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FOUNDATION SETTLEMENTS OF THE HISTORICAL BUILDING OF THE CHAHAR-BAGH MADRASSA CAUSED BY VIBRATIONS INDUCED BY UNDERGROUND TRAINS

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ABSTRACT

The Chahar-Bagh madrassa is a historical brick masonry building, including a huge dome and two minarets in addition to rooms and other spaces, which was built in Isfahan, Iran, in 1706-14 A.D. An underground railway is planned to run in its vicinity in near future. This paper presents the study on the effect of the underground railway on the foundation settlement of the building.

The finite element method has been used for the analysis of the soil and structure. The imposed load by a wagon is modelled as a harmonic load. The Fourier series are applied to determine the frequency of the dynamic load. Due to the lack of information about the exact depth of the foundation, two levels of foundation under the ground level have been used in analysis. Two- and three-dimensional analyses have been performed and compared.

Results obtained from this study have been presented in this paper.

Keywords: *Foundation Settlement, Chahar-Bagh Madrassa, Vibration, Underground Train, Isfahan, Finite Element Method*

1. INTRODUCTION

Isfahan is a city of many centuries of history in Central Iran with many historical buildings, some inscribed on the World Heritage List.In recent years a new underground railway system has been constructed and it runs through the Chahar-Bagh street, which is a national heritageand the main street of Isfahan. The Chahar-Bagh madrassa (1706-1714 A.D., Fig. 1) stands on the eastern side of the street and it is often referred to as the last great building in Iran. The madrassa contains a major mosque, with its double-shell dome and minarets semi-flanking the ivan; and it is linked to a caravanserai [1, 2]. There are concerns about destructive effects of vibrations produced by the underground railway on the historical building of the Chahar-Bagh madrassa, in particular the settlement of its foundation.

In order to study foundation settlement of the building due to induced vibrations, the finite element method [3] has been employed to calculate the dynamic response of tunnel-soil and soil-foundation interactions using two- and three-dimensional models of soil and underground railway. Obtained results can be used for further research into the effect of foundation settlement on structural vulnerability of the building.

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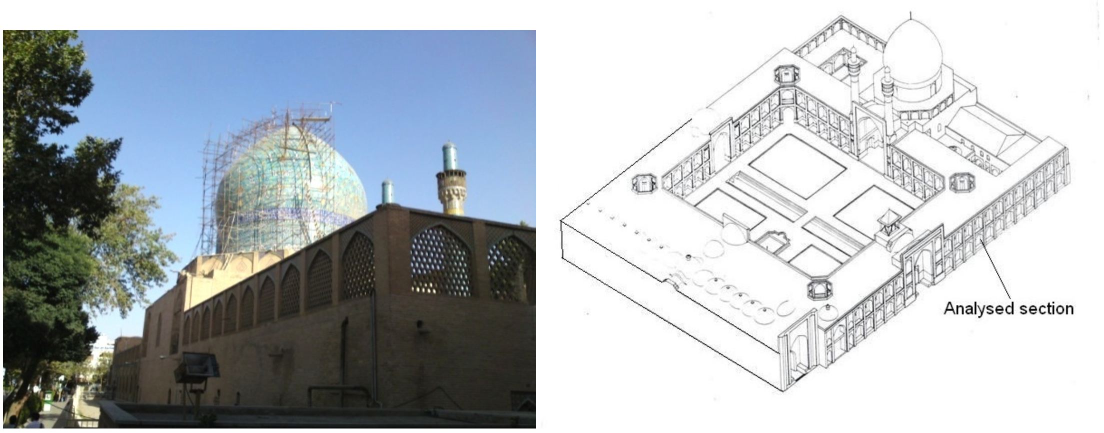

(a) (b)

Fig. 1 Chahar-bagh madrassa: a) view from south-east, b) analysed section on the western side along the Chahar-Bagh street (view from north-west)

2. GENERAL INFORMATION

2.1. Soil

Soil properties were determined from the laboratory investigations performed by Isfahan underground railway office [4, 5]. Based on the information, the soil has two layers down to the depth of 40 m, but as the upper layer is thin and both layers have similar properties only the deeper layer is taken in the model. According to the investigations Young's modules (E) and Poisson's ratio (ν) are 25.5 MPa and 0.35, respectively. The bulk density of soil (ρ) is 1800 kg/m^3. However, damping ratio of soil (φ) is assumed to be 3%. S- and P-wave velocities are determined from eqs. (1) and (2):

$$V_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{2}$$

where: V_p = P-wave velocity, E = Young's modules, ν = Poisson's ratio, V_s = S-velocity.

