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# Investigation of the Rail-induced Vibrations on a Masonry Historical Building

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**Abstract** Increasingly historic masonry buildings are subjected to higher levels of traffic and rail vibrations due to urbanization and population growth. Deterioration and destabilisation of these buildings may result, especially if they were previously damaged (e.g. earthquakes or settlement problems). To better understand building response, vibration measurements were conducted on the Little Hagia Sophia Mosque, located adjacent to Istanbul's Sirkeci-Halkali railway line. Transport-induced vibrations were recorded at several points on the ground and building. Attenuation characteristics in the ground and amplification features on the building were examined. Peak particle velocities often exceeded previously established thresholds for human perception and in some cases for structural damage. These are evaluated with respect to the building's condition.

**Keywords:** Traffic-induced vibrations, train vibrations, building vibrations, rail traffic, historical building, cultural heritage, masonry buildings.

## Introduction

Transport-induced vibrations are a common and frequent concern around the world. Variations in the contact forces between wheel and road or tracks create ground vibrations. These produce stress waves, which propagate through soil and reach nearby building foundations, causing them to vibrate. Improved wave attenuation and transmission characteristics are needed to be better understood to mitigate complaints, most are which are inhabitant discomfort, although structural damage and malfunctioning of sensitive equipment may also occur.

## Background

Several theoretical models have been presented for prediction of the propagation of rail-induced ground vibrations. Verhas proposed the line source model, the point source model, and the superposed model [1]. Each model's efficiency depends on different soil characteristics and the determination of the amount of energy carried by different wave types was difficult to identify. Dawn and Stanworth [2] reported difficulties in wave propagation modelling since the ground is heterogeneous including stratifications and discontinuities, which cause additional modes of vibration propagation along the interfaces. Their track-side vibration measurements showed that both the vibration levels and the manner in which the level decays with distance varied in a way which has so far defied prediction. Soil properties, soil profile, and site topography may greatly influence vibration levels. Levels increase as soil stiffness and damping decrease, as demonstrated by Aueresch [3], where shear wave speed was 300m/sec for stiff and 30m/sec for soft soil (both with 5% material damping); low-frequency amplitudes 100 times higher in soft soil, and track displacements 35 times higher than in stiff soil. Additionally, seasonal variations and moisture content impact transmission. Vibrations are of particular concern in historic structures, where materials may be deteriorated and the structural system hard to assess [4]. Monitoring of an early 19<sup>th</sup> century masonry building adjacent to a major road in Naples, Italy showed that the ISO 2631 [5] perception threshold for peak particle velocity (PPV) (0.14mm/s) was exceeded for all acquired data, and in some cases the vibration level exceeded the lowest damage PPV threshold found in the literature (1mm/s) [6].

## Train-induced Vibration Measurement on Little Hagia Sophia Mosque

As part of a larger study to investigate some of these issues, a vibration measurement program was performed on the masonry structure Little Hagia Sophia Mosque (built 527-536 A.D.) in Istanbul,

Turkey. Although previous analyses of the building have been published [7, 8, 9], transmission characteristics of nearby rail-induced vibrations have not been presented before. The Mosque is located in the district of Eminonu in Istanbul, close to the Marmara Sea from which it is separated by the Sirkeci-Halkalı railway line and the coastal road (Fig. 1). The site soil is composed of clay and marl of early Pliocene period. It is a cohesive type of soil composed of fine particles. A plan view of the building and the proximity to the transport lines, along with instrumentation in the garden of the mosque can be seen in Fig. 2. At their closest points, the mosque is 4.8 m from the railway line. Two tests are presented herein.

