Research Article

Vibration Measurement and Prediction for Foundation Slab Design of a High-Tech Lab Based on In Situ Testing

Zhaogang Xu,1,2 Yu Lou,1 and Liu Chen1

1Beijing Engineering Research Center of Micro-Vibration Environment Control, China Electronics Engineering Design Institute Co. Ltd., Beijing 100142, China
2School of Civil Engineering, Harbin Institute of Technology, Harbin 150001, China

Correspondence should be addressed to Zhaogang Xu; xuzg2009@126.com

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1. Introduction

Technological advances in nanotechnology and high-tech industry require an increase in the precision of high-tech equipment, i.e., scanning electron microscopes, lithography steppers, coordinate measuring machines. Such an increase in precision places a severe requirement on the stability of high-tech facilities in which precision equipment is housed because even the slightest vibrations can disturb the equipment operation [1]. Therefore, environmental vibrations induced by human activities should be controlled at low levels over long periods of time for high-tech facilities in which precision equipment is housed [2–4]. Among the human activities of interest (railway and road traffic, construction activities [5], operation of heavy machines [6]), road traffic has become a major malfunction factor for precision equipment in urban areas because the distances between the facilities and roads are decreasing due to space limitations [7].

An environmental vibration problem can be divided into three parts: the excitation source that generates vibrations, the medium that transmits the vibrations, and the receiver that must be protected from the vibrations [8, 9]. Accordingly, measures to reduce unwanted vibrations can be applied in the proximity of excitation sources, in the vibration propagation path, and at the buildings that should be protected. In general, vibration reduction measures applied around or at a close distance from the vibration sources are
defined as active measures, whereas those surrounding the buildings that are to be protected are defined as passive measures [7, 10, 11]. Literature review shows that active measures can significantly reduce the intensity of environmental vibrations and are more effective than passive measures, especially in reducing the magnitudes of low frequency vibrations [12–15]. However, due to cost problems and the uncertainty of vibration sources, passive measures are usually preferred to control unwanted vibrations at high-tech facilities [16].

Passive measures applied at a high-tech facility usually involve thickening the foundation slab, supporting the foundation slab with piles, or improving the subgrade soil. Based on a combined finite-element boundary-element method and a semianalytical method, Auersch [17] conducted a numerical study on the response of thin flexural plates resting on an elastic half-space to vibrations generated by harmonic excitation. Auersch concluded that slab thickness was the dominant parameter in controlling the vibration levels. Gao et al. [18] performed field measurement and finite-element prediction on a high-tech electronics workshop to study the reduction effect of a pile-raft foundation on floor vibrations. The results demonstrated that the pile-raft foundation averaged the gap between the floor vibrations and the VC-B curve, showing an overall positive reduction action on the floor vibrations. Sanayei et al. [19] verified an analytical prediction model of ground vibrations by performing vibration tests on a full-scale building with a slab-on-grade foundation. The vibration reduction effects of slabs with different thicknesses were investigated based on the prediction model. The conclusion showed that a thickened slab can be an effective measure for reducing external vibrations. Amick et al. [20] studied the vibration reduction efficiency of different slab types via vibration measurements and found that the piled-slab foundation performed better than the slab-on-grade foundation in reducing the vertical vibrations generated by external excitation sources. Persson et al. [8, 21] conducted a series of numerical studies on reducing building vibrations by subsoil improvement and found that improving the mechanical properties of the subgrade soil had a greater effect on controlling the vibration levels in a building for both external and internal vibration sources. Piles are more important in increasing the bearing capacity of soil, but the use of a large cement-soil bulk integrated with a concrete slab is important to attenuate vibrations that are generated by external and internal vibration sources [22].

An advantage of taking vibration reduction measures at a high-tech facility is that the essential construction space of the high-tech facility is to be fully used without the need for extra land. Particularly, thickening a foundation slab as an antivibration foundation is usually preferred for high-tech facilities [23]. Determination of the proper thickness of an antivibration foundation requires estimation of the ground vibration levels at the construction area and the surface vibration levels of the antivibration foundation. Due to the complexity of the transmission mechanisms of ground vibrations in soil and of vibrations between the subgrade soil and the foundation slab, in situ vibration measurement appears to be more reliable in determining the vibration transmission characteristics than analytical and numerical methods. However, literature that systematically demonstrates the design of antivibration foundation for high-tech facilities based on in situ vibration tests is scarce.

