Weak Zone Determination Inside The Tunnel Using H/V Ratio Method

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Abstract. Tunnel is a vital structure in transportation as it shortens the distance between places through underground. Nevertheless, since it goes via underground, there are several risks might occur, such as tunnel collapse. This occasion will result in plenty of casualties. Therefore, as the preventive attempt, there should be a particular method to determine that the tunnel is strong enough. One of the methods that may work for this case is microtremor and one of the most common method in microtremor is H/V ratio. H/V ratio is able to describe a natural frequency of a place or a structure. By using the natural frequency, the stability of the tunnel can be determined. To test out the method, a measurement is conducted in a tunnel at Institut Teknologi Bandung. This tunnel connects the main campus and the campus sports ground. It also lies under the main road which has a lot of traffics at all time. The measurement is done on the wall side of the tunnel, while the space between measurement station is 6 meters and the station cover the whole tunnel wall side. After measuring the tremor in every station, the tremor data will be processed with Geopsy software and the natural frequency of the tunnel will be acquired. Subsequently, the natural frequency of the entire tunnel will be plotted and the result from this plotting can be used to determine the weak zone of the tunnel.

1. Introduction
Tunnel is a very vital structure. In Indonesia, there is a lot of tunnel that is fully operational on the road and on railways. Some of these tunnels have already existed for so long ever since colonial age. Obviously, those aged tunnels might have some issues in their structure especially their strength. So to find out if the tunnel is strong enough to operate, it needs to be checked with a certain method. One of the method that could work for this case is microtremor method. Microtremor method utilize seismic noise to get dynamic properties of a ground or a structure.

Now, microtremor itself has many methods with different acquisition technique and processing procedure. One of the most common used microtremor method is H/V Spectral Ratio (HVSR). This method is first used by Nogoshi and Igarashi (1971) [1] and popularized by Nakamura (1989) [2]. This method is used to get natural frequency of a place by using the ratio horizontal-to-vertical ratio of the microtremor data. Throughout the years, this method has been used by many researches and it is proven to be reliable. This method’s application is usually for site characterization and microzonation. Also, this method is used to find out the vulnerability of a building. Some researchers who did this research are Nakamura (1997) who studied the correlation between K index and damage done to the building after earthquake occurred [3], Mokhberi (2015) who studied disaster factor of a building and its correlation with building material and age [4], and Triwulan et al. (2010) who studied natural frequency and damping ratio of a building to determine its strength [5] and they prove that this method
can give an expected results. But, those researches only study the vulnerability of storied buildings on the ground, while the object of this study is a tunnel which is under the ground. Nevertheless, it is something worthy to be studied.

2. Data Acquisition
This study is done in a tunnel placed in Institut Teknologi Bandung, West Java, Indonesia. This tunnel connects the main campus and the campus sports ground. This tunnel also lies under the main road which has a lot of traffic at all time. The microtremor data is taken in every station for 30 minutes. The station is placed on the wall side of the tunnel with the distance between station 6 meters. Figure 1 will show the arrangement of acquisition stations.

Then, the acquired data is processed with Nakamura method (Nakamura 1997) [3] or what commonly called as HVSR method. This method basically makes ratio between the Fourier transform of horizontal component and Fourier transform of vertical component. The output of this ratio is a new curve that is called HVSR curve. This curve tells the natural frequency and amplitude factor of the measuring station. The formula for the HVSR method is written in Equation (1).

\[
HVSR = \frac{H(\omega)}{V(\omega)} = \left(\frac{NS(\omega)^2 + WE(\omega)^2}{Z(\omega)}\right)^{1/2}
\]

(1)

By applying this method, HVSR curve will be acquired. However, there are some requirements to be fulfilled for a HVSR curve to be considered reliable. Table 1 will show the requirement for a HVSR curve to be considered as a reliable curve. From the reliable curve, the Natural frequency and Amplitude can be extracted.

![Figure 1. Locations of acquisition station (coordinate of the stations is projected on the ground).](image-url)
Nakamura in 1997 [3] proposed a formula to determine a vulnerability of building or structure. This study is already proven by making a calculation of K index of embankment, viaduct, and train rail and compared it with damage done to the structure after the earthquake. It turned out that the bigger the bigger the K index of a structure, the bigger damage it will take after an earthquake occurs. Using Nakamura theory on K index, it is then applied to the subject tunnel to find out which part of the tunnel that will be less vulnerable and which is not. The K index that Nakamura proposed can be calculated with Equation (2).

$$K_b = \frac{(A_b)^2}{F_b}$$

(2)

$K_b$ represents the vulnerability of the tunnel, while $A_b$ and $F_b$ represents Amplification factor of the tunnel and Natural Frequency of the tunnel consecutively.