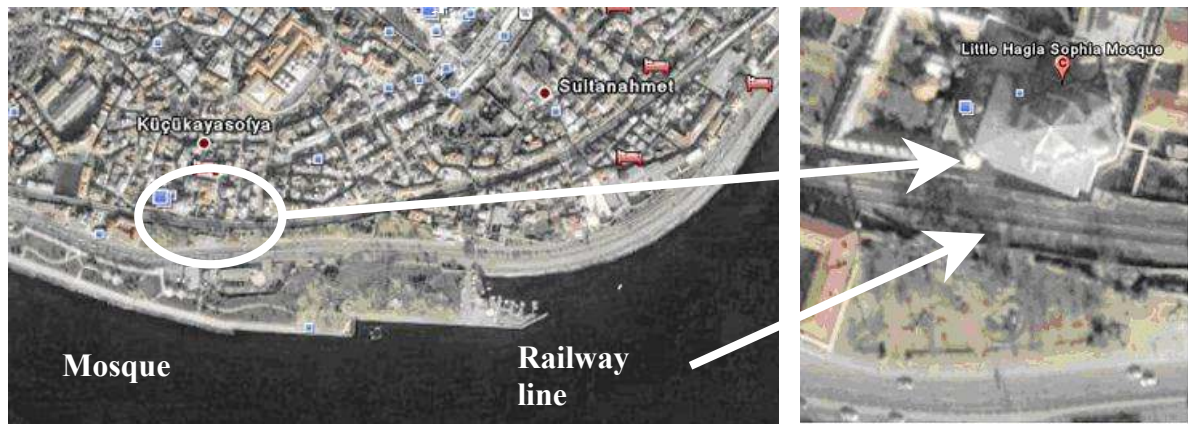


Figure 1. Bird's eye view of Little Hagia Sophia Mosque

For Test 1, within the physical constraints of the site, an area was chosen where 4 instruments could be placed in a straight line. For each passing train, ground vibration measurements were taken at 4 equidistant offsets from the railway. Seismographs are labelled as A-D, and each preceding number indicates the test [e.g. 1A means instrument A in Test 1]. Instrument A was the closest seismograph to the railway, while instrument D was the furthest (Fig. 3a). For Test 11, instrument C was placed next to the structure and A and D were placed in windows of ground and first floor respectively, while B was placed on the mid-slab close to the railway line to evaluate floor vibrations (Fig. 3b).

Three perpendicular components of train-induced ground motions (east-west, north-south, and vertical) of a total of 7 trains were measured: 3 trains in the garden during Test 1 and 4 trains on the structure during Test 11. During measurements, 4 ultra-lightweight, three-component digital output seismometers (CMG-6TD) were used. The seismometers are ideally suited for sites where there is medium level of background vibrations. Sampling rate was assigned at 500/sec to allow a broad range analysis of vibration frequency content. Daily, 118 suburban trains cross the site (1 approximately every 10 minutes) [10]. These transport 65,000-75,000 people using trains of 6 cars – 2 of which are locomotives, which pull from either end depending upon journey direction. The train weighs 3,200kN (carriage axle weight 140kN and 4-axle locomotives 160kN). Importantly, although train velocity varies 70-90km/h, vibrations on the ground and buildings can differ greatly as previously shown by Xia et. al. [11] who reported train speed increases from 60km/h to 80km/h, increased maximum ground level vibration by 23%.



