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Measurement of underground motion at the SSRF site

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For the Shanghai Synchrotron Radiation Facility (SSRF) and future Shanghai Free-Electron Laser projects, ground vibration is an important factor and, in order to attenuate it, the construction of a deep tunnel is under consideration. This paper concentrates on the investigation of ground vibration at different underground levels down to 60 m below surface, in order to understand the effect of vibration attenuation with depth. The effect of traffic is also studied using a 10 ton truck, with ground motion compared in different directions. Finally, a summary and some suggestions on these two projects are given.

Keywords: ground vibration; attenuation; depth; heavy truck.

1. Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) project is a future third-generation synchrotron light source proposed by the Chinese Academy of Sciences and the Shanghai Municipal Government. It consists of a 3.5 GeV electron storage ring, a full energy injector including a 0.15–3.5 GeV booster and a 150 MeV linac, and a dozen beamlines and experiment stations. The future Shanghai Free Electron Laser (FEL) project, designed with features of high brightness and high stability, is also planned to be built at the SSRF site. Therefore, for performance optimization of the accelerator, it is imperative to study ground motion at the SSRF site, resulting from geology and human activity, commonly referred to as 'cultural noise' (Bialowons, 2006).

The SSRF site is located in Zhang-Jiang Hi-Tech Park, Shanghai, China, where the Yangtze River enters the East China Sea. The ground is soft, mainly made of silt, clay, sand *etc.* The shear-wave velocity on the ground surface is only 130 m s^{-1} and the bedrock lies about 300 m underground. Table 1 lists the fundamental soil parameters of the different layers (Zhao, 2005), with only 11 layers shown for clarity. According to Bialowons (2006), ground vibration at the SSRF site is much larger than at other third-generation light source projects. Fig. 1 shows the SSRF site surrounded by a common road (Huatuo Road) to the west and two main traffic roads (Cailun Road and Zhangheng Road) to the north and south, respectively. Heavy trucks on Cailun Road and Zhangheng Road are the main source of vibration based on measurement reports (Ouyang, 2006). The future Shanghai FEL project will be built underground along Cailun Road. Therefore, ground vibration induced by heavy trucks on the road will have a great influence on this new machine. A tunnel is under consideration for attenuating the ground vibration.

Here we present our measurements of ground vibration at different underground levels down to 60 m below surface in order to understand the effect of vibration attenuation with soil depth. We also present our results on the effect of traffic by use of a 10 ton truck and comparing the ground motion in different directions. Finally, we summarize and offer some suggestions for the SSRF and future Shanghai FEL projects.

2. Methodology and equipment

Vibration measurements were carried out at the SSRF site in the daytime on 16–18 November 2006. We used a DAQ-24 data acquisition system from Chongqing Geological Instrument Factory, China, and a 941-B seismometer from the Institute of Engineering Mechanics, China Earthquake Administration. The signal from the sensor is amplified and then sent to the DAQ-24.

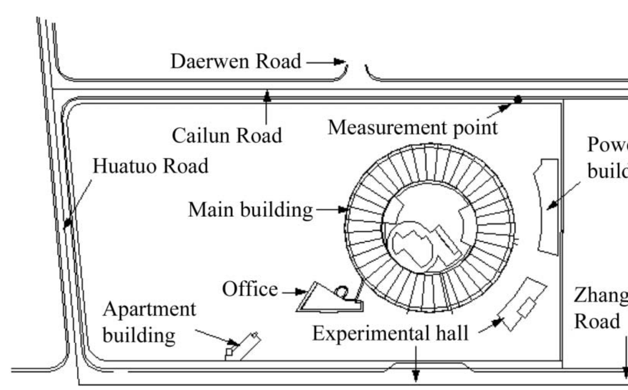

Figure 1
Layout of the SSRF site and the measurement point.