This paper focuses on the antivibration foundation design of a high-tech lab subjected to truck-induced vibrations. The vibration criterion was that the vertical vibration velocity at the surface of the antivibration foundation must not exceed 60 μm/s in the frequency range of 5–50 Hz. The road that the truck-induced vibrations come from is to be constructed simultaneously with the high-tech lab. The characteristics of such an antivibration foundation design are that the actual vibration source does not exist prior to the foundation design and the vibration criterion is stringent. To achieve the antivibration foundation design in an economical and reliable way, a general design process was proposed based on in situ vibration measurement and prediction. To obtain the vibration source response used in the antivibration foundation design, the truck-induced ground vibrations in the proximity of an existing road with the same design as the proposed road were measured at the construction site. Two antivibration foundation prototypes with different thicknesses were constructed at the site. To determine the corresponding vibration transmissibility, frequency sweep tests were conducted to measure the free-field ground vibrations and the surface vibrations of the foundation prototypes. Based on the vibration transmissibility and the vibration source response, the vibration velocities of the two foundation prototypes were predicted. The thickness of the actual antivibration foundation was determined by comparing the predicted velocities and the allowable vibration velocity. After construction of the high-tech lab and the road, the vibrations generated by the passage of a heavy truck on the road were measured to assess the performance of the actual antivibration foundation.

2. General Design Process

Because the vibration criterion required for high-tech facilities is more stringent than that normally required for civil engineering, analysis of the solutions used in similar facilities and their achieved performance is fundamental for a new design. China Electronics Engineering Design Institute Co. Ltd. has been specialized in providing solutions for the vibration control of high-tech facilities over the past six decades, such as integrated circuit manufacturing workshops and high energy photon source facility. The engineering experience helped to design the antivibration foundation for the high-tech facility in a more economical and reliable way.

The following steps constitute the general design process used in this study:

1. Site investigation was conducted to evaluate the conditions of the local soil at the construction site.
2. The truck-induced ground vibrations in the proximity of an existing road with the same design as the
proposed road were measured to determine the vibration source response.

(3) Frequency sweep vibration tests were conducted in the free field to determine the transmissibility of ground vibrations transmitted from the proposed road area to the high-tech lab area.

(4) The ground vibration transmissibility and the vibration source response combined with engineering experience led to the constructions of a 1.0 m thick and a 0.7 m thick antivibration foundation prototype at the construction site.

(5) To quantify the transmissibility of vibrations transmitted via the subgrade soil to the surfaces of the antivibration foundation prototypes, measurements were performed on the two foundation prototypes based on frequency sweep testing.

(6) Based on the vibration source response obtained in step (2) and the vibration transmissibility obtained in step (3) and step (5), the vibration velocities at the surfaces of the two foundation prototypes were predicted.

(7) The predicted vibration velocities of the foundation prototypes were compared with the allowable vibration velocity to determine the final thickness of the actual antivibration foundation.

(8) After construction of the high-tech lab and the road, the surface vibrations of the actual antivibration foundation generated by the passage of a heavy truck on the road were measured to assess the performance of the actual antivibration foundation.

The flowchart of the general design process of the antivibration foundation is shown in Figure 1.

3. Case and Site Descriptions

3.1. Case Description. The plan size of the foundation slab of the high-tech lab is 50 m × 8 m (L × W). The main vibration hazards for the high-tech lab are truck-induced vibrations coming from an adjacent road that is to be constructed simultaneously with the lab. The road runs parallel to the long side of the high-tech lab and has a width of 6 m. The distance between the boundaries of the high-tech lab and the road is 23 m, as shown in Figure 2.

The speed limit for vehicles on the road is 30 km/h. For proper operation of precision equipment housed in the high-tech lab, the peak velocity of the foundation vibrations of the high-tech lab in the vertical direction must not exceed 60 μm/s in the frequency range of 5 to 50 Hz.

3.2. Site Characteristics. The construction site of the high-tech lab is located in the northeast part of Beijing city, China. The physical and dynamic properties of the local soil were determined by a series of geotechnical and geophysical tests. In particular, Multichannel Analysis of Surface Waves (MASW) tests were conducted to determine the shear wave velocities of the subgrade soil. Standard Penetration Tests (SPT) were performed to evaluate the compactness of the soil strata in terms of the numbers of SPT blows (N63.5). In addition, the predominant period of the soil deposit was determined by microtremor tests and was found to be approximately 0.32 s. Figure 3 shows the shear wave velocity profile of the stratified soil.

