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Numerical Prediction of Subway Induced Vibrations: Case Study in Iran-Ahwaz City

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Abstract: Traffic jams in big cities have made necessary the need for use of underground metro trains more than ever. However, movement of trains with appropriate speed in between stations produces vibrations that may sometimes be disturbing for people living in the region. Actual measurement of vibrations in Tehran metro is used to predict numerically the vibrations created by passage of trains in the surrounding surface in city of Ahwaz metro under construction. With comparison of the ground surface vibrations in different stations along the Ahwaz metro route, it is concluded that in general the level of vibrations in Northeast part of the route are higher than the Southwest part, this due to the presence of the rock formation in the Northeast part. The calculated vibrations in the Northeast part are higher than the allowable, therefore, appropriate measures should be taken to decrease these vibrations. Also, According to the result of this research, with twice increase in speed of train, the ground surface vibrations increase by 4 to 6 dB which is consistent with other researches. According to this research there is no distinct relationship between vibrations and depth of water table. It is concluded that probability of the resonance occurrence along the Ahwaz metro is very low.

Key words: Prediction, metro vibration, numerical method

INTRODUCTION

With the increase in population of cities and progress of technology, people's demand toward a comfortable life has also increased. Traffic jam in big cities and shortage of parking lots have made necessary the need for use of underground spaces more than ever.

The use of underground metro trains as a fast and safe vehicle could be appropriate alternative for passengers. However, passage of trains with appropriate speed in between stations produces vibrations that may sometimes be disturbing for people living in the region. These vibrations, which are one of the most serious concerns related to region close to transportation systems, could cause buildings to shake and make rumbling sounds to be heard inside buildings. In addition to human annoyance, these vibrations could affect old buildings and sensitive equipments. They could cause fatigue in the materials of ground and structure, create differential settlement, crack in walls, resonance and other difficulties. Therefore, in designing new railroad, evaluation of vibrations due to movement of trains is one of the important parameter in selecting the route and the type of rail system.

Intense disturbance to human being in residential area occurs when the level of vibrations reach to 85 dB (FTA, 2006). However, according to ISO-2631-2 standard, human response to ground-borne vibration is very complicated and depends on many factors. Howarth and Griffin (1988) showed by different experiments that the number of train passage and the duration of vibrations in addition to vibrations magnitude, play role on human disturbance.

Precise evaluation of subway induced vibrations requires complete information about details of railing system, site geology and other information related to the sources producing and transmitting vibrations from metro line to buildings. Many of these information may not be available during initial stage of design, therefore, application of numerical modeling, using reasonable and simplifying assumptions would be very useful and informative to prediction of vibrations due to passage of metro trains. Fortunately considerable research on this subject have been conducted throughout the world in recent years e.g., Gupta *et al.* (2008), Forest and Hunt (2006a, b), Degrande *et al.* (2006a, b), Clouteau *et al.* (2005), Hemsworth (2000) and Sheng *et al.* (1999) that makes this task obtainable for cases that are in the preliminary stages of the project.

In this research, using numerical modeling in Plaxis v8, induced vibrations due to passage of trains in Ahwaz city subway currently under construction is evaluated

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and the regions with high vibration potential, are identified. The route of line 1 of Ahwaz metro with the approximate length of 23 km connects NE region of the city to SW region by passing through the downtown area and crossing Karoon River. Along this route, 8 stations were selected, each one representative of part of the route. Dynamic analysis on each station was performed and vibrations created on the ground surface due to passage of train were predicted. In addition, the effects of different parameters on these vibrations were evaluated. The findings of this research may be used by authorities for future planning and designing appropriate railing system and etc.

BASICS OF METRO TRAINS VIBRATIONS

Exact assessment of ground vibrations created during passage of underground trains requires complete knowledge of parameters that affect magnitude of these vibrations. Therefore, it is necessary that the process of vibration creation and factors influencing these vibrations to be exactly evaluated.

Some common sources of ground-borne vibration are trains, buses on rough roads and construction activities such as blasting, pile-driving and operating heavy earth-moving equipment. These vibrations cause tangible movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls and rumbling sounds insides rooms. Vibration is perceived directly or it is sensed indirectly as re-radiated noise. The frequency range of interest for subway induced vibrations is 1-80 Hz and for the re-radiated noise it is 1-200 Hz (Gupta *et al*., 2007). Disturbance due to these vibrations occurs when they exceed the threshold of human perception. The range of vibrations that disturb the human are much less than the range that cause disturbance to the regular buildings (FTA, 2006).

The human body responds to an average vibration amplitude and because the net average of a vibration signal is zero, the root mean square (rms) amplitude is used to describe the smoothed vibration amplitude. The root mean square of a signal is the square root of the average of the squared amplitude of the signal. The average is typically calculated over a one-second period. The use of unit of decibel (dB) used for describing the vibrations is also customary.

In general, subway induced vibrations include three basic parts namely source of vibration, route of propagating waves and receivers of vibration. These three parts are shown in Fig. 1. The knowledge of how these parts could affect vibrations is very effective in predicting and lessening of vibrations.

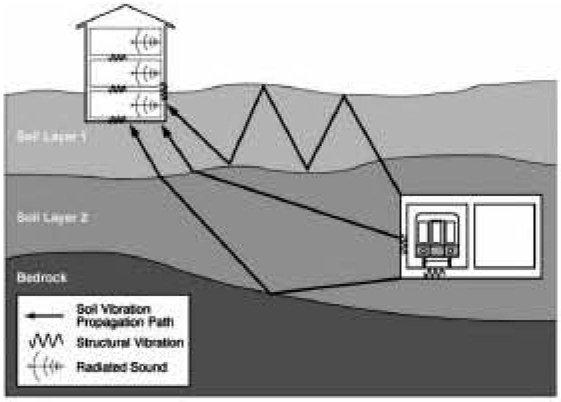


Fig. 1: Propagation of vibrations due to movement of metro trains into ground and buildings (FTA, 2006)

Vibration source: The train wheels rolling on the rails create vibration energy that is transmitted through the track support system into the transit structure. In fact this part includes all the parameters related to train performance and also the train route. Factors such as train speed, train suspension system, roughness of rail surface and wheels and rail supporting system all affect vibrations. Jointed rails, rough rails and impact of wheels on rails all cause severe increase in vibrations in the source.

Degrande *et al*. (2006a, b) measured the vibrations on the rail and also on the axle of train wheels and observed that the produced impact during the passage of wheel from the joint of the rail increases linearly with the increase of train speed. Such that 200% increase in speed of the train created an increase in vibrations of about 4 to 5 dB.

Vibration path: After creation of vibration in the source, these vibrations propagate into the surrounding medium. Soil and subsurface conditions are known to have a strong influence on the level of ground-borne vibrations. Among the most important factors are the stiffness and internal damping of the soil and depth to the bedrock. Experience with ground-borne vibrations indicates that vibration propagation is more efficient in stiff clay soils and that shallow depth to the bed rock seems to concentrate the vibration energy close to the surface and which can result in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can also have significant effects on the propagation of ground-borne vibration (FTA, 2006).

Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics. Therefore in evaluation of vibrations in numerical methods inclusion of all soil layers present at the site, even those with small thickness could lead to more exact prediction.

The presence of the water table may have a significant effect on ground-borne vibration, but a definite relationship has not been established (FTA, 2006). Unterberger (2004) using Flac 4.0 showed that there was no distinct relationship between the changes in the ground water table and the vibrations created due to the passage of trains.

Yi-Qun Tang *et al*. (2008) using continuous dynamic monitoring by means of embedded earth pressure piezometers and pore piezometers around the tunnel studied the response frequency and stress amplitude of the saturated soft clay with the distance from the tunnel due to the subway vibration loading. Also they proposed A formula for the attenuation of the dynamic water pressure response in the soil.

Vibration receiver: The vibration of the transit structure excites the adjacent ground, creating vibration waves that propagate through the various soil and rock strata to the foundations of nearby buildings. The vibration propagates from the foundation throughout the remainder of the building structure.

The receiver building is a key component in the evaluation of ground-borne vibration since ground-borne vibration problems occur almost exclusively inside buildings. The vibration levels inside a building are dependent on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil and the propagation of the vibration through the building. The general guideline is that the heavier a building is, the lower the response will be to the incident vibration energy.

NUMERICAL MODELING

In this research, the prediction of subway induced vibrations on the ground surface in Ahwaz city, is made using the computer code Plaxis V8. The tunnel, train loading and surrounding soil are modeled in plane strain condition.

Engineering geology of the city: Soil conditions of Ahwaz subway route are taken from geotechnical reports supplied from general contractor Keyson Co. of Iran. By careful study of all geotechnical boring logs of the metro route, eight soil profiles at the location of the metro stations were selected as representative of the whole route to be used in dynamic analysis. According to Fig. 2, the selected soil profiles were named as N1 to N8. By precise assessment of geotechnical profiles of these stations, as shown in Appendix, the selected soil profiles

Fig. 2: Plan view of the Ahvaz metro route

could be divided in two distinct parts. First one, the soil profiles from north half of the route mainly consisted of fine grain clay and silty layers over the bedrock formation consisting of red marl, siltstone and sandstone at a shallow depth. Second part, the soil profiles from the south half of the route on which the bedrock formation falls below a depth of 40 m under young alluvial deposits due to the presence of the Ahwaz fault. The young alluvial deposit consists of layers of fine to medium sand, clay and silt with low to medium density.

Determination of Rayleigh damping coefficient: It is very clear that damping in soil and structure affects the amount and form of dynamic response of the system very much. Although, a lot of research in this subject have been done in the past, however little information is available about the determination of damping parameters. Rayleigh damping coefficient is defined as:

$$C = \alpha M + \beta K \qquad (1)$$

where, coefficient α is related to the effect of mass on system damping and coefficient β relates the effect of stiffness on system damping.

For high values of β, vibrations with high frequencies are damped. The coefficient α and β could be determined from the damping ratio D_i, which is related to vibrations with frequency ω_i. The relationship between these parameters is as follows:

$$\alpha + \beta\omega_i^2 = 2\omega_i D_i \qquad (2)$$

Because the strains developed in the soil due to vibrations created by passage of trains are generally low we can assign a constant value for D in the Eq. 2, then:

$$\alpha = 2D\frac{\omega_1\omega_2}{\omega_1 + \omega_2} \qquad (3)$$

$$\beta = 2D\frac{1}{\omega_1 + \omega_2} \qquad (4)$$

Now, we can determine natural frequencies of soil layer in first and second mode using empirical equations and then obtain D and from that, damping coefficient α and β are computed. As it can be seen due to very low strain level, low damping ratios are obtained. By this method values of α and β for all soil layers in different stations are calculated. The values of α and β are in the range of 0.008-2.353 and 0.0083-0.00005, respectively.

Determination of train dynamic load: vibrations due to the train passage on the rail are resultant of several different mechanisms. The most important of these mechanisms are deformation of the rail system due to passage of the wheels, roughness of the rail and the wheels and the rail joints. There are several methods for determining train dynamic loading as an input for dynamic analysis. These methods include, pseudo static load function, analytical load function and direct measurement of train dynamic load. In pseudo static load function method movement of a determined load causes an oscillating load function in one section of the route. In this method the effects of roughness of rail and wheels, the geometry of rail and wheels and impacts due to train braking close to stations are ignored. In direct measurement method, by attaching several velocity meter sensors at an appropriate place near to the train track, the vibrations induced by train movement at rail-subgrade level are directly measured and after some correction, the obtained time history is used as an input loading for dynamic ground response analysis.

In this research, the third method is used and the particle velocity time history obtained from measurement in Hasanabad station in Tehran metro is used as a dynamic load input in dynamic analysis. It should be mentioned that at the time of this research, Ahwaz metro project is at its initial stage and precise information about type of wagons, rail system and subgrade system under rail is not yet known and there may be some differences between the two projects, yet the use of this method as compared with other methods is more precise. In this method all the mechanism that cause the vibration during the passage of train such as train speed, rail joints, roughness of rail and wheels, rail and wheel geometry, impacts due to train braking and etc. are recorded by measurements in Hasanabad station. For recording vibrations seismograph SSR-1 equipped with three short period seismograph SS-1 from Kinemetrics Co. was used. The SSR-1 equipment depending on number of canals was capable of recording 0.03 to 1000 samples per second. The seismograph SS-1 record the velosity with one second period with damping ratio of 0.7.

In order to record vibrations at the same time two sensors was attached, one on the tunnel floor at a distance of 3 m from the rail and second one on the ground surface. The vibrations were recorded at time interval of 0.01 sec for period of 600 sec that include the passage of train. In order to minimise traffic noise, the measurement were performed during the weekend.