Lastly, the K index of every acquisition station will be plotted to see the whole K index of the entire tunnel.

**Table 1.** Requirement for reliable HVSR curve set by SESAME (Site EffectS assessment using AMbient Excitation)

| Requirement                      | Details |
|----------------------------------|---------|
| $f_0 > 10/l_w$                   | $f_0$ - HVSR Peak frequency |
| $n_c (f_0) > 200$                | $l_w = $ Window length      |
| $\sigma A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5$ | $n_w = $ number of windows |
| $\sigma A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5$ | $n_c (f_0) = n_w \cdot l_w \cdot f_0 = $ number of significant cycles |
| $\sigma A(f)$                    | $\text{Amplitude standard deviation}$ |

### 3. Results and Discussion

From the data processing, there are three contour maps that are acquired. Those contour maps are natural frequency contour map, maximum amplitude contour map, and K index contour map. With the help of this contour map, the three parameters that were mentioned can be seen on the entire tunnel. In Figure 2.a, the contour map of entire tunnel natural frequency distribution, there several highlighted points that can be seen. Most of of the acquisition station has natural frequency of 0.94 to 1.03, but on several acquisition station, such as station 9, 10, 11, and 12, they have a high natural frequency. Those stations has natural frequency of 1.2295 Hz, 1.21023 Hz, 1.15366 Hz, 1.26053 Hz, consecutively. The station that has the highest natural frequency is station 12. High natural frequency is usually related to high velocity basement. Which means the higher the natural frequency of a spot, the stronger the basement of that place. Also, it can also be interpreted as depth difference of the basement. But, High natural frequency can also be interpreted as something else, such as high velocity anomaly under the surface. Also, it can also be interpreted as depth difference of the basement.

Next, there is the contour map of maximum amplitude of the entire tunnel as seen on Figure 2.b. In this map, it is a little bit different than the previous contour map in Figure 2.a. In this map, the highlighted points, which are the station 9, 10, 11, and 12, instead of showing high number, they show the minimum number. Most of the stations have maximum amplitude of over 2. On the other hand, station number 8, 9, 10, 11, 12 have the maximum amplitude of 1.151157, 1.43545, 1.68192, 1.6861, and 1.62166, consecutively. The maximum amplitude is usually related to amplification factor of seismic wave. A place with high amplitude will have a higher amplification factor which results a bigger damage when an earthquake happens. So, the smaller the maximum amplitude is, the less it
amplifies the seismic wave. So, it is okay to say that those stations with low amplitude is the strong part of the tunnel.

Lastly, there is the K index contour map as shown on Figure 2.c. This map shows a parallel results as the maximum amplitude map. Station 8, 9, 10, 11, 12 show a low K index number. The K index in those stations are 1.414108446, 1.675898091, 2.337452291, 2.464273018, 2.086250352, consecutively. The rest of the stations show a different range of K index number, which varies between 3-6. According to Nakamura (1997) [3], the bigger the K index, the the more vulnerable a place is and vice versa. So, from the map the station which has low K index is a stronger part of the tunnel because it less vulnerable to earthquake. This results is parallel with the result of natural frequency and the maximum amplitude. Still this results is bit different from the early hypothesis. For a tunnel that is underneath a main road, it is reasonable that the part which right below the road is the one which has high K index. But it is not case.
Figure 2. (a) Natural frequency contour map of the tunnel. (b) Maximum Amplitude contour map of the tunnel. (c) K index contour map of the tunnel.
The only explanation for the low K index of this tunnel is that tunnel was reinforced in that part. For a tunnel, it is important to design a tunnel in such a way that it will not collapse in the future. One thing that can be done to make sure the tunnel will not collapse is to build the tunnel stronger on parts that receive bigger stress. This is what is done in the tested tunnel in this study. The stronger part of the tunnel that is determined from the K index, it turns out to be underneath the main road. If the K index map is overlaid with the map from satellite, it will show that road and the low K index area are on the same place (Figure 3). The main road might cause big stress to tunnel because of the burden of the traffic that goes through that road. But, it still needs confirmation.

![Figure 3. Overlaid map of K index contour map and Image from satellite](image)

4. Conclusion
As expected, using the H/V ratio is effective to find the weak zone, or in this case the strong zone, by applying K index. As the result shows that there is a stronger part of the tunnel which happens to be underneath the main road. It seems probably the strong part of the tunnel was made deliberately to handle the stress from the road above it. This study also gives a possibility of applying microtremor in construction monitoring as it is also low in price. However, this method can also be developed even more. For example, the reduction of natural frequency of a structure over time.
References
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