a) Overview



c) Proximity of the mosque to the railway line



b) Sample instrumentation in the garden

Figure 2. Close-up of Little Hagia Sophia Mosque

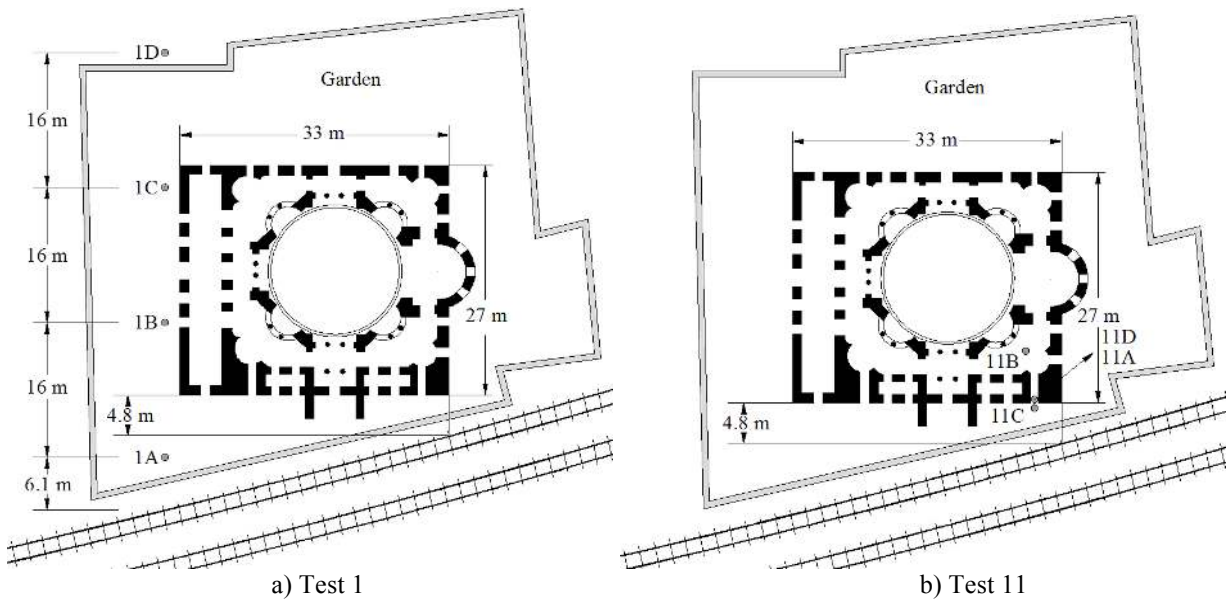


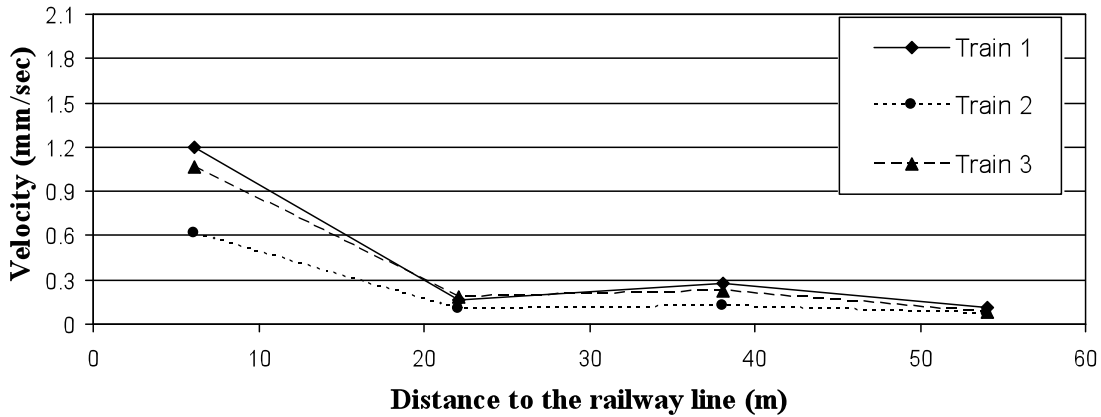
Figure 3. Measurement points locations

### Discussion

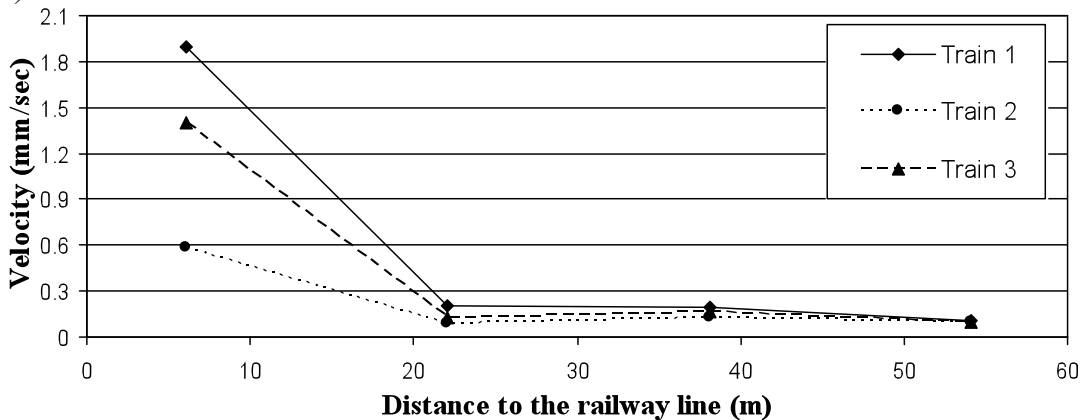
Peak particle velocities in 3 vertical directions at each point for 3 trains are presented for Tests 1 and 11 (Figs 4 and 5, respectively). In Fig. 4, ground surface wave transmission patterns comprised 2 regions. Up to ~25m from the source, amplitudes varied significantly depending on train input,