In this research the time history of velocity related to the vertical component of vibrations was selected as dynamic loading and it was applied as vertical vibration to tunnel floor in numerical modeling. It should be mentioned that because the measurement was close to the metro station, train has been decelerating, therefore the

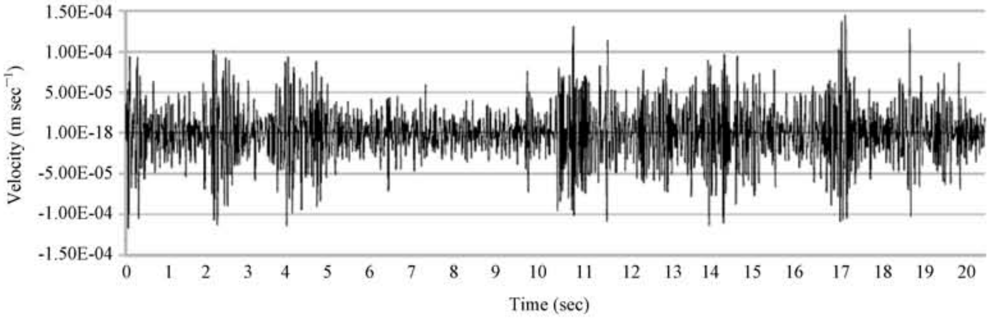


Fig. 3: Measured vibrations at rails level, during the passage of train at Hasanabad station Tehran metro

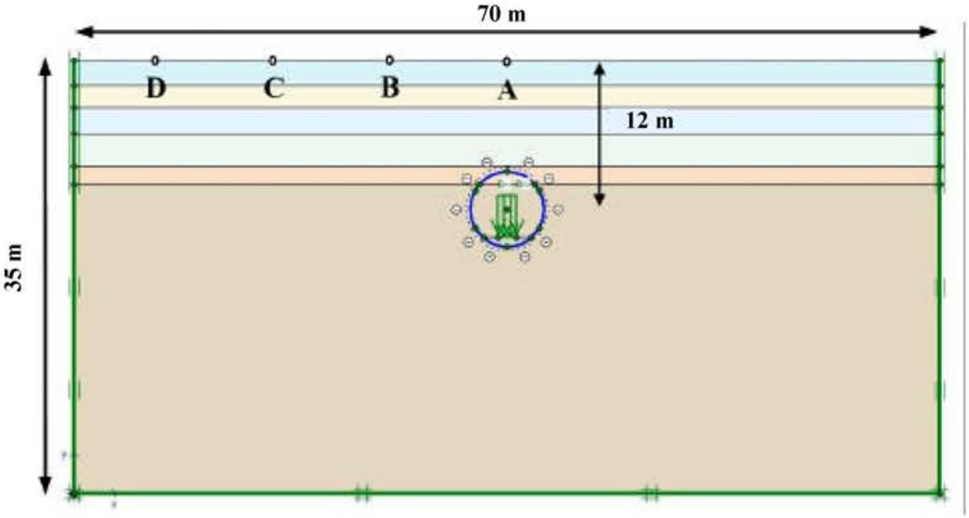


Fig. 4: View of modeling in Plaxis

measured vibration should include the vibration due to braking of the train. Therefore, the selected recording that lasts for 20.48 sec includes all the factors responsible for vibrations during the passage of train. This time history is shown in Fig. 3.

The vibrations measurement in Tehran metro is obtained only at one speed of train and information about vibrations at other train speed was not at hand. Therefore in order to determine the dynamic loading for different speeds of train, empirical method given by US Department of Transportation that is based on many measurements is used to calculate vibrations at different speed of train at a distance of 3 m from the axis of the rail. Then the velocity time history obtained in this way is scaled to the same level of vibration obtained in empirical method. The average speed for train in Tehran metro is 60 km h^{-1} and the maximum speed is 80 km h^{-1}. If we assume the same range of speed for Ahwaz metro, the above mentioned method was used in this research to predict the vibrations due to train speed of 20 to 100 km h^{-1}.

Table 1: Geometry characteristics of 2D model

Geometry characteristics	Values
Dimension of the model	70×35 m
Depth of tunnel	12 m
Diameter of tunnel	6 m
Thickness of lining	30 cm
Thickness of concrete layer at the tunnel floor	70 cm

Numerical modeling in plaxis: Here, a 2D model of tunnel, surrounding soil and dynamic loading of train with the use of Plaxis V8 is introduced in order to evaluate the vibrations propagation due to train passage to the ground surface. The geometry characteristics of 2D model (Fig. 4) are shown in Table 1 and the train dynamic loading is applied to the model as an uniform distributed loading at the rail location.

In this model, two phases of analysis is defined. The first phase consists of elasto-plastic analysis of tunnel excavation and placing the tunnel lining and the second phase includes dynamic analysis related to the passage of train inside the tunnel.

Geotechnical properties of soil layers at different stations used in numerical modeling are shown in appendix and Mohr-coulomb criterion was selected as the soil behavior model. Concrete lining properties used in the modeling are (E = 20000 MPa) and (Poisson ratio = 0.15).

In dynamic analysis, in addition to static boundary conditions, reflection of waves at the model boundaries should be considered. In fact some special boundary conditions have to be defined to account for the effect that in reality the soil is a semi-infinite medium. Without these special boundary conditions the waves would be reflected on the model boundaries, causing perturbation. To avoid these spurious reflections, the static boundaries of the model (which do not exist in reality) are taken sufficiently far away to avoid direct influence of the boundary conditions and also absorbent boundaries are specified at the bottom and right hand side boundary.

In the model 15 nodes triangular elements were used in finite element mesh. For determining the optimum size of elements in order to get reasonable precise result in a minimized time, four different meshing pattern were analyzed and the results of analysis with very fine and fine meshing were very close to each other therefore, fine meshing pattern were chosen (Fig. 5).

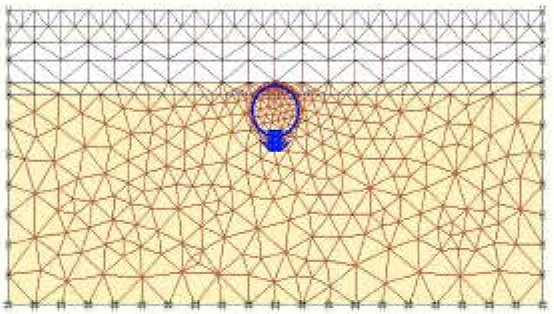


Fig. 5: Fine element generation in Plaxis model

RESULTS

Vibrations at Darvazeh station (N3): As we observe from borehole in this location (Appendix), geotechnical profile consists generally of mudstone, sandstone and siltstone. The rock formation in this location belongs to Aghajari formation. Figure 6 shows the velocity loading applied to tunnel floor and Fig. 7 to 11 show diagram of vertical particle velocity at points A, B, C and D at the surface ground. The position of these points is shown in Fig. 4. As we compare vibrations at rail level and at the surface ground, for example point A, an increase in vibrations level is observed. Also by comparing the results for point A~D we observe a decrease in vibrations with distance from the tunnel. Figure 11 shows RMS velocity in terms of decibel. In Fig. 11, average vibrations produced at the surface ground at different distances from rail axis during the passage of train with speed of 80 km h^{-1} can be seen. According to Fig. 11, vibrations at point A (zero distance from the rail on ground surface) is equal to 84 dB, at point B (10 m) = 79.7 dB, at point C (20 m) = 77.5 dB and at point D (30 m) = 73.2 dB.

One of the noticeable point of the analysis at this location is that the amount of decrease in vibrations with distance away from the tunnel is low as it is shown in Fig. 11. The diagram is flat as compared with those in other stations shown later in the study. The reason for this phenomenon is the presence of the bedrock formation close to the surface of ground. Actually, vibration energy is concentrated in the surface layers and is propagated horizontally.