Vibration measurements were simultaneously performed at ground level and in a hole at different underground levels in order to understand the effect of vibration attenuation with depth. We selected a measurement point near Cailun Road (shown in Fig. 1) and drilled holes of depths 20 m, 40 m, 50 m and 60 m, corresponding to soil layer numbers 6, 9, 10 and 11, respectively. Depths shallower than 20 m and deeper than 60 m were not considered, because no significant attenuation effects occur at depths shallower than 20 m and drilling to a depth deeper than 60 m is too costly for simple advanced prediction requirements. During the measurement, six seismometers were divided equally into two groups. Each group received signals in three directions simultaneously. One group was situated in the hole; the other was situated in the vicinity of the ground surface (see Fig. 2*a*). To remove environment noise, the seismometers in the hole were sealed in a steel cylinder (see Fig. 2*b*). Epoxy resins were used as adhesives. The steel cylinder had sufficient stiffness and strength, and measurement differences between layers could be omitted.

To study the heavy truck effect, we assigned a 10 ton truck at a speed of 40 km h^{-1}, the usual traffic speed on Cailun Road, at a horizontal distance of 8 m from the hole, where the future Shanghai FEL project will be built. In this case, measurements were not performed simultaneously and each measurement lasted about 20 s because the truck was considered a short-duration 'event'.

All measurements were recorded three times in each case with the maximum error no more than 10% for credibility. The displacement power spectrum density (PSD), integrated root-mean-square (RMS) displacement and transmissibility were derived based on the data analysis techniques described by Zhou (2005). The range of the RMS displacement was from 1 Hz up to 100 Hz (Bialowons, 2006), which is within the effective frequency band of the 941-B seismometer (Yang, 2001).

3. Measurement results

All measurement results about the RMS amplitude are summarized in Table 2. We investigated ground vibration in terms of the following three aspects: depth, truck and direction.

3.1. Variation with respect to depth

Fig. 3 shows the RMS amplitude ratio between the surface and hole in the vertical and horizontal directions with and

Table 1
Soil parameters at the SSRF site.

Soil layer	Thickness (m)	Main component	Shear velocity (m s^{-1})	Young's modulus (Mpa)	Poisson ratio	Density (kN m^{-3})
1	1.6	Fill	130	87	0.41	18.3
2	1.7	Silty clay	130	87	0.42	18.3
3	5.7	Very soft silty clay with clayey silt	112	637	0.45	17.4
4	10.7	Very soft silty clay	150	108	0.45	16.6
5	0.3	Clay	206	213	0.42	17.9
6	2.8	Sand silt with silty clay	235	270	0.36	18.0
7	8.0	Silty clay	200	200	0.41	17.9
8	3.7	Silty clay	260	367	0.43	19.4
9	8.5	Silty sand	273	381	0.34	19.1
10	17.0	Silty fine sand	318	515	0.32	19.3
11	12.1	Silty clay	305	474	0.42	18.2

Table 2
Integrated (1–100Hz) RMS displacement (μm).

		Direction					
		Vertical		East–west		South–north	
Depth	Location	Surface	Hole	Surface	Hole	Surface	Hole
20 m	Truck	2.909	0.740	0.732	0.517	0.845	0.533
	Without truck	0.348	0.197	0.233	0.168	0.231	0.157
40 m	Truck	3.451	0.503	0.905	0.208	0.981	0.190
	Without truck	0.478	0.189	0.238	0.091	0.262	0.092
50 m	Truck	2.410	0.222	0.774	0.132	0.855	0.140
	Without truck	0.691	0.159	0.347	0.101	0.331	0.106
60 m	Truck	2.619	0.209	0.863	0.161	0.793	0.123
	Without truck	0.754	0.107	0.403	0.102	0.361	0.084

