

Case examples of vibration measurement and annoyance response in residential buildings beside roads and railways

Yasunao MATSUMOTO¹; Shigenori YOKOSHIMA²; Kentaro HAYASHI³

¹ Saitama University, Japan

² Kanagawa Environmental Research Center, Japan

³ Benec Vibration and Sound Institute Inc., Japan

ABSTRACT

Vibrations induced by road traffic and railways have caused regional environmental problems in Japan where it is common that small-scale buildings for residential use are located beside roads and railways with high traffic volume. An investigation was conducted to understand the relationship between traffic-induced vibrations inside and outside of building and annoyance response of building residents. Vibration measurements were made at seven residential buildings located beside roads and railways. Those buildings were single-family houses, which were two- or three-story wooden buildings. Acceleration time histories were recorded at three locations inside and outside of buildings to understand the vibration occurring in those buildings and the dynamic characteristics of the buildings. The buildings for measurement were selected from the houses of respondents in a separate questionnaire survey on vibration annoyance. The annoyance responses obtained in the questionnaire survey were compared with the results of vibration measurements and metrics available in the international standards. Subjective responses measured in a separate laboratory experimental study were also compared with the vibration evaluation determined from vibration measurements and the annoyance responses in the questionnaire survey.

Keywords: Building vibration, Traffic induced vibration, Vibration assessment, Case examples

1. INTRODUCTION

Vibrations induced by road traffic and railways often degrade the habitability of surrounding buildings. The Vibration Regulation Law was enforced in 1976 in Japan. Road traffic vibration is one of the targets of regulation, although railway vibration is out of scope of the law for several reasons. According to an annual report by the Ministry of the Environment, Japan, number of complaints against vibration in residential environment showed an increasing trend in recent years (1). In addition, there were many cases in which the assessment based on the law was inconsistent with adverse comments on vibration raised from building occupant. The problems in the vibration regulation may include the fact that the regulation is applied to vibrations outside of building, which can differ from vibrations in buildings.

The previous studies of community responses to vibration have been much less than the studies of community responses to noise. Therefore, a questionnaire survey on vibration annoyance and associated field vibration measurements were conducted in areas where the effect of vibrations induced by road traffic and railway could be expected (2). During the survey, vibration measurements inside of several residential buildings, from which responses to the questionnaire survey were received, were conducted to accumulate the information about the dynamic characteristics of residential buildings and the relationship between vibration exposure and annoyance response in residential buildings. This paper presents the results of those measurement as case examples of vibration measurement and annoyance response in residential buildings beside roads and railways. In addition, the results of field measurement of vibration and annoyance response were compared with the results of a laboratory experiment to understand possible

¹ ymatsu@mail.saitama-u.ac.jp

² yokoshima.7c7q@pref.kanagawa.jp

³ hayashi-k@benec-vsi.co.jp

difference between subjective responses determined in laboratory studies and subjective responses obtained from field measurements (3).

2. OVERVIEW OF FIELD MEASUREMENTS

The measurements of vibrations induced by road traffic and railways were conducted in seven residential buildings. All buildings were wooden single-family detached houses with two or three stories. The residents of those buildings gave permission for a measurement inside of the building during a questionnaire survey on traffic induced vibration and noise reported in the reference (2). Table 1 summarizes the information of residential buildings and sources of vibration. The table also shows the annoyance response given by the resident of each building in the questionnaire survey to a question to ask the degrees of annoyance caused by vibration induced by road traffic or railway in the last 12 months (2). The responses were given by selecting among from "Extremely", "Very", "Moderately", "Slightly" or "Not at all".

Table 1 – Summary of residential buildings

Building No.	Number of floors	Vibration source			Questionnaire Response (2)
		Type	Size	Approximate traffic volume	
1	2	Surface railway	8 tracks	980 trains/day	Extremely
2	2				Extremely
3	2	Elevated railway	4 tracks	600 trains/day	Moderately
4	2	Underground railway	2 tracks	N/A	Extremely
5	2	Surface and elevated roads	6 lanes (surface) and 4 lanes (elevated)	120000 vehicles/day	Extremely
6	2				Very
7	3	Surface road and railway	2 lanes	17000 vehicles/day 980 trains/day	Very

The measurements were conducted at location, time and day that the permission from residents were obtained. The duration of measurement at each building was about 1 hour for which the residents were asked to keep quiet environment and avoid activities in the building to a possible extent.