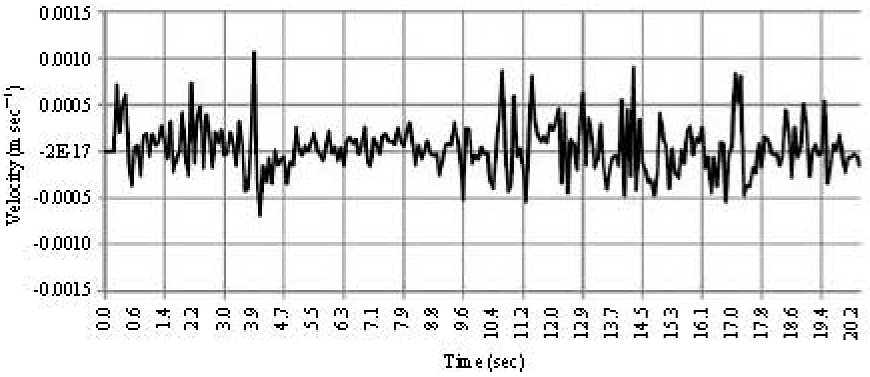


Fig. 6: Velocity loading applied to tunnel floor, train speed = 80 km h^{-1}, Darvazeh station (N3)

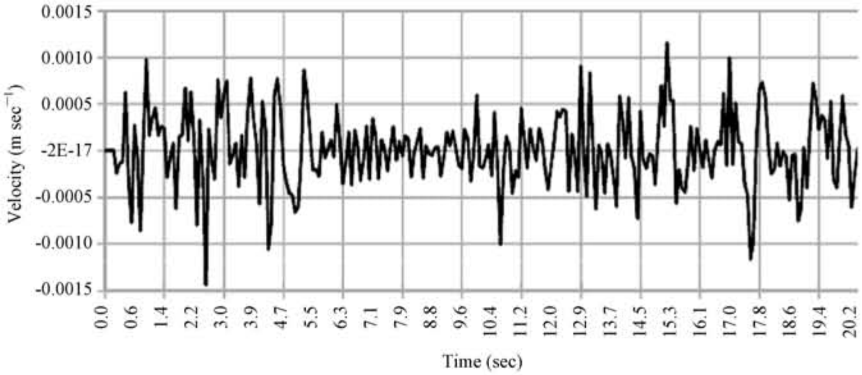


Fig. 7: Computed velocity with time at point A, train speed = 80 km h^{-1}, Darvazeh station (N3)

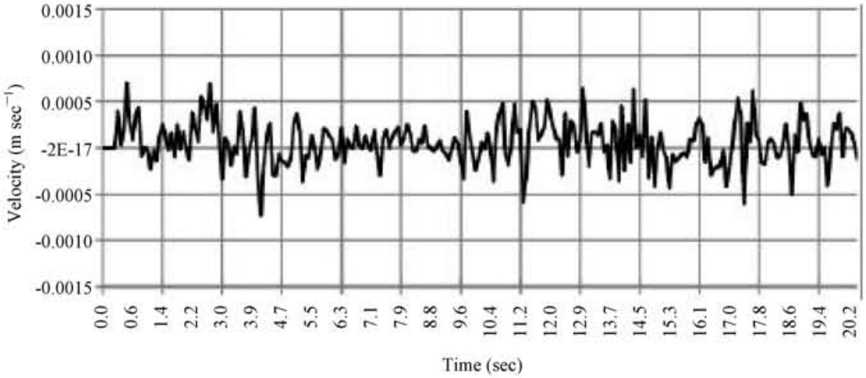


Fig. 8: Computed velocity with time at point B, train speed = 80 km h^{-1}, Darvazeh station (N3)

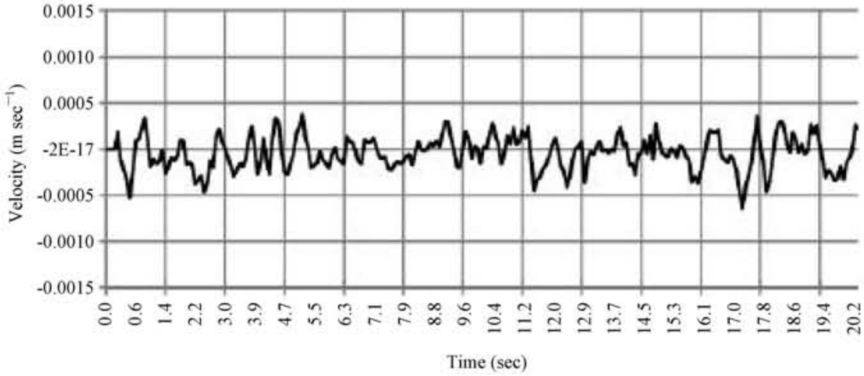


Fig. 9: Computed velocity with time at point C, train speed = 80 km h^{-1}, Darvazeh station (N3)

Vibrations at Kargar station (N8): Geotechnical profile at this station that is shown in Appendix consists of young alluvial deposits including clayey, silty and sandy deposits. The first 2 m of soil consist of fill materials then it turns to brown medium to firm silty clay to depth of 3.8 m, to medium fine sand to depth of 5.9 m, to medium to firm brown sandy silt to depth of 8.5 m, to firm to very firm brown clay to depth of 10 m and finally to dense sand to depth of 35 m.

Figure 12 shows the result of analysis for train with speed of 80 km h^{-1} at point A located above the axis of the rail on the ground surface.

As we compare Fig. 12 with Fig. 6, we observe that the vibrations at tunnel level, has been damped as they

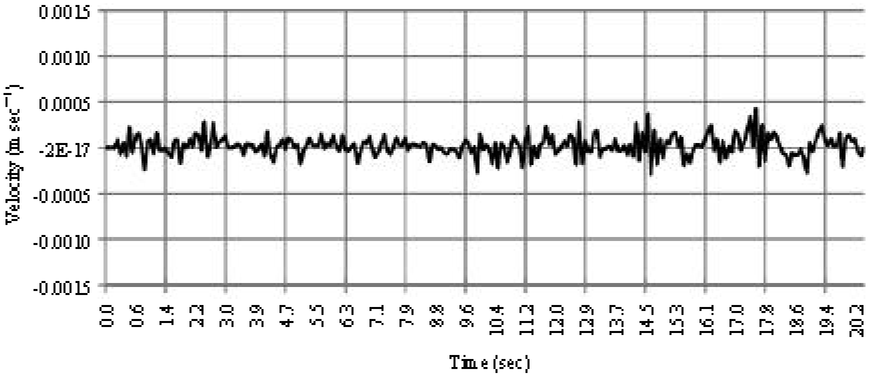


Fig. 10: Computed velocity with time at point D, train speed = 80 km h^{-1}, Darvazeh station (N3)

