the analysis, GEOPSY software was used for HVSR and FAS curves analyses. GEOPSY is scientific and open source software from www.geopsy.org [13], for geophysical research and applications which dedicated for ambient vibration processing for HVSR and FAS analyses. A 15-sec of automatic window length selection with an anti-triggering algorithm and a cosine taper of 5% were used. Fourier spectra were computed for each window length and smoothed by a Konno Ohmachi smoothing constant of 40.

The simplest way to identify modal frequencies is to inspect Fourier Amplitude Spectra (FAS) of the records, and when the FAS reach peak values at frequencies corresponding to modal frequencies [14]. Classical HVSR method can lead to very good results in identification of predominant soil frequencies, but does not add much value to the identification of frequencies in building [15]. Significant peaks of FAS and HVSR curves were distinguished and evaluated in order to predict the originality of predominant frequencies ($f_o$) and its fundamental ground frequencies ($F_o$) from ambient vibration sources.

3. Results and Discussions

In general three vibration modes were expected to be occurred from this partially damaged building. Figure 4 (a) shows two modes occurred from the NS direction of frequencies at 2.99 to 3.10 Hz (1st mode) and 5.63 to 5.84 Hz (3rd mode) indicated by sensors S1 and S2 with the former positioned at the center and the latter at the East wing of the building. In the West wing only a single sharp peak was obtained by S3. As similar trend of spectral curves shown in other horizontal measurement carried out on L1 floor by S2 and S3, but with a significantly lower amplitude of the second mode of frequency of S1 (see figure 4(b)). Different scenario was observed in the EW direction with a predominant frequency occurring at 4.85 Hz (2nd mode) displaying a single sharp peak of the FAS curve in the horizontal measurements on L2 and L1 floors as indicated in figure 5 (a) and (b).

The building has deformed in translational mode of bending from the transverse axis and shear along the longitudinal axis. It can be easily identified from diminishing amplitudes of both frequencies (2.99 to 3.10 Hz and 4.85 Hz) when lowering to the ground level as marked and illustrated in figure 6. Similar scenario can be observed from figure 4 and 5 (a) to (b) when the peak amplitude of horizontal spectra from every sensor raised at almost synchronize crest from both frequency modes.

However, the building was expected to experience torsional mode after reached 5.63 to 5.85 Hz when the sensors entering to damaged zones bays. At this mode of frequency, inverse pattern of peak horizontal spectral curves in the NS direction have been altered by some sensors significantly based on measurements taken from the upper and first floors (see figure 4 (a)). Damages seen could have been triggered by the neighbouring wing attached to it without separation thus not allowing for independent structural movements. Defects are visible along the last six bays from column 20 onwards.
The structural damages dominated on the East wing allowing additional deformation amplitude on the upper floor to experience twisting at these bays but vice versa to free damage bays. The twisted amplitude of the mid sensor has been reducing when reach to lower floor (see figure 6), however at position of S2, the amplitude maintained to be the highest among all sensors. It is clearly shown from the altered configuration due to structural defects concentrated only in the East wing of this building, uneven deformation mode (torsional) could be easily distinguished from the horizontal spectral curve of ambient vibration measurements carried out. A point of worth noting is most standard schools in Malaysia are mostly regular in plan and elevation, but absence of expansion joints or malfunction expansion joints has been seen to induce undesirable strain and movement, and lead to structural damage especially in seismicity region. It is desirable to use seismic separation or expansion joint in order to divide the buildings into independent parts which may provide a regular seismic behaviour [16].

Figure 4. (a) FAS curves at column 1, 10 and 20 on the upper floor from the NS direction, (b) FAS curves at column 1, 10 and 20 on the first floor from the NS direction, (c) and (d) HVSR curves on the South part of the school (FI 461)
Figure 5. (a) FAS curves at column 1, 10 and 20 on the upper floor from the EW direction, (b) FAS curves at column 1, 10 and 20 on the first floor from the EW direction, (c) and (d) HVSR curves on the North part of the school (FI 469).

The absence of similar frequency ranges and curve patterns from S1 on floors L2 and L1 in the West wing further supported the possibility of an occurrence of soil-structure resonance and suppression of independent responses. Soil-structure resonance can exacerbate response of a structure when the fundamental frequency of the structure coincides with the predominant frequency of ground on which the structure is founded [17]. From the measurements taken on the ground, multiple peaks in the HVSR curves are seen in figure 4 & 5 (c) and (d). From the result, the lowest natural frequencies found at 1.42 Hz in, followed by 2.58 to 3.22 Hz and 4.85 Hz above. Both FAS peaks in the NS direction and the single peak in the EW direction are close to the main peaks of the site’s HVSR curves triggering a potential resonance. The extent of structural and non-structural damages to the first floor could have been result of a site-structure resonance effect. A similar observation was described by [14] where
damage was mainly concentrated at the first floor level of the structure level and there was an evidence of soil-structure resonance.

Besides, several impedance sub-soil layers were existed which are considered significant due to multiple-peaks of HVSR curve [18,19]. Similar finding was found by [20] by indicating three major layer of velocity representing three types of geomaterials with possible different characteristics from seismic refraction survey conducted along the same line on the demolished site.

![FAS Method](image)

**Figure 6.** FAS curves in the NS and EW directions at column 10 from respective floors

4. Conclusions

Microtremor assessment conducted in SMK Kundasang on its 3-storey existing reinforced concrete building and site has led to the prediction of 2.99 to 3.10 Hz (1st mode) and 4.85 Hz (2nd mode) as the predominant natural frequencies in the transverse and 5.63 to 5.85 Hz (3rd mode) in the longitudinal directions of the building. Observation of two modes of building frequencies made on the transverse FAS curves with the latter being attributed to the torsional mode induced by serious structural damage only on the East wing causing non-uniform displacements despite the building being regular and symmetrical in shape. There is only a slight difference between the predominant and fundamental frequencies of the building and ground. In this case, the resonance effect could be one of the main reasons contributed to structural damage induced by previous earthquakes event. Although no microtremor data are available prior to the reported damage, physical evidence of structural failures on the first floor level seems to support the occurrence of soil-structure resonance.

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