2.2. Building foundations

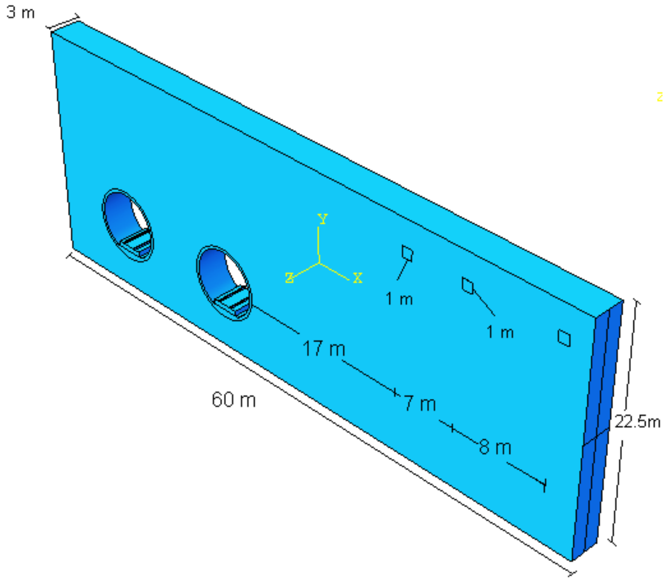

Fig. 2 Cross-section of soil indicating the locations of three foundations under the building and above two tunnels

There is no information about exact location, size and depth of building foundations. Information used in the research has been taken from traditional masons and local experts with experience from similar buildings. The foundations are made of brick set in *saruj*. *Saruj* is a waterproof slow setting composed of 10 parts slaked lime, 7 parts volcanic ash (or 2 parts rice chaff, containing silica), 1 part clay, 1 part quicksand and appropriate amount of reed (to prevent cracking). Bulk density (ρ), Poisson's ratio (ν) and Young's modules (E) of foundations are assumed to be 1900 kg/m^3, 0.3 and 5200 MPa, respectively [6].

Analysed section (western part) of the building is along the eastern side of the Chahar-Bagh street (Fig. 1(b)). The studied foundations are three continuous foundations with a cross-section of 1 m square that support the western part of the building. The foundations are located at horizontal distances of 17 m, 24m and 32 m from the eastern tunnel under ground. In analysis, two different levels have been assumed for the location of the foundations, i.e. 2 m and 3.5 m under the ground level (Fig 2).

2.3.Tunnels

The new Austrian Tunneling Method (NATM) was used to construct a twin tunnel nearby the Chahar-Bagh madrasa. Each tunnel is a single track embedded at depth of about 19.5 m. The tunnels have an internal radius of 3.2 m and a wall thickness of 0.3 m. Horizontal distance of the axes of the tunnels is 12.8 m (Fig. 2) [4].

Each individual tunnel has a concrete slab, on which railways are placed. Dynamic loads are applied on rail profiles. Interactions between rail profiles and the slabs are also considered. The rail profiles are connected to the slabs with springs in certain distances, instead of modelling the springs, a damping ratio (φ) equal to 5% is assumed for the contact interaction. According to the details of released information, a rubber mat with a 0.25 m of thickness is placed between slabs and the main structure of tunnels. Because the thickness of the mat is very small, only a damping ratio of the mat corresponding to laboratory reports is given to the software[7]. The damping ratio (φ) is assumed 5%. The slabs and main structure of tunnels are connected by sharing nodes at the surfaces. However,interaction of two members is also considered. Mechanical properties of concrete shown in Table 1 are from laboratory tests performed by Isfahan underground railway office [4, 5].