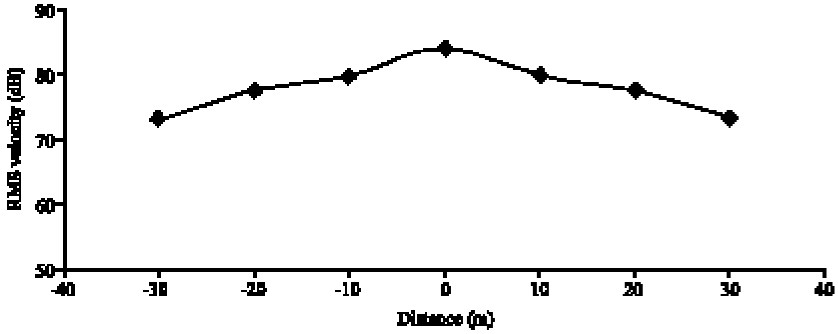


Fig. 11: Ground surface vibrations at different distances from rail axis, train speed = 80 km h^{-1}, Darvazeh station (N3)

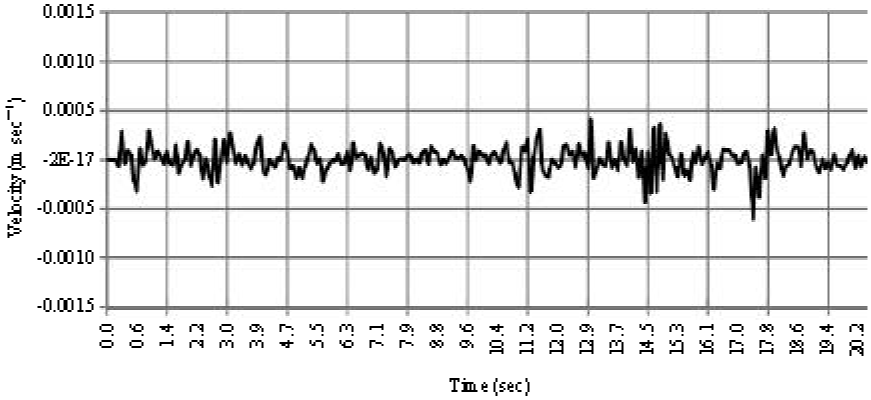


Fig. 12: Computed velocity with time at point A, train speed = 80 km h^{-1}, Kargar station (N8)

reach the surface of ground at this station. Figure 13 shows RMS velocity in terms of decibel at different points away from the axis of the rail. As it is shown in Fig.13, the level of vibrations rapidly decreases with distance away from the axis of the rail. For example at distance 30 m from the rail (point D), vibrations have decreased by 17 dB. The most important reason is significant geometric damping of the waves due to the presence of bedrock formation at much deeper elevation at this location. In fact, propagation of waves downward into the ground, without any considerable reflection, can cause a rapid decrease of vibration level at the surface with distance away from the axis. This prediction is completely different from N3 station explained earlier. We can also observe that the

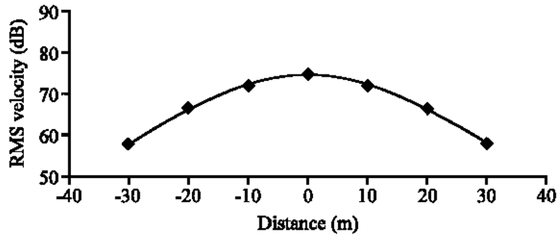


Fig. 13: Ground surface vibrations at different distances from rail axis-train speed = 80 km h^{-1}, Kargar station (N8)

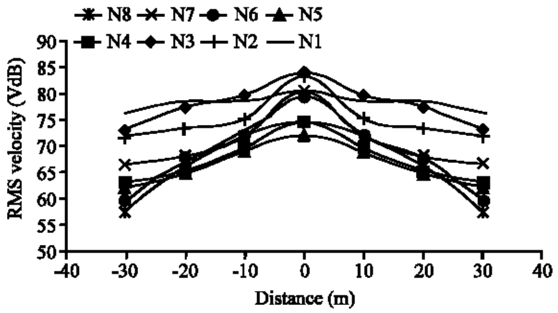


Fig. 14: Ground surface vibrations at different distances from rail axis-train speed = 80 km h^{-1} all stations

level of vibrations in this station is lower than those in station N3. These differences are due to different layering and material properties at the two stations.

Vibrations of ground surface along the metro route: The results of analysis for other stations at speed of 80 km h^{-1} are shown in Fig. 14. By comparing vibrations of ground surface at different stations from Northeast (N1) to Southwest (N8) along the metro route we can see a general decrease in the level of vibrations. However, there are some exceptions to this general trend. For example, in station N7 the level of vibrations is slightly higher than that in station N8 despite of the similarity in soil profile. This phenomenon could be due to the presence of layer of dense sand at the depth of 18 m at the station N7 which acts like a bedrock formation and causes reflection of waves to the surface layers. In general, the level of vibrations in North part of the Ahwaz metro route is higher than that in Southern part. This observation is consistent with the depth of rock along the route. Geotechnical boring logs of the metro route, in selected stations are shown in Appendix.

Decrease in vibrations with distance from the rail axis: One of the noticeable points in the surface ground vibration curves in Fig. 14 is the slope of these curves, which indicates the rate of decrease of vibration with increase in distance from the axis of the rail. The slope of curves in Northeast of the route is very low. This means that the vibrations due to passage of train could affect even the buildings in far distances. On the other hand the slope of the curves in Southwest of the route is higher which means vibrations damp very fast with the distance from the axis of the rail and they could only affect the buildings in close distance. In Fig. 15, this point is clearly observed for stations Zeytoon (N1) and Kargar (N8)

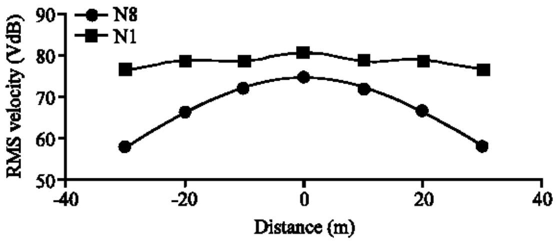


Fig. 15: Comparison of slop of curves of ground surface vibrations with distance-speed = 80 km h^{-1}

One of the most important reasons for this difference in behavior between the ground surface vibrations curves in Northeast and Southwest stations is the depth of bedrock. The shallow depth of bedrock in Northeast part of the route causes effective propagation of vibrations to the ground surface. Major parts of waves will be reflected back to the surface as they hit the bedrock and therefore with multiple reflections of waves they propagate horizontally in surface layers.

In Fig. 16 and 17, particle velocity vectors after passage of train from station N3 and N8 are shown. The difference in the pattern of vectors in Fig. 16 and 17 can be seen clearly.

