Identification of Natural Frequency of Low Rise Building on Soft Ground Profile using Ambient Vibration Method

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Abstract. Natural frequency is the rate at which a body to vibrate or oscillate. Application of ambient vibration (AV) excitation is widely used nowadays as the input motion for building predominant frequency, f₀, and ground fundamental frequency, F₀, prediction due to simple, fast, non-destructive, simple handling operation and reliable result. However, it must be emphasized and caution to isolate these frequencies (f₀ and F₀) from spurious frequencies of site-structure effects especially to low rise building on soft ground deposit. In this study, identification of f₀ and F₀ by using AV measurements were performed on ground and 4-storey primary school reinforced concrete (RC) building at Sekolah Kebangsaan (SK) Sg. Tongkang, Rengit, Johor using 1 Hz of tri-axial seismometer sensor. Overlapping spectra between Fourier Amplitude Spectra (FAS) from and Horizontal to Vertical Spectra Ratio (HVSR) were used to distinguish respective frequencies of building and ground natural frequencies. Three dominant frequencies were identified from the FAS curves at 1.91 Hz, 1.98 Hz and 2.79 Hz in longitudinal (East West-EW), transverse (North South-NS) and vertical (UD) directions. It is expected the building has deformed in translational mode based on the first peak frequency by respective NS and EW components of FAS spectrum. Vertical frequency identified from the horizontal spectrums, might induces to the potential of rocking effect experienced by the school building. Meanwhile, single peak HVSR spectrum at low ground fundamental frequency concentrated at 0.93 Hz indicates to the existence deep contrast of soft deposit. Strong interaction between ground and building at similar frequency (0.93 Hz) observed from the FAS curves on the highest floor has shown the building to behave as a dependent unit against ground response as one rigid mass.

1. Introduction

Dynamic characteristic parameters of ground and building such as natural frequency can be used as an effective indication tool to investigate local soil condition, site-structure effect and building configuration deficiencies. Ambient vibration is one of the most popular techniques to predict the natural frequency of a building or ground. Ambient vibration can be described by all natural and
artificial sources of noise generated near to the surface of the earth in the vicinity of the recording instrument [1]. Ambient vibration measurement may provide stable result with long time span, and this technique can be used to identify possible areas or structures that may be damaged in future by earthquake or monitoring a structure’s state of health through time [2]. AV investigation is 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. [3,4,5,6].

Geophysical testing can deliver results of significant quality, but care is needed against their limitations with physical soundings and understanding with proper calibration and validation methods to be archived [7]. Other challenges must be tackled wisely from ambient vibration methodology such as compatibility of the equipment and recording parameters, influence of current environmental conditions, interference of natural and artificial noise disturbance, methods on data processing as well as reliability and interpretation of the findings. Since ambient vibrations composed by various sources of seismic noise wave field from nature and human activities, the origin natural frequency of an investigated structure can be disrupted. Thus, careful data processing must be conducted.

In this paper, ambient vibration fieldwork has been performed to determine the natural frequency of ground and four storey reinforced concrete building at SK Sg. Tongkang. The ambient vibration signals were recorded by using tri-axial seismometer sensors. The recorded AV signals on building from North-South (NS), East-West (EW) and Vertical (UD) components were divided into several windows. These windows were filtered against significant noise intrusion, before converting them into frequency domain spectrum by using Fast Fourier Transform (FFT) method. Respective FFT spectrums were averaged to form the mean Fourier Amplitude Spectra (FAS). Clear peaks from FAS curve were identified for consideration of predominant building frequencies, $f_0$. Transformation procedure of ground AV signals was also applied to form $FAS_{NS}$, $FAS_{EW}$ and $FAS_{UD}$. These FAS spectrums were then computed into quadratic average ratio between the horizontal FAS components to the vertical FAS component which has been popularized by [8] that known as Horizontal to Vertical Spectral Ratio (HVSR) method. Clear and significant peak from HVSR curves were evaluated to represent the ground fundamental frequencies, $F_0$. These computational protocols of FAS and HVSR methods were performed automatically by employing the open source software of GEOPSY (Geophysical Signal Database for Noise Array Processing) [9]. Finally, to distinguish the origin peak frequency of ground and building against any spurious or dominated peak frequencies which could be participated from the intrusion of ground response or apparent of vibrations from nature or artificial sources, overlapping protocol between $FAS_{NS}$, $FAS_{EW}$ and $FAS_{UD}$ (building) and HVSR (ground) curves were carried out.

