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Measurement of ground borne vibrations for foundation design and vibration isolation of a high-precision instrument

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ABSTRACT

This study focuses on the foundation design and vibration isolation of a high-precision instrument subjected to ground-borne vibrations. The allowable vibration level for the proper operation of the sensitive equipment was 50 μg in a frequency range of 1–300 Hz. Prior to foundation design, first, an extensive field survey including geological and geophysical tests were performed in situ to obtain the static and dynamic physical properties of the soils. Next, vibration levels at various locations in the vicinity of moving vibration sources at the site were measured by accelerometers in one third octave frequency range from 1 Hz to 1000 Hz. Background vibration levels at the site were also measured while all of the vibration sources were inactive. Based on the measurements, a special foundation system was designed to reduce the vibration levels at the base of the precision instrument to allowable vibration limits while the vibration sources were active. Consequently, measurements were performed on the actual true scale foundation structure constructed at the site to assess the vibration isolation performance of specially designed structure. The actual vibration levels on top of the inertia mass show good agreement with the predicted values.

1. Introduction

High-precision instruments such as electron microscopes and coordinate measuring machines are very sensitive to internal and external vibrations. There are two types of techniques to isolate and control the vibrations, namely active and passive isolation. Active isolation limits or controls the vibrations near the sources; whereas passive isolation protects the instrument from the effect of surrounding vibrating sources. Lei and Benli [1] and Collette et al. [2] stated that the active isolation was more effective than the passive isolation, especially for low frequency vibration isolation purposes, however it was not a practical and economical solution for external ground-borne vibrations caused by heavy vehicles such as trucks and crawler vehicles [3]. Due to cost problems and uncertainty of ground borne vibrations, passive isolation is usually preferred to meet limit vibration criteria for the proper operation of the high-precision instruments.

Working machinery and human activities in buildings are the main sources of internal vibrations whereas, external vibrations are caused by outside sources such as vehicle traffic, power generators outside the building and construction activities. Recently, the traffic-induced ground vibration has become a major environmental issue in urban areas since the distance between the buildings and the roads are decreasing due to space limitations in heavily populated cities. Traffic induced vibrations are in particular dominated by heavy vehicles moving on the roads where pavements are not smooth. Watts [4] found that the heavy vehicles moving on a road with surface irregularities produce most of the perceptible vibrations within five meters distance to the road. In another study of Watts [5], simple vibration prediction models were proposed considering the maximum height/depth of the irregularities on the road, the speed of the vehicles and the distance to the measurement location. Hunt [6] and Hao and Ang [7] developed numerical models to predict the traffic induced vibrations. In these studies, road roughness was described in a stochastic method by utilizing power spectral density function. Lak et al. [8] and Agostinacchio et al. [9] investigated the heavy vehicle induced vibrations on flexible and rigid pavements experimentally. It was observed that peak particle velocities in proximity of the road were strongly affected by the height of surface irregularities and velocity of vehicles. Watts and Krylov [10] proposed empirical relationships for the vibration levels at foundations by considering the effects of road

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humps and speed control cushions. Width and Bodare [11] used transfer functions to predict the vibration levels inside a building due to specific ground motion generated outside. Taniguchi and Sawada [12] studied the characteristics of heavy vehicle-induced ground vibrations by using test trucks. They pointed out that the Rayleigh wave was dominant in those vibrations and the fundamental frequency could range from 10 Hz to 20 Hz. Al-Hunaidi and Rainer [13] carried out field tests and measured the traffic-induced vibrations. The authors observed that the frequency content of the vibrations changed between 10 Hz and 40 Hz. Hunaidi and Tremblay [14] performed detailed site measurements in order to investigate the vibration levels due to road traffic in Montreal. It was found that the predominant frequencies of truck-induced vibrations fell in the range between 10 Hz and 20 Hz.

Second group research focuses on the attenuation of ground-borne vibrations by applying passive isolation for the sensitive areas or building foundations where vibration limits are set for the proper operation of sensitive instruments.