Site investigation showed that the soil profile consists of 1.5 m silty clay over 20.5 m sandy gravel with moderate and high compactness. The moderately dense sandy gravel consists of gravel and approximately 35% medium sand. The high dense sandy gravel consists of gravel and approximately 25% medium sand. The ground material under the sandy gravel is moderately weathered granodiorite. Because the geological exploration boreholes did not reach to the bottom of the moderately weathered granodiorite, its thickness was unknown. The groundwater table was observed 20 m below the ground surface. Geotechnical parameters and average N63.5 values of the soil are given in Figure 4.

4. Antivibration Foundation Prototypes

Two round prototypes of the antivibration foundation with diameters of 8 m were built at the construction site, as shown in Figure 5. The north foundation prototype was 1.0 m thick and the south foundation prototype was 0.7 m thick, as shown in Figure 5(a). The distance between the centers of the two concrete foundation prototypes was 60 m.

First, the 1.5 m thick silty clay was dug up in the areas where the 1.0 m and 0.7 m thick foundation prototypes were constructed, and 0.5 m and 0.8 m thick sandy gravel backfill were filled and packed in a layer-by-layer manner (each layer was 25 cm thick) with a compaction degree of 0.95. Next, a 1.0 m thick and a 0.7 m thick concrete foundation prototype were constructed and cured for 28 days.

5. Measurement Program

Since the proposed road is to be constructed simultaneously with the high-tech lab, the ground vibrations in the proximity of a road with the same design at the site were first measured to determine the vibration source response. Two additional vibration tests were performed in the design process to predict the likely surface vibration response of the antivibration foundation. After construction of the high-tech lab and the road, measurements were conducted to obtain the vibration level at the surface of the designed antivibration foundation exposed to the passage of a heavy truck on the road.

5.1. Test Plan. Test 1 was conducted to obtain the vibration source response. In test 1, the velocities of the ground vibrations at a location 1 m away from the boundary of an existing road at the construction site were measured and taken as the vibration source response. The existing road had the same design as the proposed road. The ground vibrations were generated by the passage of an 18-ton truck on the road, as shown in Figure 6. The truck drove on the road from north to south five times with a speed of 30 km/h.
The measurement distance for the vibration source response was determined based on two factors: (1) To ensure that the measured vibration response contains as much real information about the vibration source as possible, the measurement distance should be as close to the road boundary as possible. (2) There is enough installation space for the vibration measurement system. In this study, 1.0 m is the most appropriate distance for measuring the vibration source response.

Because the foundation prototypes and the high-tech lab were constructed at different areas (see Figure 5(a)), test 2 was designed to validate the consistency of the three construction areas by measuring and comparing the ground vibration response at test points NP1, SP1, and L1. Test 2 was necessary to demonstrate that the three areas show good consistency in ground vibrations such that the vibration transmissibility between the subgrade soil and the foundation prototypes could represent that between the subgrade soil and the actual antivibration foundation. In test 2, test points NP1, SP1, and L1 were the respective center points of

**Figure 1:** Flowchart of the design process of the antivibration foundation.

**Figure 2:** Layout of the high-tech lab and road.

**Figure 3:** Shear wave velocity profile.
the construction areas of the north foundation prototype, the south foundation prototype, and the actual antivibration foundation. As illustrated in Figure 5(a), test points NP1, SP1, and L1 had the same distance to the vibration source, namely, 30 m.

The aim of test 3 was to determine the transmissibility of free-field ground vibrations transmitted from the proposed road area to the high-tech lab area. Ground vibration transmissibility was determined by measuring and comparing the ground vibration response at test points S1 and L1.
in the free field. As illustrated in Figure 5(a), test point S1 was 4 m away from the vibration source and 1 m away from the boundary of the proposed road. Test point L1 was the center point of the construction area of the actual antivibration foundation. The distance between test point S1 and test point L1 was 26 m.