2. Methodology

SK Sg. Tongkang is a public school which offers for preschool and primary educations. The design and build works of this school was managed by Public Works Department Malaysia (JKR). A new 4-storey building was constructed in 2010 based on conventional concrete design method of moment resisting frame with non-load bearing wall system of clay brick. The standard building configurations of this school building are, 3.6 meters storey height, 3 meters spacing between bays, 7.5 meter building width and 2.1 meters length of cantilever corridor with 1.05 meters height of parapet wall. The school was constructed on very soft ground profile based on 30 meters depth reference, at standard penetration test blow count only reached SPT ‘N’ ≤ 6 extracted from two borelog record done by IKRAM group [10]. Figure 2 and 3 show the investigated building and site for identification of natural frequency.

Ambient vibration instruments consist of three units Lennartz portable tri-axial seismometer of 1 Hz eigenfrequency sensors (S) with 400 V/m/s output voltage, CityShark II data logger up to 3 stations, and 1 GB memory flash card data storage (see figure 1). Three seismometers were placed, levelled and aligned to the magnetic North direction which parallel to the transverse axis of the investigated building. The sensors were connected by geophone reinforced cable to the data logger. The data logger is operated under 12 volts of direct current. All ambient vibration signals from three
major components of NS, EW and UD were stored into the flash card and manually transferred to the notebook.

Two lines of B and C for ground ambient vibration measurements were positioned in-front and at the rear of building as given in figure 2. The number measurements involved in every line is tabulated in table 1. Meanwhile, four ambient vibration measurements were conducted on the upper floor (3rd floor). All sensors were arranged and positioned along the corridor that closer to the main frame joint. The arrangement of sensor positions and number measurements involved for building were illustrated in figure 3 and itemized in table 2.

![Figure 1. Ambient vibration instruments](image1)

![Figure 2. SK Sg. Tongkang site, (a) layout plan and position of sensors on ground surface and, (b) photographs during the ambient vibration testing.](image2)

| Measurement lines | File Index No. | Sensor 1 (S1), Ref. Point | Sensor 2 (S2), Ref. Point | Sensor 3 (S3), Ref. Point |
|-------------------|----------------|--------------------------|--------------------------|--------------------------|
| Line B            | 398            | In line to C9 (~24 m from S1’) | Close to C18 (~27 m from S1’) |
| Line B            | 399            | In line to C9 (~15 m from S1”) | Close to C13 (~15 m from S1”) |
| Line C            | 401            | In line to C9 (~24 m from S1’) | Close to C18 (~27 m from S1’) |
| Line C            | 402            | In line to C9 (~15 m from S1”) | Close to C13 (~15 m from S1”) |
A 15 sec of windowing process was applied to every ambient vibration wave field in GEOPSY. Each window is processed by automated anti-triggering function. A cosine taper of 5% has been applied on both sides of each window. Another parameter of Konno and Ohmachi smoothing constant at bandwidth of 40 was used. From these main parameters, the spectral amplitude through FFT analysis was computed for every window at each NS, EW and UD components to generate respective mean FAS curves. Similar parameters were applied for HVSR computational protocols. The maximum peak amplitude from the mean spectrum of FAS and HVSR was automatically identified by GEOPSY.
Finally, these FAS and HVSR curves were overlapped to distinguish the respective frequency of ground and building.