Three measurement locations were selected among from ground near the building, foundation, 1st floor and 2nd floor, depending on the permission from residents. The measurement on building floor was made at a location where the vibration magnitude was expected to be maximum in a room with wooden floor. The measurement on the ground was made on a hard surface covering the ground, such as on a concrete surface in garage.

The Vibration Level Meters, RION VM-53, were used to measure accelerations in three orthogonal axes with data recorders, either RION DA-20 or TEAC es8. Acceleration time histories were recorded at either 1000 samples/s or 1280 samples/s, depending on the available sampling rate in the data recorders. No frequency weightings were applied to the acceleration during the measurement.

3. RESULTS OF VIBRATION MEASUREMENTS

This section presents the results of vibration measurement in all buildings described above, except Buildings 5 and 7. In those two buildings, the vibration measurement was not possible at locations where the residents usually stayed and felt vibration during their daily life and, therefore, the comparison between the vibration measurement results and annoyance response discussed later may not be appropriate. The results of Building 1 are not shown in this paper due to limitations of space.

The data presented in this paper are the results of 1/3-octave band analysis. The maximum value

in each frequency band was determined during a pass-by of train for railway and a series of pass-bys of vehicle dependent on traffic signal pattern for road traffic that induced the maximum overall magnitude during the measurement. In the following figures, those maximum values in each frequency band are presented using the Vibration Acceleration Level, VAL, specified in JIS C 1510 and 1517 (4, 5). Root mean square, r.m.s., accelerations were calculated for each frequency band with the exponential averaging with a time constant of 0.63 s and converted to VAL in dB with a reference of 10^{-5} ms^{-2} , as opposed to 10^{-6} ms^{-2} defined in ISO 1683 (6). Differences in VAL between different measurement locations in a building are also presented in the following figures.

3.1 Building 2 - surface railway

Figure 1 shows a schematic diagram showing positional relation between the building and the nearest rail track and the measurement results for Building 2. The dominant frequency range of vibration transmitted to the building appeared to be 10 to 63 Hz. The vibration in Z-axis was dominant at the ground. The vibration decreased at the foundation in all axes in the frequency range above 20 Hz. However, the vibration in Z-axis increased at the building floor in the frequency range above 31.5 Hz, which was thought to be caused by vibration of building floor, as reported previously. In X- and Y-axes, the vibration increased at the 2nd floor at a frequency of 5 Hz. This increase might be caused by a horizontal vibration mode of building structure.