Test 4 was designed to determine the transmissibility of vibrations transmitted via the subgrade soil to the surfaces of the foundation prototypes. Vibration transmissibility from the subgrade soil to the surfaces of the two foundation prototypes was obtained by measuring the vibration responses at test points NP1 and SP1 and comparing them with the ground vibration response at test point L1. In test 4, test points NP1, SP1, and L1 were the respective center points of the north foundation prototype, the south foundation prototype, and the construction area of the actual antivibration foundation, as illustrated in Figure 5(a).

After construction of the high-tech lab and the road, test 5 was performed to assess the performance of the actual antivibration foundation. In test 5, surface vibrations at the center point of the actual antivibration foundation generated by the moving of a heavy truck on the road with a speed of 30 km/h were measured, as shown in Figure 7. By comparing the measured vibration responses with the vibration criterion, the performance of the actual antivibration foundation was verified. It should be noted that test 5 was performed 28 days after the antivibration foundation was constructed but before the epoxy self-leveling floor was constructed.

In the tests that determined the consistency of the three construction areas and the vibration transmissibility, an electromagnetic vibration excitation system was used as a vibration source to generate harmonic excitation at frequencies varying from 5 Hz to 50 Hz with steps of 1 Hz. The excitation at each frequency lasted 25 seconds. As shown in Figure 8, the excitation system contained four main elements: a signal generator, a power control cabinet, an electromagnetic exciter, and an air-cooled machine.

5.2. Instrumentation and Data Processing. The data acquisition system used at a test point mainly contained an ultralow frequency vibration sensor (GMS-100HP-T) and one 4-channel data acquisition device (INV3062U) to record the vibration velocities in the vertical direction, as shown in Figure 9.

The vibration level was evaluated using the peak velocity of the measured velocity time histories. The peak velocity was obtained from the velocity time histories as

\[ v_{\text{peak}} = \max|v(t)|, \]  

where \( v(t) \) is the measured velocity time histories.

To quantify changes in the vibrations transmitted from one point to the other, the transmissibility was used to calculate the relationship between the vibration levels at two test points. The transmissibility function represents the output-output relationship of a dynamic system, as defined below:

\[ T_{ij}(\omega) = \frac{X_i(\omega)}{X_j(\omega)} \]  

where \( T_{ij}(\omega) \) is the frequency-dependent transmissibility between test points \( P_i \) and \( P_j \), and \( X_i(\omega) \) and \( X_j(\omega) \) are the vibration responses at test points \( P_i \) and \( P_j \), respectively. \( \omega \) is the vibration frequency.

In this study, the ground vibration transmissibility from the proposed road area to the high-tech lab area is denoted by \( T_{RH} \):

\[ T_{RH}(\omega) = \frac{v_{H}(\omega)}{v_{R}(\omega)} \]  

where \( v_{R}(\omega) \) is the ground vibration velocity at test point S1 1 m away from the boundary of the proposed road. \( v_{H}(\omega) \) is the ground vibration velocity at the center point L1 of the construction area of the high-tech lab. \( v_{R}(\omega) \) and \( v_{H}(\omega) \) were simultaneously measured in test 3.

The vibration transmissibility from the subgrade soil to a foundation prototype is denoted by \( T_{SF} \):

\[ T_{SF}(\omega) = \frac{v_{F}(\omega)}{v_{H}(\omega)} \]  

where \( v_{F}(\omega) \) is the surface vibration velocity at the center point (NP1 or SP1) of a foundation prototype. \( v_{H}(\omega) \) is the ground vibration velocity at the center point L1 of the construction area of the high-tech lab. \( v_{F}(\omega) \) and \( v_{H}(\omega) \) were simultaneously measured in test 4.

The velocity time histories \( v_{F}(t) \) of a foundation prototype were predicted as

\[ v_{F}(t) = \text{IFFT}(\text{FFT}(v_{VS}(t)) \cdot T_{RH}(\omega) \cdot T_{SF}(\omega)), \]
where \( v_{VS}(t) \) is the velocity time histories of the vibration source used in the antivibration foundation design measured in test 1. FFT () means to perform fast Fourier transform. IFFT () means to perform inverse fast Fourier transform.

### 6. Results and Discussion

#### 6.1. Vibration Source Response

The 8-second velocity time histories of the ground vibrations before and after the truck passed the test location were taken to determine the vibration source response used in the antivibration foundation design. In this study, the vibration frequency that was of interest was 5 Hz to 50 Hz. Thus, 5–50 Hz bandpass filtering was first performed on the 8-second velocity time histories, as shown in Figure 10. The results showed that the peak velocities were notably similar. The mean of the peak velocities is 1236 \( \mu \text{m/s} \) for the five pass-by events. In addition, the velocity for any one of the five pass-by events peaked at the moment when the truck passed the test location. Thus, it is rational to adopt the data around the peak velocity to design the antivibration foundation.