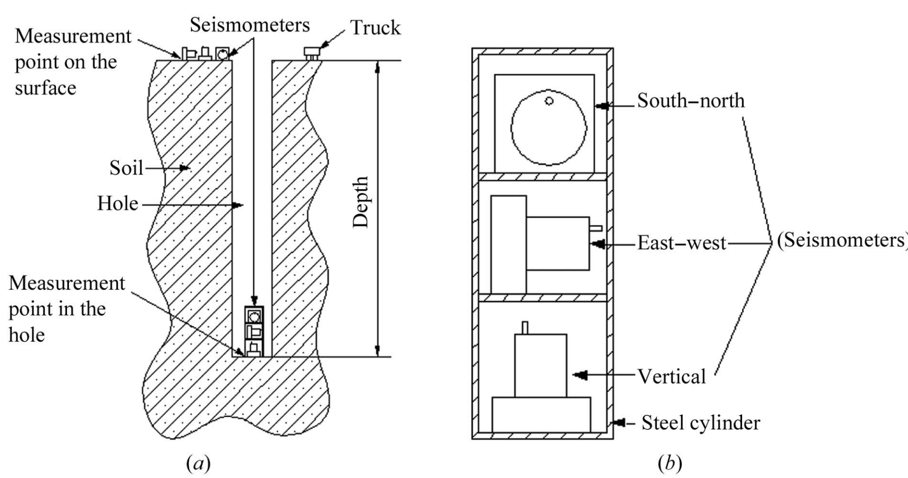

Figure 2
Schematic diagram of the vibration measurement: (*a*) the measurement point, (*b*) seismometers in the hole.

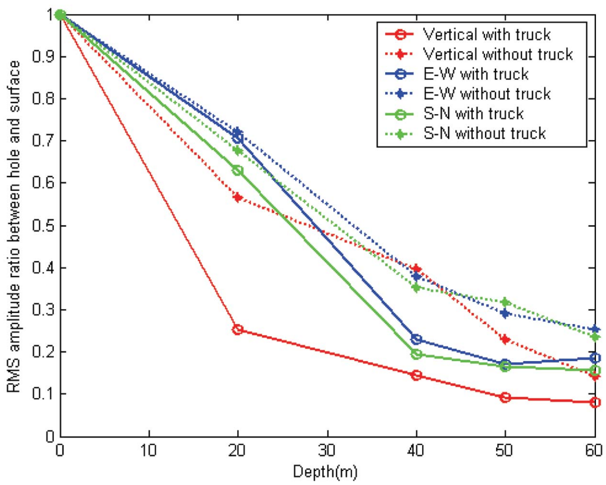

Figure 3
Vibration attenuation effect by depth.

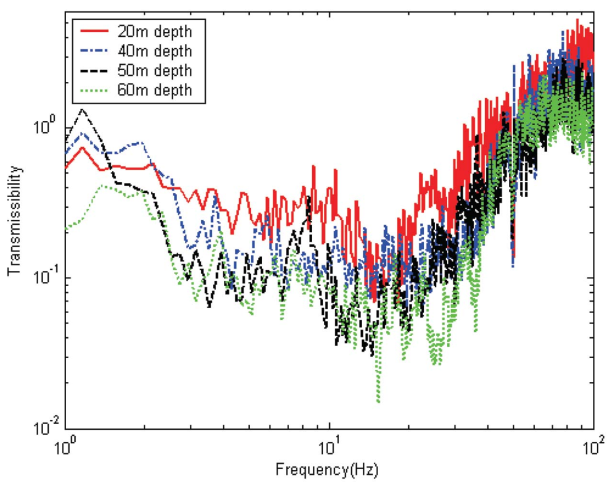

Figure 4
Transmissibility by depth (vertical direction).

without the truck. It can be seen that in every case there is an apparent decaying trend in the RMS displacement ratio as one moves deeper and deeper down the hole. This implies that vibration generated from the ground surface decays as it propagates further. However, no significant attenuation effect exists below a depth of 50 m, especially when the truck is present.