Effect of train speed on vibrations: The speed of train along the route between stations varies, therefore in order to predict exact vibration at each point along the route it is necessary to evaluate the ground vibrations at different train speed. Figure 18 shows changes in speed of train with time and with the traveled distance between two metro stations.

As it is observed in this Fig. 18, the train begins to travel at the station from zero speed, after a distance of about 250 m it reaches to maximum speed of 80 km h^{-1} and it travels at this constant speed for a distance of about 600 m. Then at a distance of about 250 m from the next station then train begins to decelerate until it reaches speed of zero when it arrives at the station. This is repeated in other parts of the route between stations.

In order to evaluate the effect of train speed on vibrations, train dynamic load related to speed of 20, 40, 60, 80 and 100 km h^{-1} was applied to the model at stations

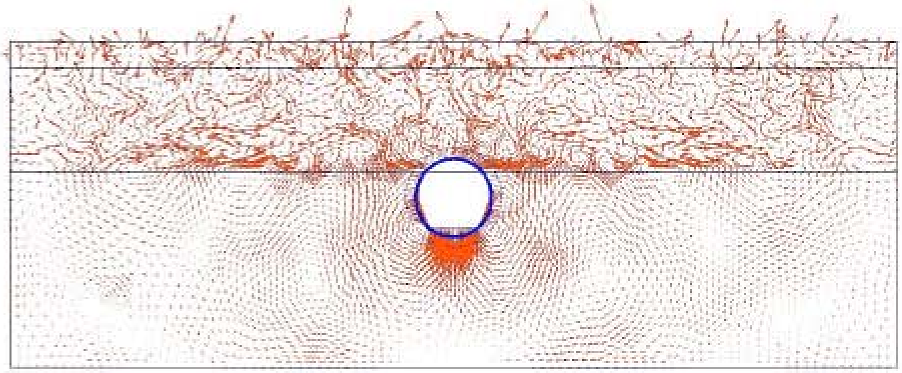


Fig. 16: Concentration of vibration energy at surface layers due to reflection of waves during impact with rock-Darvazeh station (N3)

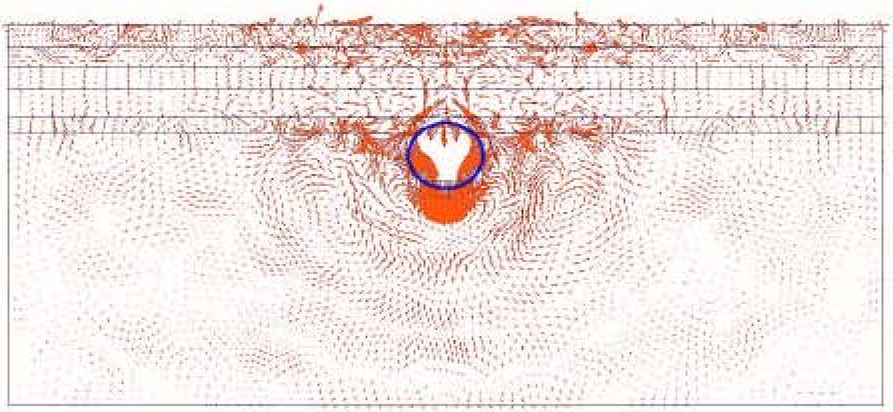


Fig. 17: Particle velocity vectors, Kargar station (N8)

Fig. 18: Changes in distance and speed of train with time between two stations

N1 to N8 and dynamic analysis was performed. Figure 19 shows the changes of the ground surface vibrations in terms of rms velocity at a distance of 20 m from the axis of tunnel at different speed of train. According to Fig. 19, when train speed becomes twice, the ground vibrations increases by about 4 to 6 dB. This result is consistent with experiments performed by US Department of Transportation. Figure 20 and 21 also show the changes in peak particle velocity at the ground surface with distance from the axis of the rail at different train speed. it is observed that PPV at the ground surface decrease with distance from the axis of the rail and this decrease at further distances is not much affected by train speed.

Effect of depth of ground water table on vibrations: Depth of ground water table along the route of Ahwaz metro is very close to the ground surface. Also because of seasonal floctuation of ground water table, it is necessary to evaluate this effect on the level of vibrations. Therefore, dynamic analysis with train speed of 80 km h^{-1} was performed at Kargar station (N8) with different depth to the ground water table. Figure 22 shows the results of this analysis. According to these results, there is no regular relationship between the ground surface vibration and depth of ground water table. For example, vibrations at a distance of 30 m from the axis of the rail, when depth of ground water table is at 3.8 m is equal to 57.9 dB. With lowering the water table the vibrations is increased such

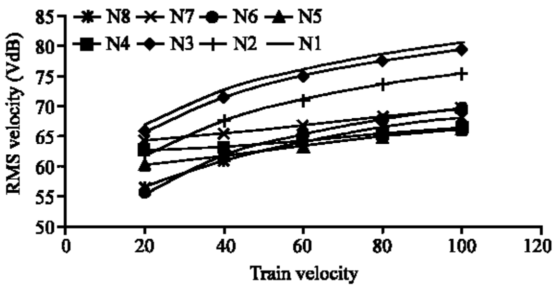


Fig. 19: Changes in level of ground surface vibrations with speed at point C (20 m from the axis of rail)

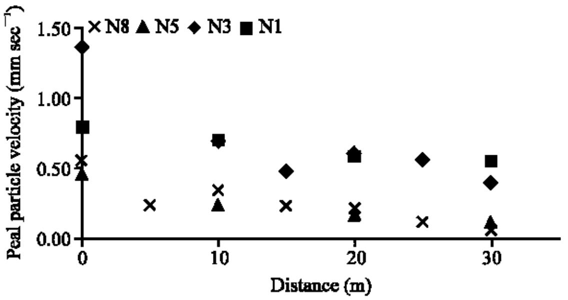


Fig. 20: Maximum particle velocity at different distances from the axis of the rail train speed = 80 km h^{-1}

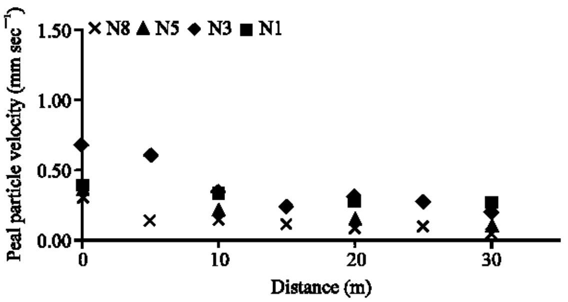


Fig. 21: Maximum particle velocity at different distances from the axis of the rail train speed = 40 km h^{-1}

that when water table is at depth of 11.5 m the vibrations at a distance of 30 m from the axis of the rail amount to 63.65 dB and with further lowering of water table, the level of vibration decreases again. Therefore, For precise evaluation of the ground surface vibrations, it is necessary that the depth to the water table to be determined exactly.

