Response of metro-induced ground vibrations: Underground and elevated systems

Abstract

Metro railway systems are a vital component of urban infrastructure; however, train-induced structural and ground-borne vibrations in underground and elevated corridors can affect structural serviceability, human comfort, and vibration-sensitive facilities. The present study investigates the generation, propagation, attenuation, and uncertainty of metro-induced vibrations under operational conditions and develops an integrated field–analytical–numerical framework for vibration assessment and engineering prediction.

Extensive field investigations were conducted at eight operational sites of Metro Railway Kolkata, comprising four underground tunnel sections and four elevated metro corridors. Vibration measurements were acquired at source and receiving locations over seven consecutive days using accelerometers and geophones. The recorded time histories were processed through event-based segmentation, denoising, Fast Fourier Transform, one-third octaveband analysis, and Continuous Wavelet Transform to characterise vibration in the time and frequency domains and identify train-induced vibration signatures. For the underground system, the field measurements showed dominant vibration components generally within 50–90 Hz, with additional low-frequency components below 10 Hz. Vibration levels were higher at the site underlain by river sand than at the clayey site, demonstrating the influence of subsurface conditions on vibration transmission. Under single-tunnel operation, the highest PPV occurred near the UP-line tunnel crown, while simultaneous operation of both tunnels resulted in reductions of approximately 40–60% at the DOWN-line crown. Vibration attenuation was also strongly distance-dependent, with measured vibration energy reductions of approximately 22–37% at the monitored locations. Comparison with established empirical models showed deviations generally within 15–20%.

For the elevated system, the dominant vibration content was generally within 40–90 Hz, with frequency components below 10 Hz associated primarily with train speed and those around 25–31.5 Hz associated with the rail fastening system. Peak acceleration decreased by approximately 95% between the investigated track-to-ground locations, while PPV decreased by approximately 96% from 2 to 12 m from the track centreline. The measured results indicated that, under the site-specific conditions investigated, residential and vibration sensitive structures were unlikely to experience cosmetic damage beyond approximately 6 m from the track centreline; human-annoyance criteria were satisfied beyond approximately 8 m, while vibration-sensitive equipment criteria were satisfied beyond approximately 12 m. Measurement uncertainties ranged from 2–19 dB for accelerometer-based structural measurements and 0.5–5 VdB for ground-borne vibration measurements. Complementary

analytical and finite element simulations were performed using multidegree- of-freedom train models coupled with tunnel–soil and pile group–soil interaction models.
The numerical predictions were validated against field measurements, with deviations generally within 10%. Parametric investigations showed that train speed, tunnel depth, pier height, and soil shear-wave velocity govern vibration transmission. For the underground system, soil shear-wave velocity was the most influential parameter, followed by train speed and tunnel depth; for the elevated system, pier height was the dominant parameter, followed by soil shear-wave velocity and train speed. The numerical investigations further indicated that, for the investigated conditions, underground vibration setback requirements based on the 65 VdB criterion could vary from approximately 10–12 m under favourable conditions to 28–30 m under the worst-case combination of train speed, tunnel depth, and soil stiffness. For the elevated system, the corresponding 65 VdB contour extended to approximately 15 m under the worst-case condition and reduced to approximately 10 m under favourable conditions. These findings provide an engineering basis for assessing vibration propagation, identifying controlling parameters, and establishing preliminary setback and mitigation requirements during the planning and design of metro infrastructure. The developed relationships and prediction framework are applicable within the investigated ranges of operational, structural, geometric, and geotechnical conditions, and further validation is required for extrapolation beyond these conditions.

Keywords: Metro-induced vibration; Soil dynamics; Railway geotechnics; Field investigation; Vibration propagation and attenuation; Train–track interaction; Soil–structure interaction; Finite element analysis