Fig. 4 shows spectra of transmissibility from the ground surface to the hole. We can also see that from 1 to 50 Hz there is an obvious decaying trend as the depth becomes larger. However, it appears that ground vibration is not attenuated but is slightly amplified (a value larger than 1) in the frequency range larger than 50 Hz. This phenomenon has also been found by Yang *et al.* (2003). Fortunately, the amplitude (ground motion) above 50 Hz is so small that it can be omitted. Besides, the transmissibility of about 2–30 Hz has the lower value in the whole frequency range of 1–100 Hz. This suggests that ground vibration in this frequency range can be effectively attenuated by depth.

In order to better understand the effect of vibration attenuation with depth, based on Tuluka (2007), the exponential function $y = 1.0717\exp(-0.0309x)$, calculated by the least-square methods, is used to fit the measurement data in the vertical direction without the truck, where y is the RMS displacement ratio between the hole and the ground surface, and x is the depth of the hole. The correlation coefficient between the fit curve and the measurement data is 0.99. Fig. 5 shows that the fit curve is in a good accordance with the measurement data.

Table 3
Integrated (1–100 Hz) RMS displacement ratio with and without the truck at a depth of 50 m.

Direction	Surface	Hole
Vertical	3.488	1.396
East–west	2.231	1.307
South–north	2.583	1.321

In addition, according to Bialowons (2006), the average RMS displacement of ground vibration at the SSRF site is 292 nm, which is much larger than that of the similar DESY X-ray Free Electron Laser facility (XFEL) project, which is only 38.7 nm in Schenefeld and 28.9 nm in Osdorf. Therefore, to achieve the same vibration amplitude levels, the depth of a tunnel should be 76 m or 83 m for the future Shanghai FEL project.

3.2. Variation with respect to the truck

From Fig. 3 we can see that, by comparing with the case without the truck, ground vibration induced by the truck can be more effectively attenuated at the same depth. However, the effect becomes less significant as the depth increases, especially above 50 m.

Since the depth of 50 m seems to be critical, we will concentrate on investigating it in the following. Table 3 shows the integrated RMS displacement (1–100 Hz) at a depth of 50 m. We can see that all RMS displacement ratios with and without the truck are larger than 1, and those values measured in the hole are smaller than those measured on the ground surface, which suggests that the truck has a large influence on ground motion, especially on the ground surface. Fig. 6 shows the vertical variation of ground motion spectra in a 50 m-deep

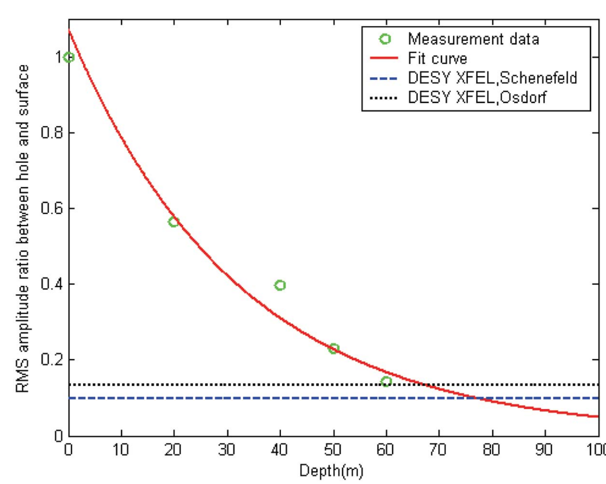

Figure 5
RMS vertical displacement ratio *versus* depth.