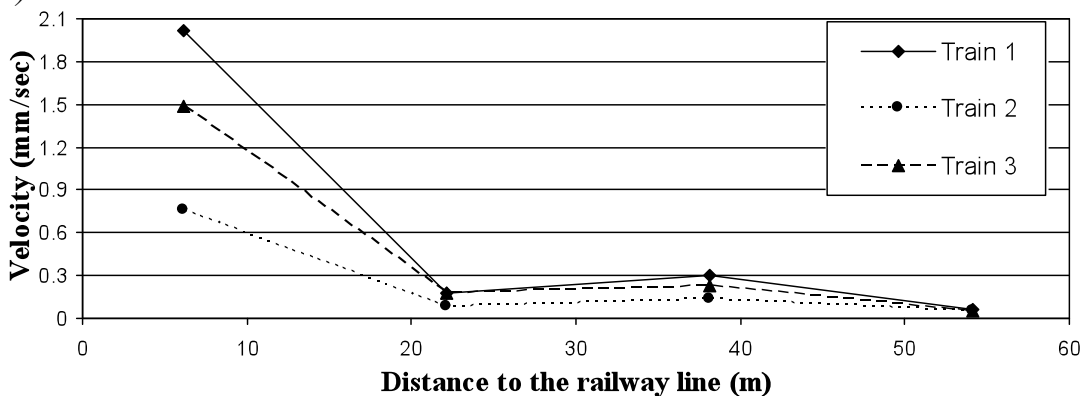
thus representing a critical region. Beyond this point, response was quite uniform, although of importance's is that in this second region amplitudes exceeded 0.3mm/sec, putting them within human perception and possible structural damage, if building amplification occurs [12]. Vertical vibration components were slightly larger than the east-west and north-south components. This is attributable to the fact that Rayleigh waves predominate on the ground surface, and their vertical components are dominant over horizontal components. Moreover, the anisotropy and heterogeneity of the soil may also cause that [13].