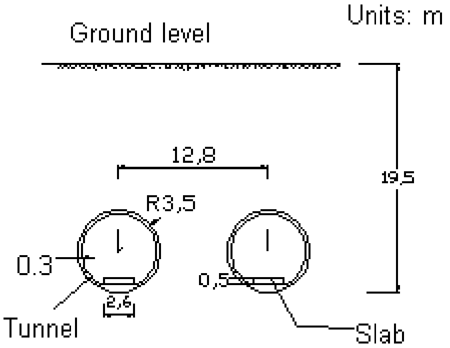

Fig. 3 Cross-sectional view of tunnels [4]

Table 1 Mechanical properties of concrete slabs [4, 5]

Young's modules (E) (MPa)	Poisson's ratio (ν)	Yield stress (MPa)	Bulk density (ρ) (kg/m^3)
29400	0.3	34.6	1900

3. MODELLING OF VEHICLE-TRACK SYSTEM

In finite element analysis, the dynamic loads of wagons are applied to the models. Fig.3 shows the distances of the axles of a wagon used for loading [8]. A train contains five wagons. As wagons are similar their equivalent load has been considered as a harmonic load. The Fourier series have been applied to determine the frequency of the dynamic load. The maximum speed of trains, 80 km/h (22.22 m/s), which produces the highest level of vibration, is used for loading. The total weight of a wagon with passengers is 100 t[8], half of which is supported by each rail profile under the wagon. Applied load on each rail profile as a function time ($P(t)$) is given by eq. 3:

$$P\,(t) = \left\{ \begin{matrix} 0 & 0 < t[0.054\ \mathrm{s} \\ f & 0.054 < t[0.153\ \mathrm{s} \\ o & 0.153 < t[0.72\ \mathrm{s} \\ f & 0.72 < t[0.82\ \mathrm{s} \\ 0 & 0.82 < t[0.88\mathrm{s} \end{matrix} \right\} \qquad (3)$$

where: f = 50 tis half the weight of a wagon on each rail profile.
For example, for calculating the first interval in eq. (3), the time for the first axle with a velocity of 22.22 m/s to pass the distance of 1.2 m (Fig. 3) is 0.054 s (eq. (4)).

$$t = \frac{1.2\ m}{22.22\ m/s} = 0\ .054\ \mathrm{s} \qquad (4)$$

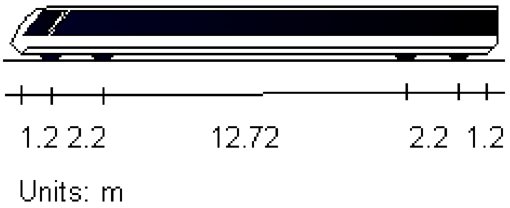

Fig. 3 Wagon axles distances

4. MODELLING

Three models have been used for analysis; a two-dimensional plane-strain model of 60 × 22.5 m^2 with unit width and two three-dimensional models of 60 × 22.5 m^2 with a width of 1.5 m and 3 m (Fig. 2). A major difficulty in modelling such problems is defining borders that can absorb elastic waves. If borders do not absorb elastic waves and reflect them back to the soil, it will affect the results. To resolve this problem, Das suggests embedding dashpots at certain distances on borders to absorb elastic waves [9]. The dashpot coefficients(C) in two- and three-dimensional modellings are defined by eqs. (5) and(6), respectively.

$$C = V_s.\rho.\ L \qquad (5)$$

$$C = V_s.\rho.\ A \qquad (6)$$

where: V_s= local values of shear wave velocity, ρ=bulk density of soil, L = length of the corresponding soil partition where dashpot is applied, A= the area of the partition which the dashpots are supported in three-dimensional modelling.
The number of dashpots and the lengths of soil partitions must be defined by iteration. In each step, the numbers of dashpots must be increased up to the convergence of results. In order to determined he material damping coefficients of components, the frequency of the model was computed by the software at first. For both two- and three-dimensional models the natural frequency (ϖ) was calculated 2.5978 rad/s. The damping ratio (φ) of soil was assumed 3%, which is corresponds to linear elastic deformation. The attenuation characteristics of the slabs and tunnels were neglected; however, a damping ratio of φ= 5% was applied for the rubber mats bellow the slabs [7].
It is found that train induced vibration contains two-directional motions in two-dimensional analysis, and the vertical motion is dominant. Although in three-dimensional analysis the number of motions is three, but the magnitude of longitude motions is very small and still the vertical motion is dominant. However, in this paper only "pseudo-resultant" displacement d is quantified by eq. (7) and presented.

$$d = [d_1^2 + d_2^2{}_{+} + (d_3^2)]^{0.5} \qquad (7)$$

where: d_1 = horizontal displacement, d_2= vertical displacement and d_3 = longitude displacement (only used for three-dimensional analysis).