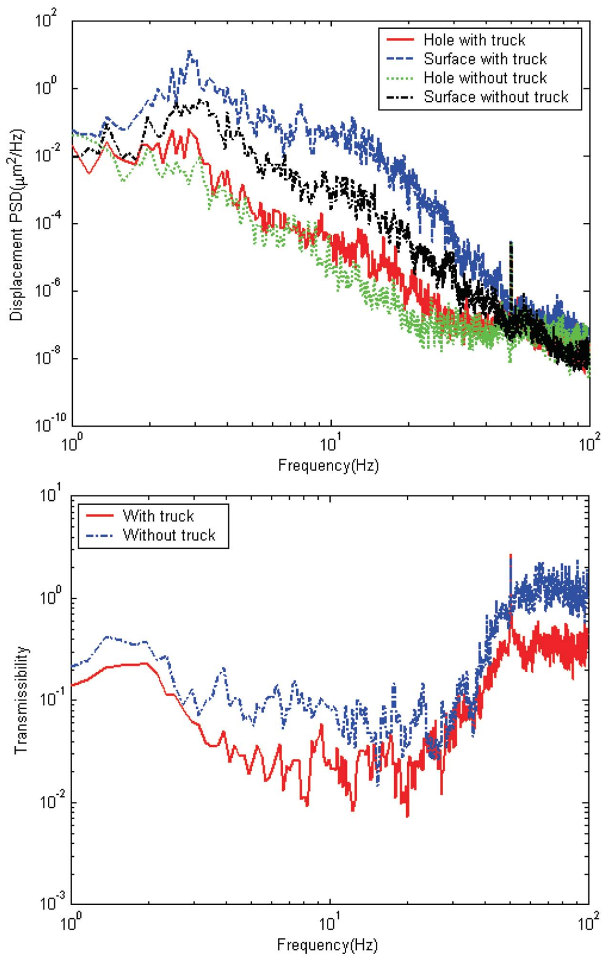

Figure 6
Vertical vibration at a depth of 50 m: (*a*) displacement PSD (μm^2 Hz^{-1}); (*b*) transmissibility from ground surface to hole.

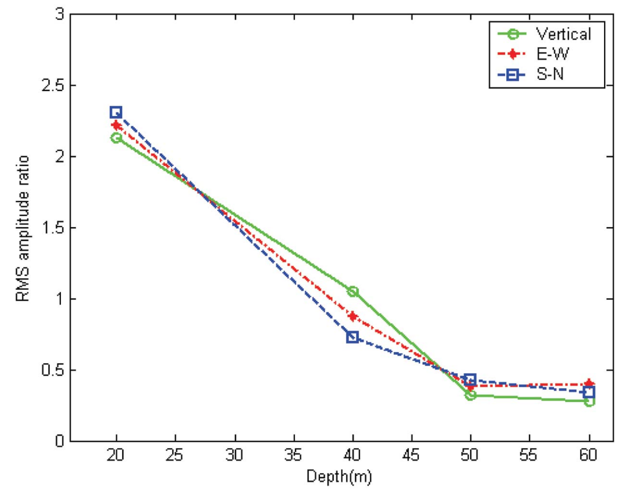

Figure 7
RMS displacement ratio between the hole with the truck and the surface without the truck.

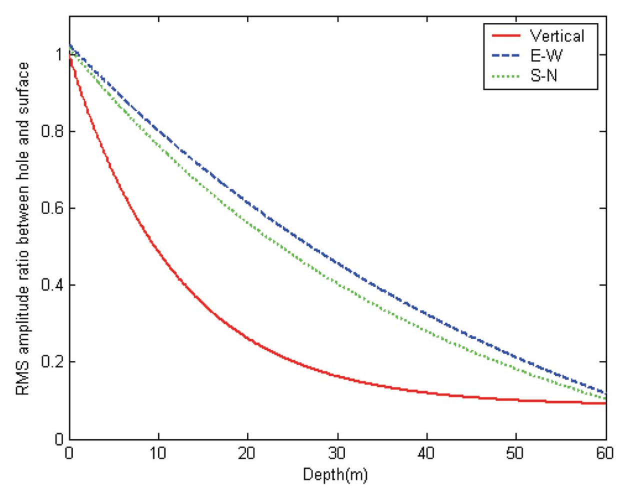

Figure 8
Fit curves of RMS displacement ratio between the hole and surface (with truck).