a) East-west



b) North-south



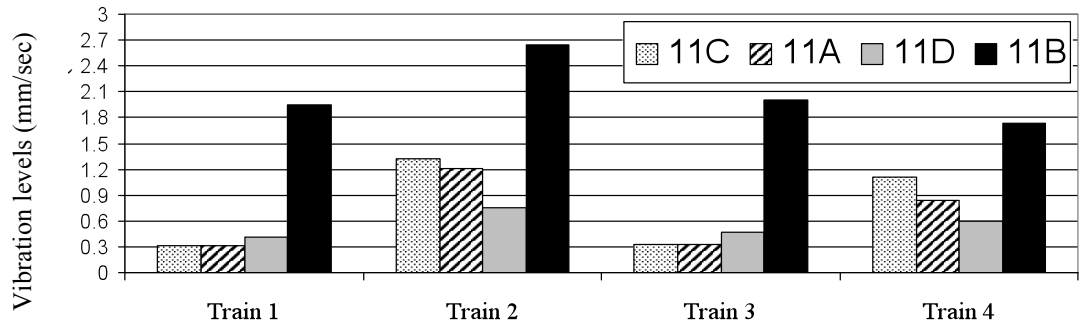
c) Vertical

Figure 4. Wave transmission of train-induced ground vibrations during Test 1

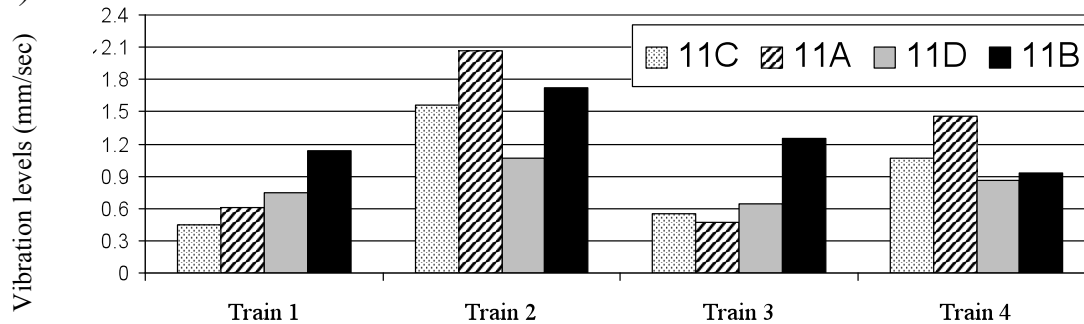
Additionally, an amplification zone in the ground was discovered 35-45m from the source (Fig. 4). Similar to that reported by Xia et. al. [11]. Such amplification zones may be critical during design. Furthermore, source vibration levels varied greatly (Fig. 4). For example, vertical vibration level differences between trains 1 and 2 in Test 1 was about 62%. The variation is mostly attributable to train speed (generally varying 70-90km/h) as equipment and live loading changed little as reported by Xia et. al. [11]. Measurements of ground-borne vibrations showed slight dominance of the vertical component on the ground (Fig. 4). This was more noticeable in falling weight studies [14].

However, in this study, as horizontal components are not negligible and may cause horizontal vibrations of building when they interact with high frequency modes of structures as explained by Erkal et. al. [12]. Additionally, the ground vibrations presented in this study are the peak particle velocities recorded for each passing train at different distances. Therefore they can be regarded as building foundation level valued for further investigation of building and human response [15].

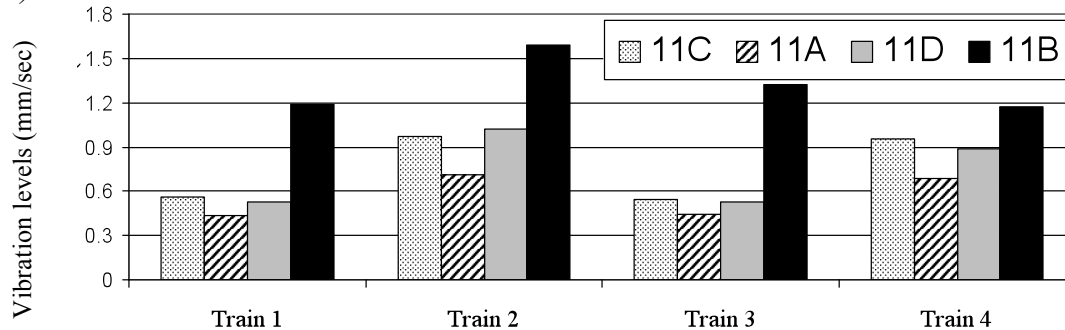
Most codes and studies rely on a maximum PPV to evaluate the severity of traffic-induced vibrations. Figure 5 depicts PPV values of vibrations on the building (Test 11). Although the PPV are not sufficiently large to generate severe structural damage, in some cases the vibration levels exceeded the lowest damage PPV threshold found in literature (1mm/sec) [6], All PPV values were larger than 0.3mm/sec as perceptible to human body [5] and many of them larger than 0.8mm/sec as distinctly perceptible [16]. Furthermore, in each direction, mid-slab vibrations predominate, due to the flexibility of the slab compared to heavy carrying system of the masonry building. Vibration levels was as high as 2.65mm/sec on mid-slab on the first floor and 2.06mm/sec on the structural core of the building. Since human beings are very sensitive to traffic-induced vibrations and are often disturbed by intensities well below those required to overstress structures, in the retrofit of old masonry structures, human response to traffic-induced vibrations should be considered as a serviceability limit state.



a) East-west



b) North-south



c) Vertical

Figure 5. Vibration levels on the structural system of the Mosque during Test 11.

### Conclusions

Efforts to increase public transportation may have the intended consequences of generating higher ground vibrations and negatively impacting architectural heritage, especially unreinforced masonry

structures give their low tensile strengths. To better understand such potential vulnerabilities, a field study was performed on Little Hagia Sophia Mosque, Istanbul, Turkey. The study included the measurement of traffic-induced ground vibrations in the garden and on the structural system of the heritage building. Potentially critical peak particle velocities were found as far as 60m, with a high level of variability within the first 25m from the source and a small amplification zone 30-45m from the source. Given that buildings can also amplify vibrations, establishment of critical zone must be considered with care as well as full consideration of lateral as well as vertical vibration components. In general vibration records on the building showed that PPV values were perceptible and may present structural damage over time.

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