Research indicate that air springs, steel spring elements, rubber pads, open and filled trenches are efficiently utilized as passive vibration isolators in the vicinity of the sensitive instrument. In the design process, selection of the proper isolation technique requires the estimation of likely vibration levels to be generated in the site. With and Bodare [11] stated that prediction of vibration levels at variable distance to the railway traffic was a difficult task, since there were many unknown parameters such as speed of train, weight of cars, roughness of the wheels and rails, structural properties and ground characteristics. In another study, Amick [15], Gordon [16] and Bessason et al. [17] studied vibration criteria of sensitive-equipment. It was recommended that one-third octave band measurements should be used in the design of vibration isolation of sensitive equipment to simplify the complexity of a typical vibration spectrum. Rivin [3] determined the requirements for vibration isolation of high-precision equipment. The author concluded that in most of cases, vibration isolation criteria can be satisfied by passive isolators having high damping. Besides, it was stated that in some cases installing the precision machine on massive foundation blocks reduced the rocking effect and increased the effective rigidity.

Within the scope of the current study, a case study that focuses on the foundation design and vibration isolation of high precision instrument exposed to ground vibrations was discussed in detail. The sensitive instrument will be located at ground level where it may be subjected to the external sources including heavy moving vehicles. For the proper operation of the high-precision equipment, in this study, it was desired that the root mean square (RMS) peak acceleration magnitude of vibrations had not to exceed 50 μg in the frequency range of 1–300 Hz under the pedestal of the instrument. In the foundation design process, as the initial step, ground characteristics were investigated by utilizing geotechnical and geophysical surveys. Consequently, to predict the ground-borne vibration levels and frequency content, an extensive site vibration measurement program was applied. Measurements at the probable location of sensitive equipment were taken for two different scenarios where, truck and crawler vehicles are the main sources of vibrations. Vibration characteristics at the points were extensively monitored to investigate the attenuation of ground borne vibrations within the soil induced by activities of heavy trucks and crawler vehicles. Results of vibration tests were validated with finite element modeling to investigate the effect of soil damping and elastic modulus of the soils for different vibration scenarios [18]. For comparison purposes, background vibrations in the site were measured while all the vibration sources in the vicinity were shutdown. Effect of surface irregularity were not taken into consideration in the current study since this is a site specific investigation.

Predictions based on site surveys, analytical approach and vibration analyses led to a proper selection of the isolation element consisting of spring and damper elements for the seismic mass and foundation system. After the construction of actual foundation-isolator-seismic mass system at the site, measurements were repeated for the same scenarios applied in design process. Vibration levels and frequencies at the base level of the sensitive instrument were investigated to assess the performance of suggested passive isolation system.

2. Site investigation

Soil profile, groundwater table levels and dynamic properties of the soil layers were determined by utilizing an extensive soil exploration program at site. Furthermore, geophysical tests were performed to determine shear wave velocities, elastic moduli and Poisson's ratio of the layers at the site. Shear wave velocity profile was obtained by employing multichannel analyses of surface waves (MASW) [19,20]. This is a non-destructive test that evaluates the propagation characteristics waves generated by the seismic source located at a known distance from the array. Microtremor tests were conducted to obtain dynamic properties of the site such as predominant period and soil amplification ratios. Based on the geophysical tests, natural period of the site is found as approximately 0.70 s. Physical soil properties and the shear wave velocity profile obtained from the site investigation are given in Table 1 and Fig. 1 respectively.

3. Vibration measurements for the isolation system design

A detailed measurement program was implemented in order to determine the vibration levels at specified site locations for different scenarios. High sensitivity seismic constant charge line drive accelerometers [21] capable of measuring ground-borne vibrations

Table 1
Soil profile and properties obtained from site investigations.

Depth (m)	Soil type	Unit weight (t/m^3)	Groundwater depth	SPT (N_{60})
0–4	Medium clay	1.7	No groundwater	21–50
4–10	Dense sand	1.8	No groundwater	>50
10–20	Very dense silt	1.8	No groundwater	>50

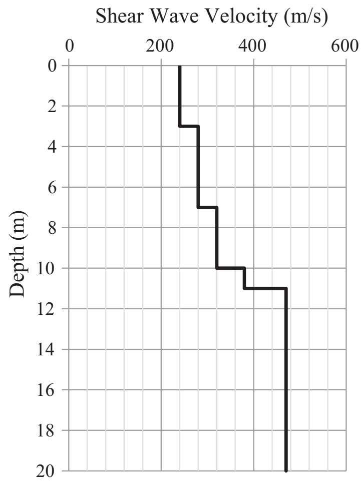

Fig. 1. Shear wave velocity profile of the site.