The consistency of the peak velocities in the time domain of the vibration source responses for the five pass-by events confirmed that the vibration measurement to obtain the vibration source response by measuring the ground vibrations in the proximity of a road was repeatable. Therefore, the measured velocity time histories of the ground vibrations were reliable for use as the vibration source response in the antivibration foundation design of the high-tech lab. In this study, the 1-second data around the
The peak value of the velocity time histories with the mean peak velocity (1236 μm/s) was selected as the vibration source response, as shown in Figure 11(a). To understand the frequency characteristic of the vibration source response, the fast Fourier transform with a frequency resolution of 1 Hz was performed on the selected 1-second velocity time histories in Figure 11(a). The velocity spectrum of the selected vibration source data is shown in Figure 11(b). The velocity spectrum of the selected vibration source data was used to guide test 3 and test 4.

6.2. Consistency of the Three Construction Areas. Consistency verification of the construction areas of the north foundation prototype, the south foundation prototype, and the actual antivibration foundation was achieved via test 2. Free-field ground vibrations generated by harmonic excitation at the center points NP1, SP1, and L1 of the three construction areas were measured simultaneously. The vertical velocities of the free-field ground vibrations at the three construction areas are shown in Figure 12. The velocity-frequency curves of the three construction areas were almost exactly the same for the free-field ground vibrations. This result demonstrated that the construction areas of the north and south foundation prototypes were of good consistency with that of the high-tech lab in vibration response.

Figure 13 shows the difference in the vertical velocities of the three construction areas. The maximum difference in the velocities between the north and south foundation prototype areas was 2.01 μm/s at 19 Hz. The maximum difference in the velocities between the north foundation prototype and the high-tech lab areas was 2.04 μm/s at 30 Hz. The maximum difference in the velocities between the south foundation prototype and the high-tech lab areas was 1.91 μm/s at 36 Hz. As was expected, the difference in the vertical velocities of the three construction areas was small. This is because the three construction areas are adjacent and the strata from the vibration source to the three areas are relatively uniform.

The results described above confirmed that the vibration propagation path was similar for the construction areas of the north foundation prototype, the south foundation prototype, and the high-tech lab, and thus the three construction areas had good consistency and could be used as control subjects for subsequent tests.

6.3. Transmissibility of Ground Vibrations. In determination of the ground vibration transmissibility via test 3, the velocity spectrum of the vibration source response in Figure 11(b) was used to adjust the output energy of the excitation system to guarantee that the vibration source response generated by the excitation system was similar to the truck-induced vibration response. Figure 14 shows the velocity-frequency curves of the vibration source and the high-tech lab areas. The transmissibility of ground vibrations transmitted from the vibration source point S1 to the center point L1 of the high-tech lab area was calculated by equation (3) and is shown in Figure 15.

It was observed from Figure 15 that the transmissibility of ground vibrations transmitted from the proposed road area to the high-tech lab area was frequency-dependent. In other words, the propagation characteristics of ground vibrations at different frequencies were different. This emphasized that it is essential to determine the ground vibration transmissibility via the frequency sweep tests.

6.4. Vibration Transmissibility between the Foundation Prototypes and Subgrade Soil. In determination of the vibration transmissibility via test 4, the velocity spectrum of the vibration source response in Figure 11(b) was used to adjust the output energy of the excitation system to guarantee that the vibration source response generated by the excitation system was similar to the truck-induced vibration response. The transmissibility between a foundation prototype and the subgrade soil represents the ability of the foundation
Figure 11: Vibration source response used in the antivibration foundation design: (a) velocity time history, (b) velocity spectrum.

Figure 12: Velocity of free-field ground vibrations.

Figure 13: Difference in the velocities of free-field ground vibrations.
prototype to reduce vibrations transmitted from the soil underneath.