3. Results and Discussions

FAS\textsubscript{NS}, FAS\textsubscript{EW} and FAS\textsubscript{UD} computed from ambient vibration records on building were given in figure 4 (a) & (b) and figure 5 (a) & (b). Multiple peaks of 0.96 Hz, 1.98 Hz and 2.79 Hz were identified from the FAS\textsubscript{NS} mean curves, couple peaks at 0.96 Hz and 1.91 Hz from FAS\textsubscript{EW} mean curves and only a single peak of 2.79 Hz found from FAS\textsubscript{UD} mean curves. Meanwhile, a single sharp peak of HVSR mean curves was obtained at 0.93 Hz from both measurement lines of B and C as shown in figure 4 (c) & (d) and figure 5 (c) & (d).

Identification of predominant building frequencies distinguished from overlapping protocol has successfully distinguished the origin of spurious first peak frequency at 0.96 Hz. It was clearly observed from figure 4 (a) and figure 5 (a), the first peak frequency depicted from FAS curves in NS and EW directions have been contaminated by the ground vibration response at identical peak frequency as given by both HVSR curves in figure 4 (c) & (d) and figure 5 (c) & (d). At this frequency, it was believed the building has response dependently to the ground vibration which then behaves as one rigid mass. Strong ground amplification may contaminate the building responses and causes inaccurate estimation on the building natural frequencies [11,12]. The amplification is become higher when the ground is grouped under softer classification that usually shows at low frequency. Strong effect of ground borne vibration includes movement of the building floors, shaking of items, rattling of windows or even a rumbling floor [13]. It was obviously felt strong vibration in vertical direction on the upper floor by the equipment operator during the AV testing immediately after heavy vehicles came and passing through the state road, which located only about 150 meters away from the building. Data logger occasionally triggered by the alerts buzzer system due to saturated ambient vibration signal when high gain value implied. This problem has been fixed with appropriate gain level to avoid signal saturation, as saturation does affect the Fourier spectrum. By eliminating this peak, the first and second modes of building natural frequency were found between 1.84 Hz to 2.27 Hz (see table 3), followed by the subsequence modes at 2.79 Hz to 2.88 Hz dominated by the UD component.

Subsequent peak frequencies from the NS (1.98 Hz) and EW (1.91 Hz) directions were very close (see figure 4 (a) and figure 5 (a)) due to translation mode. Previous study carried out by [14] at SK Sri Molek Batu Pahat with typical building configuration but slightly long up to 60 meter length, shows at significant differences of building frequencies between 4.20 Hz and 4.35 Hz at the first and second modes. Its ground fundamental frequencies have indicated between 2.69 Hz to 3.20 Hz which classified under dense soil group. Comparison made between FAS and HVSR findings of both schools has concluded, even though the building configuration and number of stories are almost comparable, the evaluation of the first mode frequency have been differed more than twice. The existence of open hall (TRG 8) and unfilled wall at canteen (TKP 9) on the ground floor and first floor of SK Sg. Tongkang, could influence this big gap of frequencies differences. From the general relationship of \( f_0 = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \), the relationship of lighter mass (M) and lower stiffness (K) will reduce the natural frequencies (natural period, \( T_0 \) is inversed to natural frequency) and vice versa.

Friction pile foundation system was used in SK Sg. Tongkang building construction to sustain the building mass on the soft ground based on justification made according to the borehole record which was terminated at 45 meters depth at only SPT'N' < 19. The standard procedures over simplifying the ground where the type of foundation as well as interaction between the soil and the structure is not taken into account as well as the structure is normally considered as fixed base at the ground level [15]. According to [16], if the ground supporting a building is not stiff, this can represents sway and rocking motions of the foundation. In addition, corresponding peak vertical frequency appearance from horizontal spectrum has been reported by [17], can be interpreted as the frequency of rocking mode. Due to the above features and indicators, the ground-structure interaction has been expected presence from the significant peak frequency appearance at 2.79 Hz from FAS\textsubscript{NS} curves observed, corresponded from peak frequency of FAS\textsubscript{UD} which has allowed the building to vibrate in rocking mode. When comparison has been made to conventional fixed base foundation
Figure 4. (a) NS direction: FAS curves at 3rd floor, (b) UD direction: FAS curves at 3rd floor, (c) HVSR curves at lines B/S3-S1-S2 and (d) HVSR curves at lines C/S3-S1-S2.