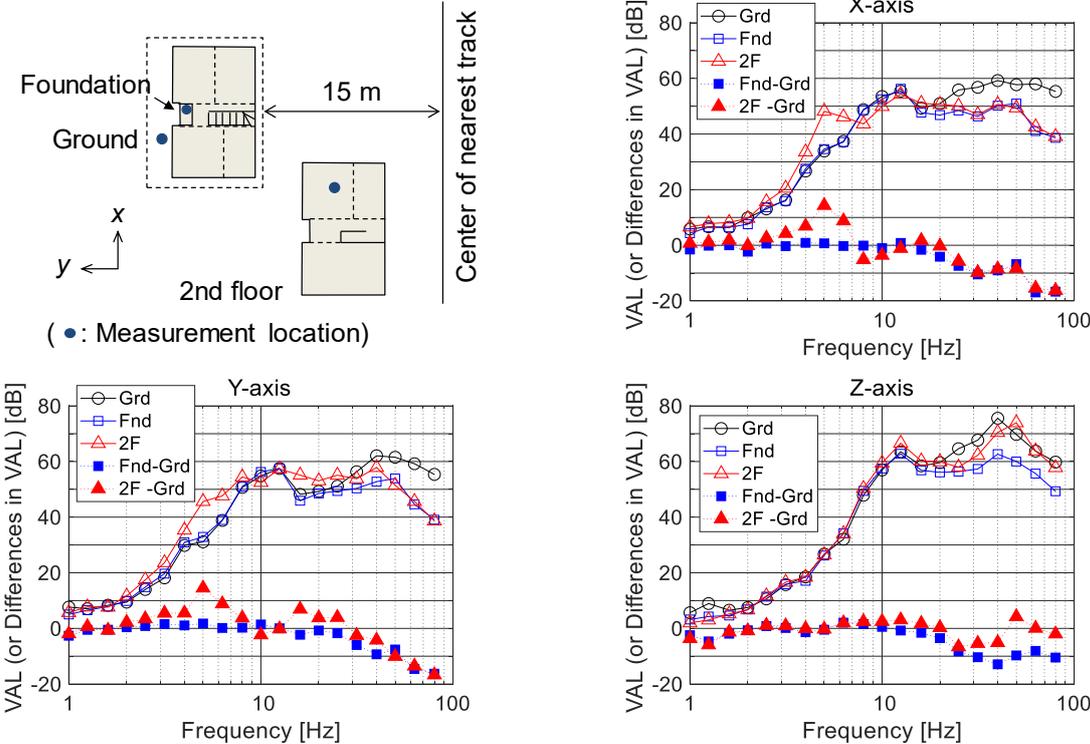


Figure 1 – Building 2. Surface railway. (Grd: ground. Fnd: foundation. 2F: 2nd floor. VAL ref. 10^{-5} ms^{-2} .)

3.2 Building 3 - elevated railway

Figures 2 shows the positional relation between the building and the nearest rail track and the measurement results for Building 3. The dominant frequency range of vibration transmitted to the building appeared to be between 40 and 50 Hz. Vibration magnitude at the ground were similar in three orthogonal axes, which was not observed for surface railway as shown in Figure 1. Although the vibration magnitude was relatively small, a peak can be observed at 3.15 Hz in the vibration at the ground in all directions, which may be caused by the dynamic characteristics of elevated structures. As in Building 2, increases in the vibration in Z-axis at a higher frequency range and increases in the vibrations in X- and Y-axes were observed, although the frequency range where those increases were observed are different in those two buildings.

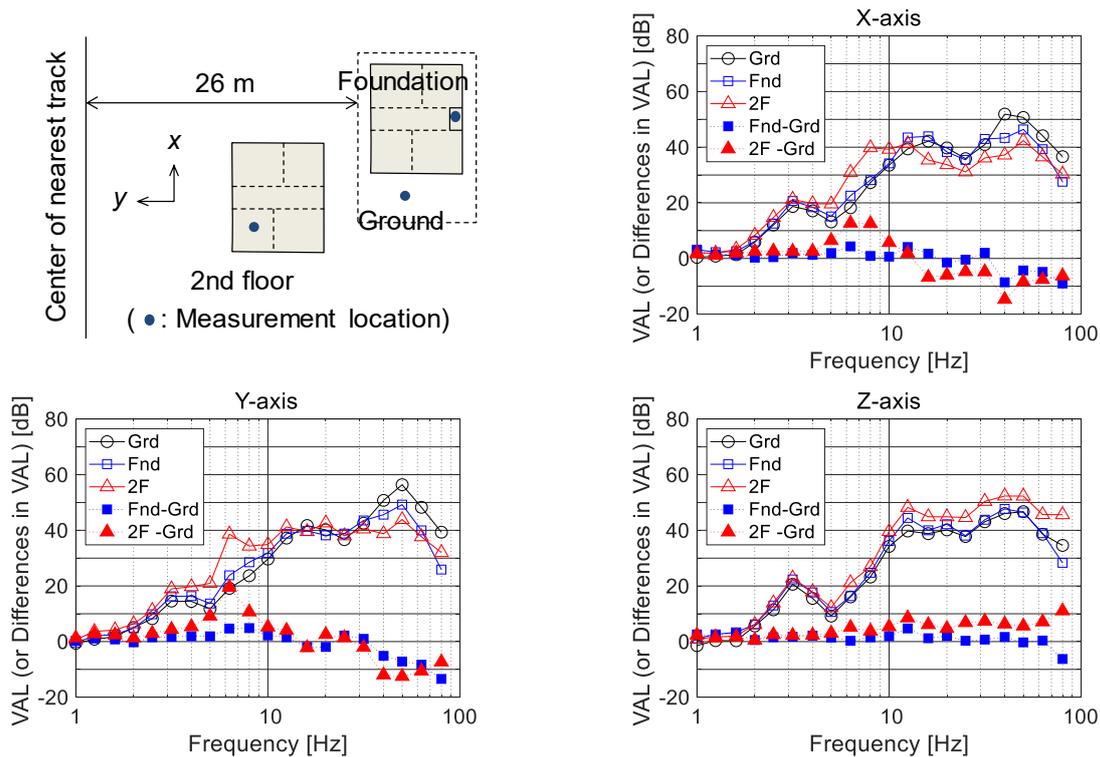


Figure 2 – Building 3. Elevated railway. (Grd: ground. Fnd: foundation. 2F: 2nd floor. VAL ref. 10^{-5} ms^{-2} .)