Resonance during passage of train: One of the important aspects in evaluation of subway induced vibrations that should be taken into account is determination of natural frequency of railing system and frequency content of dynamic loading of train. When the magnitude of the two

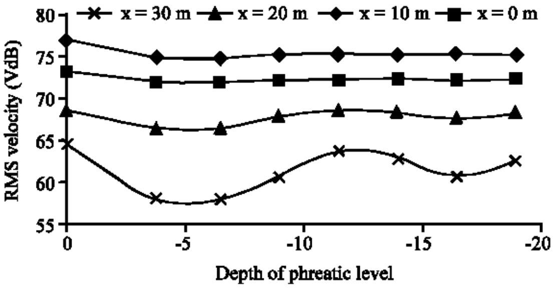


Fig. 22: Changes in vibrations at different depth of water table-Kargar station (N8)

frequencies are close to each other, the occupance of resonance is probable. In other word the rail system, rail support and tunnel lining should be designed in such way that natural frequency of the whole system is far enough from prominent frequency of dynamic loading of train.

In order to determine the natural frequency of the railing system we used trial and error method in which a harminic sinusoidal loading with different frequencies is applied to the railing system for 2 sec. Then for evaluating natural frequency of the system in free osilation, it was allowed to osilate without outside loading for 2 sec. This loading function is shown in Fig. 23. After that, the ground surface vibrations due to this loading were obtained. At Zeytoon station (N1) harmonic loading with frequencies of 1 to 5 Hz was applied to the model and the resulting response is shown in Fig. 24. As it is observed in Fig. 24, the ground surface vibration due to this loading pattern with frequency of 1 Hz is irregular and the amplitude of vibration is very low. With increase in loading frequency, the vibrations become more regular and the amplitude is increased. As it is clear from Fig. 24 vibrations at loading frequency of 3 Hz have highest amplitude and at higher frequencies the amplitude of vibration is decreased and the vibration becomes irregular again indicating the occupance of resonance at frequency of 3 Hz. Therefore from this observation we can conclude that the natural frequency of the system in this station is 3 Hz. By repeating this procedure for other stations, it is concluded that natural frequency of the railing system along the metro route in Ahwaz geology is about 2-3 Hz.

In order to determine frequency content of train loading function, using fast Fourier transformation, time domain function is converted to frequency domain as shown in Fig. 25. As it is observed from Fig. 25, the predominate frequency of train loading is in the range of 10 to 25 Hz. Therefore, comparing the predominant frequency of train loading and natural frequency of the system along the Ahwaz metro route, it is concluded that the probability of resonance occupance is very low.

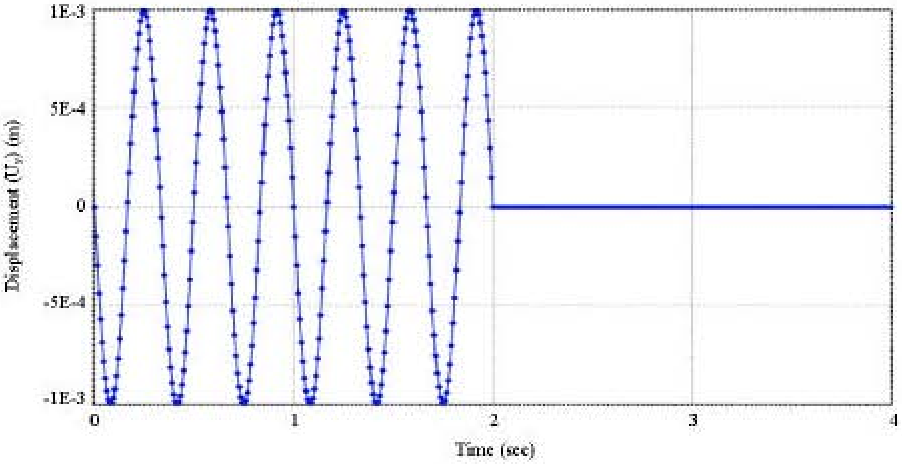


Fig. 23: Sinusoidal loading with frequency of 3 Hz and maximum amplitude of 0.001 m

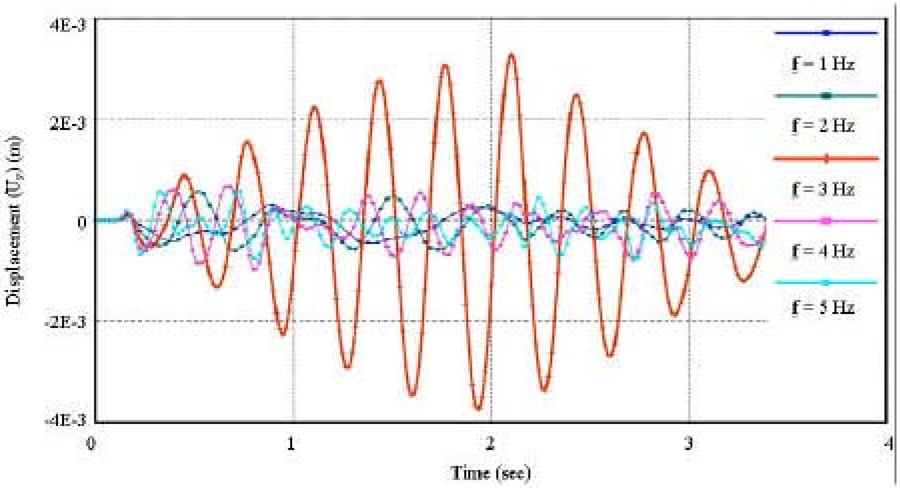


Fig. 24: Ground surface vibrations at a distance of 20m from the axis of the rail due to harmonic loading at different frequency-Zeytoon station (N1)