5. RESULTS

Obtained displacements of the foundations have been presented in Figs. 4-9, for two- and three-dimensional (with a width of 3 m) models, for three foundations located at horizontal distances of 17 m, 24 m and 32 m from the eastern tunnel in two different cases of foundations located at 2 m and 3.5 m under the ground level (Fig. 2).

For the foundation located at 17 m from the tunnel and 2 m under the ground level (Fig. 4) displacements are increasing from 0 s to 2.5 s, where they are maximum; 0.115mm for two- and 0.10 mm for three-dimensional models. Displacements start decreasing after 2.5 s and they become negligible at 10 s. For the same foundation at 3.5 m under the ground level similar displacements are obtained at the same time (Fig. 7).

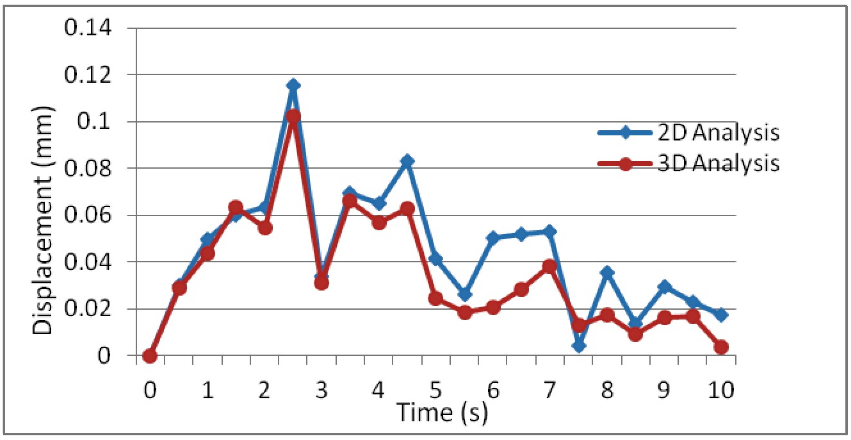

Fig. 4 Displacement of foundation (horizontal distance = 17 m, depth = 2 m)

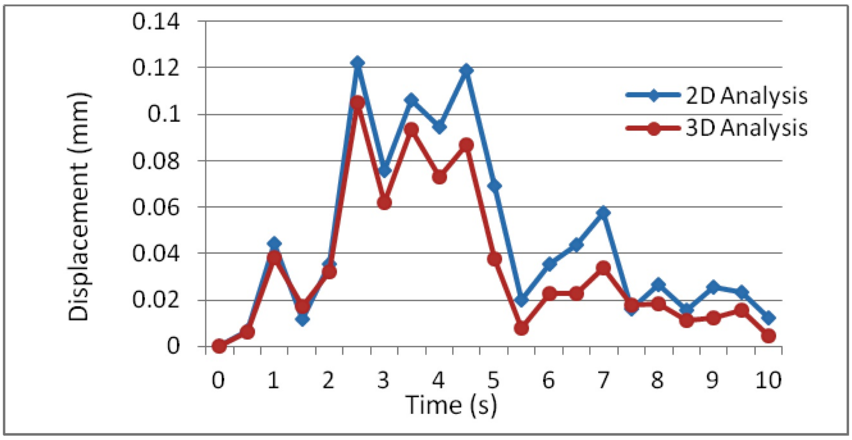

Fig. 5 Displacement of foundation (horizontal distance = 24 m, depth = 2 m)