Figure 16 shows the velocity-frequency curves of the surface vibrations at the center points (NP1 and SP1) of the two foundation prototypes and the ground vibrations at the center point (L1) of the high-tech lab area. The velocities of the surface vibrations of the north foundation prototype with 1.0 m thickness were smaller than those of the ground vibrations at the high-tech lab area in the whole analyzed range of frequency, implying continued vibration reduction ability of the north foundation prototype in the whole analyzed range of frequency. However, the south foundation prototype with 0.7 m thickness caused amplification of the vibrations at frequencies of 8 to 13 Hz. In addition, the velocity-frequency curves of the north and south foundation prototypes were different, implying different frequency response characteristics due to their different thicknesses.

The transmissibility between the foundation prototypes and the subgrade soil was calculated by equation (4) and is shown in Figure 17. The transmissibility of vibrations transmitted via the subgrade soil to the north foundation prototype with 1.0 m thickness was lower than 1, explaining the continued reduction action of the north foundation prototype in the whole analyzed range of frequency. However, the transmissibility of vibrations at frequencies of 8 to 13 Hz transmitted to the surface of the south foundation prototype with 0.7 m thickness was higher than 1, explaining the amplification effects of the south foundation prototype on the vibrations at 8 to 13 Hz.

6.5. Vibration Prediction for Foundation Prototypes. The time histories of the vibration velocities of the two foundation prototypes were predicted based on the velocity spectrum of the vibration source response in Figure 11(b), the ground vibration transmissibility in Figure 15, and the vibration transmissibility from the subgrade soil to the foundation prototypes in Figure 17, as shown in equation (5). The predicted velocity time histories of the two foundation prototypes are shown in Figure 18. The peak velocities of the surface vibrations of the north and south foundation prototypes were 47.5 μm/s and 60.5 μm/s, respectively. The peak velocity of the surface vibrations of the north foundation prototype was smaller than that of the south foundation prototype because the vibration reduction ability of the north foundation prototype with 1.0 m thickness was stronger than that of the south foundation prototype with 0.7 m thickness. Based on the vibration control criterion of 60 μm/s, it was concluded that the final thickness of the actual antivibration foundation should be 1 m.

6.6. Vibration Responses of the Actual Antivibration Foundation. After construction of the high-tech lab and the road, vibration tests were conducted to measure the surface vibrations at the center point of the actual antivibration foundation. The 8-second velocity time histories of the surface vibrations before and after the truck passed by the test point were recorded. Figure 19 shows the 5–50 Hz bandpass-filtered velocity time histories of the surface vibrations for five truck pass-by events. The peak velocities
were approximately 38 \( \mu \text{m/s} \) for the five truck pass-by events, smaller than the vibration criterion of 60 \( \mu \text{m/s} \).

The consistency of the peak velocities of the surface vibrations of the designed antivibration foundation for the five truck pass-by events confirmed that vibration measurement used to obtain the response of truck-induced vibrations for the designed antivibration foundation was repeatable. In other words, the measured vibration velocities of the designed antivibration foundation were reliable for assessing the performance of the antivibration foundation. The test results showed that the designed antivibration foundation for the high-tech lab satisfied the required vibration control criterion.

7. Conclusions

Road traffic-induced vibration is a potential hazard for high-tech facilities in which precision equipment is housed. Thickening the foundation slab is an effective measure to control the unwanted vibrations at a high-tech facility. In this study, the design process of the foundation slab for a high-tech lab exposed to truck-induced vibrations was discussed in detail. Prediction of the likely surface vibration levels of the antivibration foundation of the high-tech lab was achieved using the corresponding vibration transmissibility obtained by in situ frequency sweep tests. Based on the results of this case study on the antivibration foundation design for a high-tech lab, the following conclusions were drawn:

(1) The measurement process used to obtain the vibration source response by measuring the ground vibrations in the proximity of a road was repeatable. The measured responses of the ground vibrations were reliable for use as the vibration source data in the antivibration foundation design of high-tech facilities.
The transmissibility of ground vibrations transmitted from the proposed road area to the high-tech lab area and the transmissibility of vibrations transmitted via the subgrade soil to the surfaces of the foundation prototypes were both frequency-dependent. The frequency dependence of vibration transmissibility confirmed the necessity of determining the vibration transmissibility by in situ frequency sweep testing.

Measurements conducted after construction of the high-tech lab and the road showed that the designed antivibration foundation was able to reduce the vibration level at the high-tech lab to an acceptable level. Thus, the thickened foundation slab further proved to be an effective vibration reduction measure for high-tech facilities.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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