3.3 Building 4 - underground railway

Building 4 was located about 30 m away from an underground rail tracks mainly for freight trains, as shown in Figure 3. The measurement results presented in the figure imply that significant vertical vibration was transmitted to the building, particularly, in the frequency range above 31.5 Hz, although the measurement at the ground was not made for this building. In Z-axis, the vibrations in the building showed different characteristics for the 1st and 2nd floors, which may be due to differences in the dynamic properties of the floors. In this building, the amplification of horizontal vibrations occurred relatively wider frequency range, i.e., 3.15 to 8 Hz, than the other buildings.

3.4 Building 6 - surface and elevated roads

Building 6 was located about 30 m away from surface and elevated roads. The effect of elevated road on vibration along the road appeared to be minor because the traffic volume in the surface road was much higher than the traffic volume in the elevated road. Figure 4 shows the results of measurement. The dominant frequency range of vibration transmitted to the building appeared to be around 10 to 16 Hz. For horizontal vibrations, the vibrations measured at the 2nd floor tended to be greater than the vibrations at the foundation in the frequency range above 4 Hz in this building. In particular, the horizontal vibrations in the frequency range 5 to 6.3 Hz amplified by the building had a similar magnitude to the dominant frequency components of vertical vibration around 10 Hz. The vertical vibration increased at frequencies above 25 Hz at the 1st and 2nd floor, compared to the foundation, as observed in the other buildings.

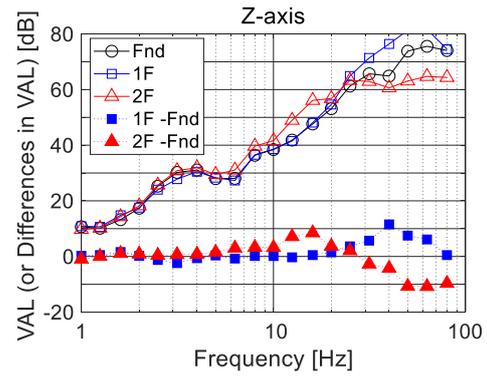
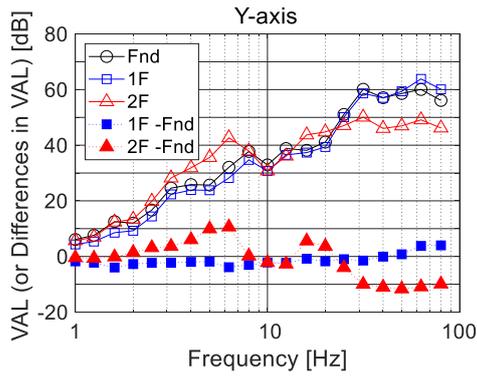
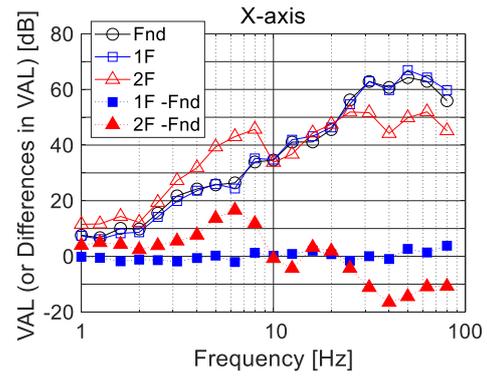
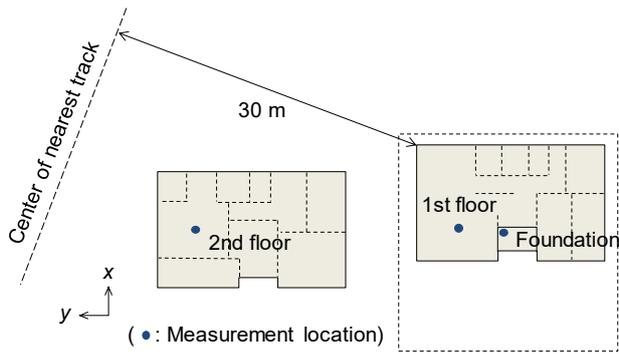


Figure 3 – Building 4. Underground railway.

(Fnd: foundation. 1F: 1st floor. 2F: 2nd floor. VAL ref. 10^{-5} ms^{-2} .)