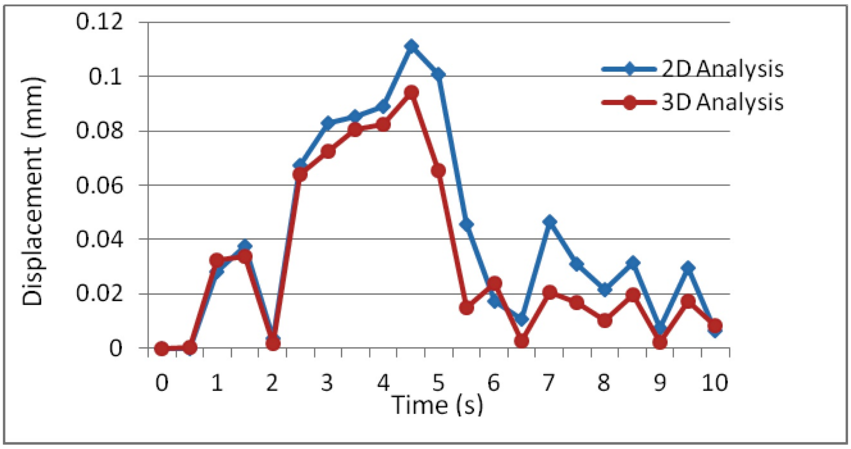

Fig. 6 Displacement of foundation (horizontal distance = 32 m, depth = 2 m)

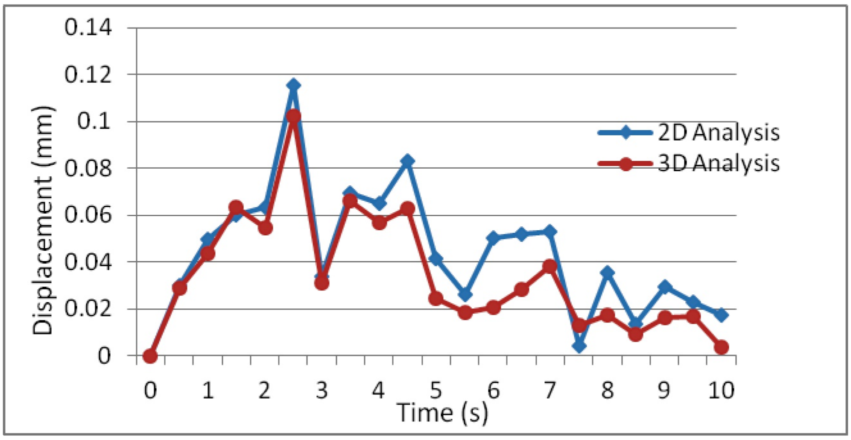

Fig. 7 Displacement of foundation (horizontal distance = 17 m, depth = 3.5 m)

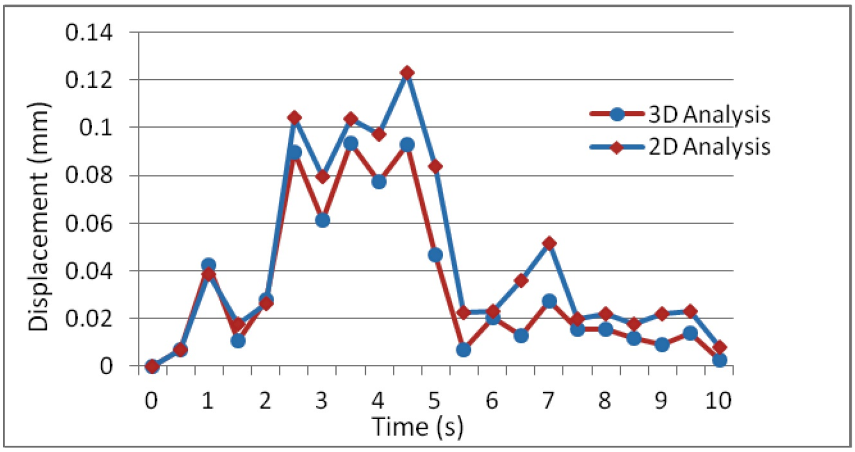

Fig. 8 Displacement of foundation (horizontal distance = 24 m, depth = 3.5 m)

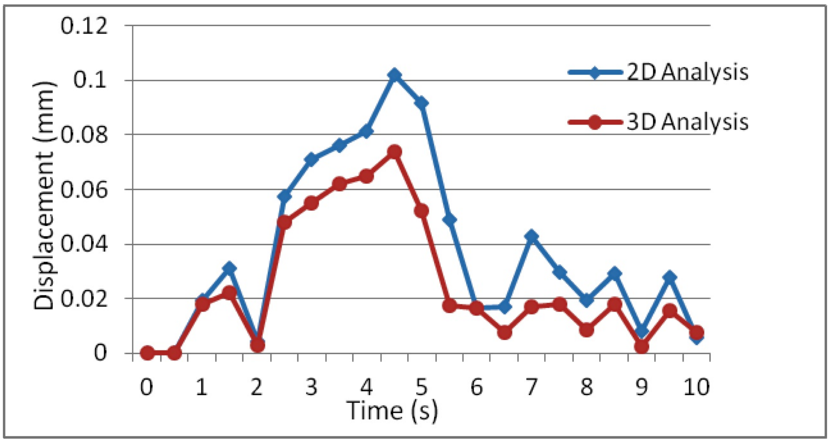

Fig. 9 Displacement of foundation (horizontal distance = 32 m, depth = 3.5 m)