Figure 5. (a) EW direction: FAS curves at 3rd floor, (b) UD direction: FAS curves at 3rd floor, (c) HVSR curves at lines B/S3-S1-S2 and (d) HVSR curves at lines C/S3-S1-S2.
soft clay group with sediment thickness more than 12 meters. Their ground classifications tables can be referred from [20].

**Table 3.** Peak frequencies from three main components of SK Sg. Tongkang from FAS curves.

| Column No. | NS direction, $f_o$ | EW direction, $f_o$ | UD direction, $f_o$ |
|------------|----------------------|----------------------|----------------------|
|            | First Peak (Hz)      | Second Peak (Hz)     | Third Peak (Hz)      | First Peak (Hz) | Second Peak (Hz) | First Peak (Hz) | Second Peak (Hz) |
| C1         | 2.27                 | -                    | 1.91                 | 2.19            | 2.88             | -                |
| C3         | 1.98                 | -                    | -                    | 1.91            | 2.98             | -                |
| C5         | 1.98                 | 2.60                 | -                    | 1.98            | -                | 2.79             |
| C7         | 1.84                 | 2.60                 | -                    | 1.98            | 2.79             | -                |
| C9         | 1.91                 | 2.69                 | -                    | 1.91            | 2.79             | -                |
| C9         | 2.05                 | 2.43                 | -                    | 1.91            | -                | 2.79             |
| C9         | 1.91                 | 2.69                 | -                    | 1.98            | 2.79             | 3.92             |
| Avg C9     | 1.98                 | 2.69                 | -                    | 1.98            | 2.79             | -                |
| C11        | 1.91                 | 2.60                 | -                    | 1.98            | -                | 2.79             |
| C13        | 2.05                 | 2.43                 | -                    | 1.98            | -                | 2.79             |
| C15        | 1.98                 | -                    | 1.91                 | -               | 2.79             | -                |
| C18        | 2.19                 | 2.69                 | 3.31                 | 1.91            | -                | 2.69             | 3.67             |
| Overall ranges | 1.84 to 2.43 to 3.31 | 1.91 to 2.19 | 2.79 to 3.67 |
| Mean all   | 1.98                 | -                    | 1.91                 | -               | 2.79             | -                |

**Table 4.** Ground fundamental frequencies of SK Sg. Tongkang from HVSR curves

| File Index No. And Measurement Points | HVSR, $F_o$, First Peak (Hz) |
|---------------------------------------|-------------------------------|
| 399 S3"B                              | 0.93                          |
| 398 S3'B                              | 0.93                          |
| 398 S1'B                              | 0.93                          |
| 399 S1"B                              | 0.93                          |
| 398 S2'B                              | 0.93                          |
| 399 S2"B                              | 0.93                          |
| 402 S3"C                              | 0.93                          |
| 401 S3'C                              | 0.93                          |
| 401 S1'C                              | 0.93                          |
| 402 S1"C                              | 0.90                          |
| 401 S2'C                              | 0.93                          |
| 402 S2"C                              | 0.93                          |
| Mean line B                            | 0.93                          |
| Mean line C                            | 0.93                          |

4. Conclusions

A simple overlapping technique between FAS and HVSR curves based on ambient vibration records measured by seismometer sensors has been successfully identified the predominant frequencies of 4-storey building of SK Sg. Tongkang and its fundamental frequencies of soft ground. The first peak frequency of HVSR curves clearly observed in the FAS curves has been influenced by strong ground vibrations that induced the building as dependent unit against the ground response as one rigid mass.
Subsequent modal frequencies extracted from the mean FAS curves representing the dominant movements of translational and rocking modes along longitudinal-transverse and vertical axes. Consideration of ground conditions and their interaction could be one of the main reasons might that contribute to the dissimilarity of the $f_o$ prediction against pervious study at SK Sri Molek done by [14] even with typical building configuration but different foundation system compared to SK Sg Tongkang.

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