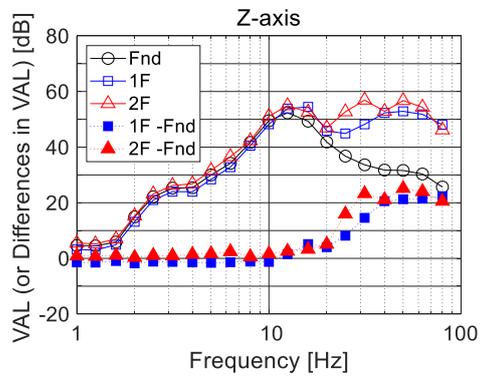
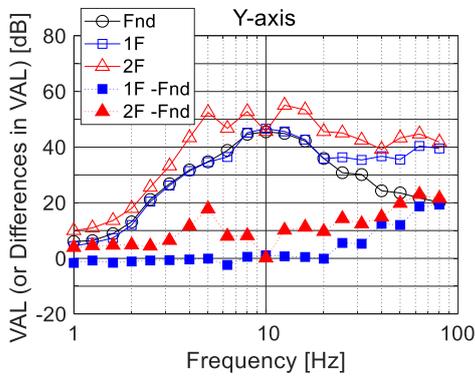
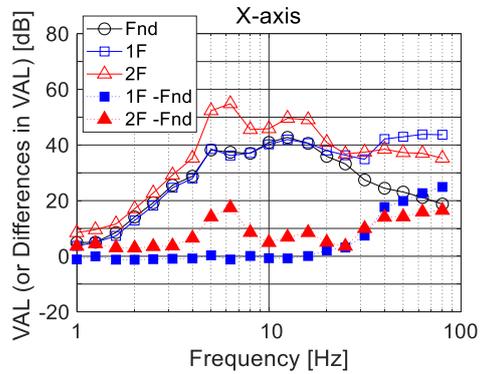
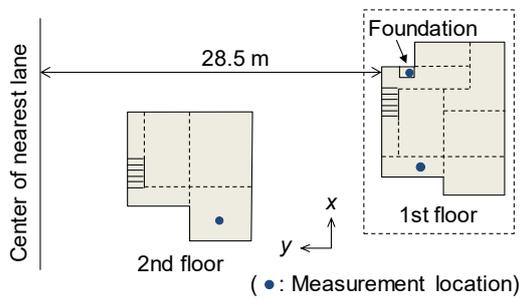


Figure 4 – Building 6. Surface and elevated road.

(Fnd: foundation. 1F: 1st floor. 2F: 2nd floor. VAL ref. 10^{-5} ms^{-2} .)

4. VIBRATION EVALUATION AND ANNOYANCE RESPONSE

4.1 Vibration evaluation and questionnaire response

Vibration evaluation was determined from the measured data based on ISO 2631-1 and -2 (7, 8). A previous experimental study in a laboratory showed that the Vibration Dose Value, VDV, was one of the best metrics to represent vibration discomfort (7). In this paper, therefore, VDV was used as a metric to evaluate vibration effect. A "single event VDV" was determined for each pass-by of train for railway vibration or each series of pass-bys of vehicle dependent on traffic signal pattern for road traffic vibration. The maximum single-event VDV for each building during the measurement is shown in Table 2. The values for Buildings 5 and 7 were not determined for the reason described above.

Table 2 shows the annoyance response given by the resident of each building in the questionnaire survey (2), which are already shown in Table 1. As observed in the table, the vibration in the building with higher degree of annoyance response tended to result in a greater single event VDV.

In addition, Table 2 shows the estimations of VDV for 24 hours on the ground at the positions of those buildings determined in the previous study based on the vibration measurements made outside of the building for several hours (2). The estimation of 24-hour VDV seems to be consistent with the annoyance response, except Building 5. The residents in Building 5 claimed that they were extremely annoyed by a couple of heavy trucks ran at a high speed in early mornings when the traffic volume was low. Their annoyance response may not be able to be evaluated by a metric based on vibration exposure only: there can be some combined effects from other factors, such as sleep disturbances and time of the day.

The single event VDV shows a similar trend to the estimation of 24-hour VDV, which implies that the VDV determined for a single event could be used to assess vibration environment to some extent. However, the single event VDV may have underestimated the vibration severity in Building 6 with a large road traffic volume, compared to Buildings 1 to 3 where the dominant vibration source was railway. The consideration of the effect of traffic volume, in other words, the duration and frequency of vibration exposure may improve vibration assessment, as expected.