For the foundation at 24 m from the tunnel and 2 m under the ground level (Fig. 5) maximum displacements are 0.12 mm and 0.105 mm for two- and three-dimensional models, respectively, at 2.5 s. For the same foundation at 3.5 m under the ground level maximum displacements are 0.12 mm and 0.095 mm at 4.5 s (Fig. 8).

For the foundation located at 32 m from the tunnel and 2 m under the ground level (Fig 6.) maximum displacements for two- and three-dimensional models are 0.11 mm and 0.095 mm, respectively, at 4.5 s. These are equal to 0.10 mm and 0.075 mm at 4.5 s for the same foundation 3.5 m under the ground level (Fig. 9).

Three-dimensional results indicate that that maximum displacement ranges from 0.075 mm,at 4.5 s for the foundation located at 32 m from the tunnel and 3.5 m under the ground level, to 0.105 mm,at 2.5 s for the foundation at 24 m from the tunnel and 2 m under the ground level.

Maximum displacements from two-dimensional analyses vary from 0.10 mm, at 4.5 s for the foundation at 32 m from the tunnel and 3.5 m under the ground level, to 0.12 mm, for the foundation at 24 m from the tunnel and 2 m (at 2.5 s) or 3.5 m (at 4.5 d) under the ground level.

The displacement of foundations located at 24 m from the tunnel is about 5% greater than that of foundations located at 17 m and 32 m from the tunnel.

Maximum displacements from two-dimensional analysis are between 14% and 33% larger than those from three-dimensional analysis.

The displacements of foundations at 2 m under the ground level are from 5% to 21% larger than those 3.5 m under the ground level.

6. CONCLUSIONS

The finite element method has been used to study the effect of underground railway on the foundation settlement of the Chahar-Bagh madrassa, a historical brick masonry building in Isfahan, Iran. Dynamic tunnel-soil and soil- foundation interactions have been considered in analysis. Two- and three-dimensional linear elastic analyses have been performed and obtained results have been compared. Maximum displacements resulted from two-dimensional analysis are 14% to 33% greater than those obtained from three-dimensional analysis. Maximum displacements of foundations from three- and two-dimensional analyses are 0.105 mm and 0.12 mm, respectively. Foundations horizontally located at 24 m from the tunnel experience displacements about 5% larger than foundations at 17 m and 32 m from the tunnel. The displacements of foundations at 2 m under the ground level are 5% to 21% larger than those 3.5 m under the ground level.

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REFERENCES

[1] Hejazi M. (1997) *Historical buildings of Iran: their architecture and structure*. Southampton and Boston, Computational Mechanics Publications (WIT Press).

[2] Hejazi M., Mehdizadeh-Saradj F. (2012) *Persian architectural heritage: form, structure and conservation*. Southampton and Boston, WIT Press.

[3] Kuhlemeyer K., Lysmar, L. (1973). Finite element method accuracy for wave propagation problems. *Journal of Soil mechanics and Foundations* 421- 427.

[4] Central Office of Isfahan Underground Railway (2006)*Mechanical reports of soil and tunnel material.* Isfahan.

[5] Alamoot Company Ltd (2004). *Geology and geometry reports for the line1.* Isfahan.

[6] Moghadam H. (2004) *Rehabilitating of masonry buildings* (in Farsi). Tehran, Sharif University Publication, 35-56.

[7] Vibration isolation mat, *FIP MAT TM25*, Fip Industrial Italy.

[8] Report of Iranian Rail Transportation Company (2008)*CSR Nanjing Puzhen Rolling Stock Co.*

[9] Das. B. M.(2010) *Geotechnical engineering handbook.* USA, Ross Publication Inc.