hole compared with simultaneous measurements taken on the ground surface. From PSD spectra in Fig. 6(*a*), we find that the plot of surface with truck peaks at almost 3 Hz, which indicates that the natural frequency of the truck is approximately 3 Hz. This peak has also been found at other sites of third-generation light sources (Bialowons, 2006). We can also see that at that frequency the displacement PSD of the surface with the truck is higher by one order of magnitude compared with the surface without the truck, which is higher by two orders compared with the hole with the truck, and higher by three orders compared with the hole without the truck. Fig. 6(*b*) shows the vibration transmissibility from the ground surface to the 50 m-deep hole. We can see that both cases have a similar trend in terms of the whole frequency, although the value with the truck is relatively low, meaning that the vibration attenuation effect in this case is better.

Next, we investigate whether the depth or the truck is the dominant factor in the variation of ground motion. Fig. 7 shows ratios of RMS displacement between the hole with the truck and the ground surface without the truck. We can see that the value at a depth of 20 m is larger than 1, which suggests that the amplification effect induced by the truck on the ground vibration is more pronounced than the attenuation effect induced by the depth; at a depth of 40 m, the two factors have a balanced impact; and at depths of 50 m and 60 m the truck has a lower influence than the depth.

3.3. Variation with respect to direction

Generally, the influence of the depth and the truck on the ground motion in the horizontal direction [east to west (E–W) and south to north (S–N)] is similar to that in the vertical direction (see Fig. 3), although the RMS horizontal displacement ratios at a depth of 20 m are much larger than at other greater depths, which implies that horizontal vibration attenuation is not effective by shallower stratum whether in the presence of the truck or not.

For the critical depth of 50 m, Table 4 shows the RMS displacement ratio between the vertical and horizontal directions. We find that the vertical displacement is larger whether on the ground surface or in the hole, especially in the presence of the truck, although the vertical vibration attenuation effect is better than the horizontal vibration attenuation (see Fig. 8).

Table 4
Integrated (1–100 Hz) RMS displacement ratio between different directions at 50 m depth.

	Vertical *versus* east–west		Vertical *versus* south–north	
	Without truck	With truck	Without truck	With truck
Surface	1.991	3.114	2.088	2.819
Hole	1.574	1.682	1.500	1.586

Therefore, we should pay more attention to the vertical vibration.

4. Summary and suggestions

We have measured ground vibration at different underground levels down to 60 m below the surface in order to understand the effect of vibration attenuation with soil depth. We have also studied the cultural noise by using a 10 ton truck, the main vibration source at the SSRF site, and compared the ground motion in different directions. The following conclusions can be drawn.

(i) A deep tunnel would have the advantage of attenuating ground vibration, especially in the frequency range 2–30 Hz.

(ii) The natural frequency of the 10 ton truck is almost 3 Hz. The truck has a great influence on ground motion, especially on the surface.

(iii) At a depth of 20 m, the amplification effect induced by the truck on ground vibration is more pronounced than the attenuation effect induced by the depth; at a depth of 40 m, the two factors have a balanced impact; and at depths of 50 m and 60 m, the truck has a lower influence than the depth.

(iv) The depth of 50 m is critical, below which no significant attenuation effect exists, especially in the presence of the truck. At a depth of 50 m, the RMS displacement with the truck arrives at 222 nm, much larger than that without the truck, although the vibration attenuation effect with the truck is better than that without the truck.

(v) The vertical displacement is larger than the horizontal displacement whether on the ground surface or in the 50 m-deep hole. Also, the vertical vibration attenuation effect is better than the horizontal, especially with the truck.

Based on these conclusions, we suggest to the SSRF and future Shanghai FEL projects that 10 ton trucks should be prohibited on Cailun Road, and the depth of the tunnel can be 50 m by simultaneously considering the vibration attenuation effect and economics. If we want to achieve the same vibration amplitude levels as the DESY XFEL project in Schenefeld or in Osdorf, the depth of a tunnel should be 76 m at least.

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