Table 2 – Vibration evaluation and annoyance responses

Building No.	Vibration source	Single event VDV [ms ^{-1.75}]	Estimation of 24-hour VDV [ms ^{-1.75}] (2)	Questionnaire Response (2)
1	Railway	0.0499	0.0850	Extremely
2	Railway	0.0583	0.0925	Extremely
3	Railway	0.0106	0.0137	Moderately
4	Railway	0.0901	N/A	Extremely
5	Road traffic	N/A	0.0369	Extremely
6	Road traffic	0.0160	0.0656	Very
7	Road and Rail	N/A	N/A	Very

4.2 Comparison with laboratory experiment

The results of single event VDV were compared with the results in previous laboratory experiment in Figure 5 (3). In the previous experimental study, the evaluation of subjective responses to vibrations in detached houses caused by external vibration sources such as road traffic, railway and construction work was investigated in a laboratory experiment involving human subjects. The input stimuli in the experiment were generated from selected field vibration records for the duration shorter than 30 s, equivalent to a single event. Additionally, sinusoidal vibrations were used as input stimuli in the experiment. The subjective responses were measured by rating vibration discomfort in a living space with a 7-step scale from VII (not uncomfortable at all) to I (extremely uncomfortable). The responses determined from that ordinal scale were then converted to responses in an interval scale by the method of successive categories. In Figure 5, the results are shown in both interval and ordinal scales.

Figure 5 shows the comparison of the single event VDV determined for Buildings 2, 3 4 and 6 with the previous experimental results. Buildings 2 and 4, whose annoyance response were "extremely", had the single event VDV in the range of subjective scale in the experiment between III and V, and from II to IV, respectively. Building 3 with the annoyance response of "moderately" showed the single event VDV corresponding to the subjective scale of VII, i.e., "not uncomfortable at all". The single event VDV for Building 6 also in the same range, although the annoyance response was "very".

It is sometimes claimed that subjective responses measured in laboratories are severer than responses in real residential environments for several reasons. The comparison made in Figure 5 may not necessarily support such a view. It can be interpreted that, for the same VDV, the annoyance responses in questionnaire survey were severer than the discomfort responses measured in laboratory experiment. However, a direct comparison between the responses in laboratory and the responses in real residential environments was not appropriate in this investigation, partly because the response to single vibration event was not determined in real residential environments. The annoyance responses obtained from the building residents shown here were based on the evaluation of vibration annoyance in the last 12 months, which may have been affected not only by vibration magnitude but by the traffic volume, combined effect from noise, and so on.

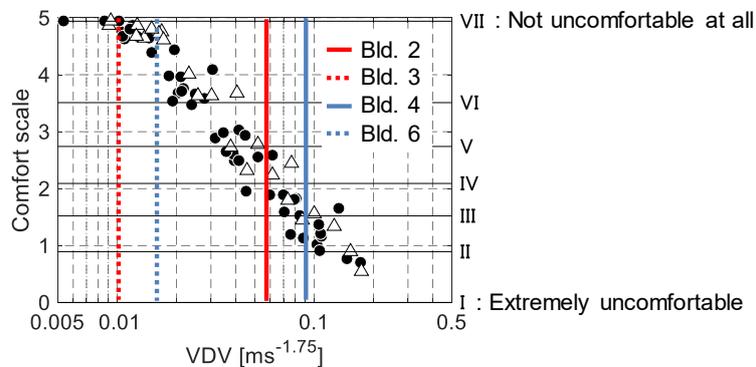


Figure 5 – Comparison of measurement with previous laboratory experiment results (3). ●: input stimuli from field records; △: sinusoidal vibration. (Annoyance response - Building 2: Extremely; Building 3: Moderately; Building 4: Extremely; Building 6: Very.)

5. CONCLUSIONS

The case examples of vibration measurement and annoyance response in detached single-family houses discussed in this paper may show actual situations of habitability in residential buildings located beside roads and railways in Japan. The vibration measurement results showed examples of the characteristics of traffic induced vibrations and the dynamic properties of residential detached buildings. The comparison between vibration measurements and annoyance responses implied that metrics of vibration assessment that considered the magnitude, duration and frequency of vibration events could be used to predict a subjective response in residential environment for a long term, such as for one year in the study referred to in this paper. The Vibration Dose Value determined from a single vibration event might represent a long-term response to some extent and be used for an initial survey. Subjective responses measured in the previous laboratory study showed some consistency with annoyance responses in residential environment.

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