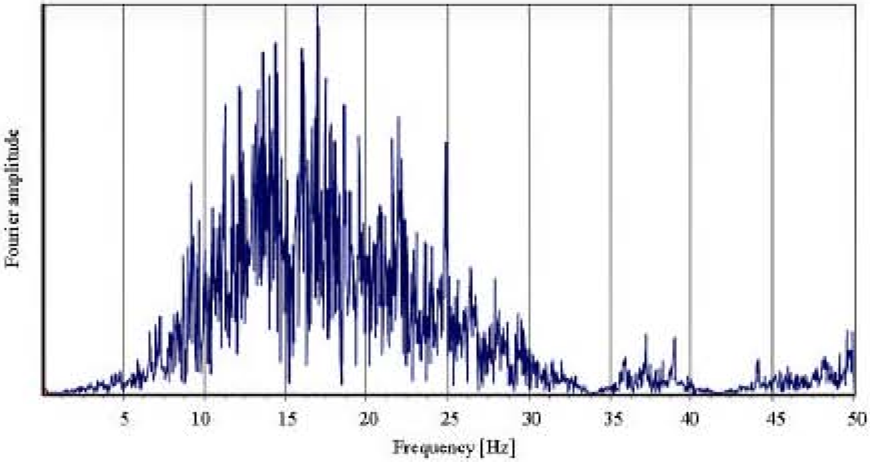


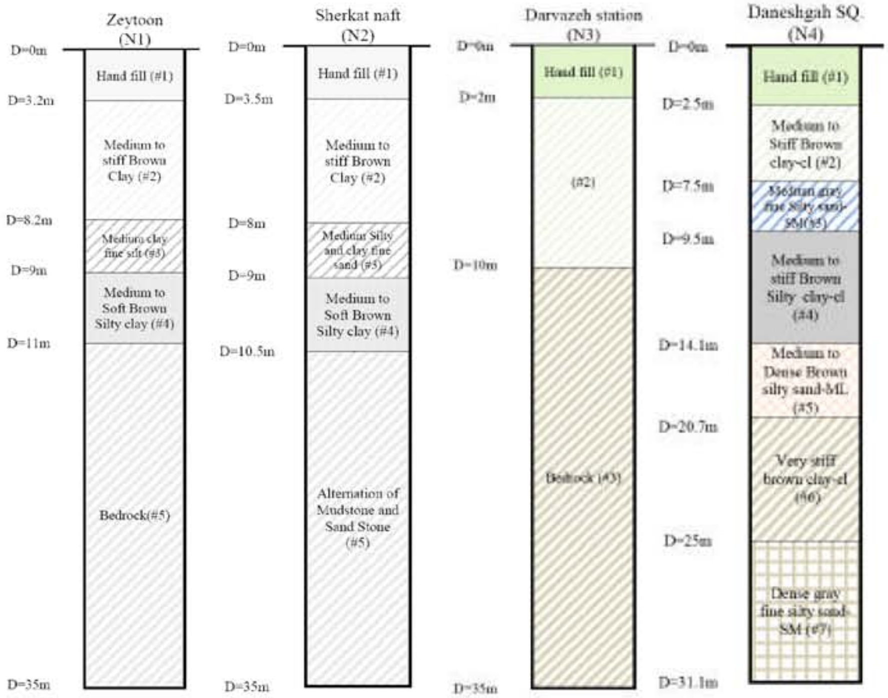
Fig. 25: Train loading function at frequency domain

CONCLUSIONS

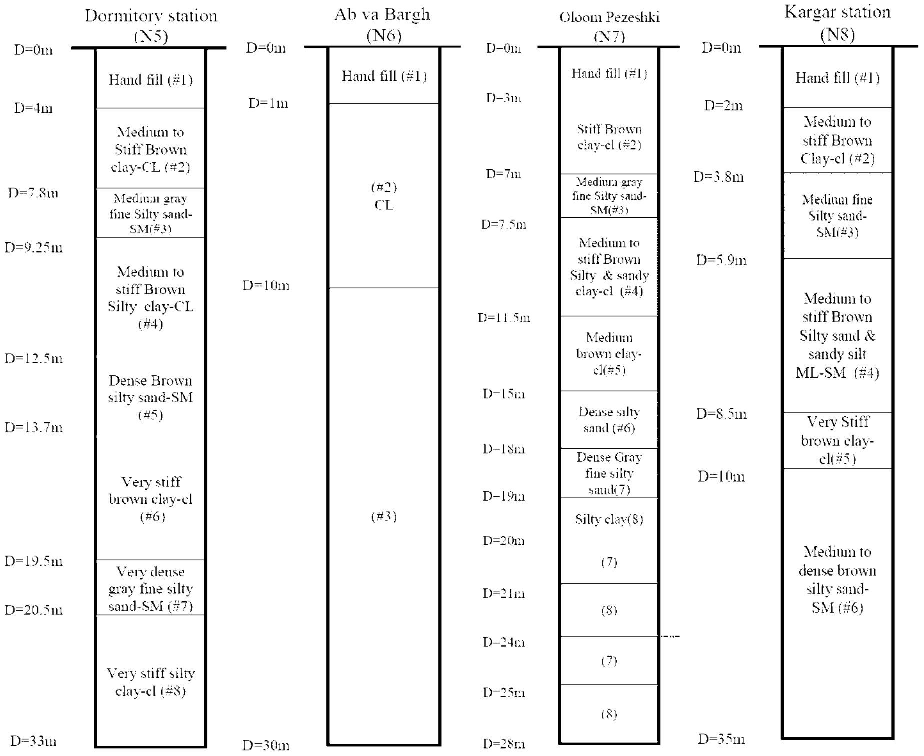
According to dynamic analysis performed, the following conclusions are reached in regard to subway induced vibrations in Ahwaz geology.

- With comparison of the ground surface vibrations in different stations along the Ahwaz metro route, it was observed that in general the level of vibrations in Northeast part of the route are higher than the southwest part. One of the most important factor responsible for this observation is the shallow depth of the rock and also soil profile in the Northeast part of the route
- Assuming allowable vibration of 75 dB for residential building and 30 to 70 passage of train each day, it seems that when the speed of train is 80 km h^{-1} in Darvazeh station (N3) at a distance of 25 m from the axis of the rail, Zeytoon station (N1) at a distance of 30 m and Naft station (N2) at a distance of 10 m from the axis of the rail, the vibrations at the ground surface become more than 75 dB and appropriate measures should be taken to decrease these vibrations
- Because of shallow depth of rock in Norheast part of the route, vibration energy due to passage of train is concentrated in the surface layers and these vibrations affect the buildings in far distances from the axis of the rail
- The speed of train is an inportant factor in vibrations due to passage of train.According to the result of this research, with twice increase in speed of train, the ground surface vibrations increase by 4 to 6 dB which is consistent with other researches
- Maximum particle velocity at the ground surface decreases with distance from the axis of the rail and this decrease is not affected by the speed of train at a distance about 15 m from the axis of the rail
- The depth to water table is one of the effective factors in level of propagated vibrations to the ground surface. However, according to this research there is no distinct relationship between vibrations and depth of water table
- According to this research the natural frequency of the railing system and soil profile along the Ahwaz metro route is about 2 to 3 Hz and the predominant frequency of train loading is determined to be 10 to 25 Hz, therefore, it is concluded that probability of the resonance occurrence along the Ahwaz metro is very low

APPENDIX



Appendix continued:



Appendix: Boring logs of stations and soil parameters used in dynamic analysis

Appendix: Geotechnical properties of soil layers at different stations used in numerical modelling

								(Damping parameters)			
Layer	γ_d (kN m^{-3})	ω_n (%)	C_u (kN m^{-2})	ϕ (deg)	I_p	E (kN m^{-2})	K_0	D	α	β	K (cm sec^{-1})
Zeytoon station (N1)											
No. 1	15.0	~	-	25	-	2000	0.57	1.2	0.190	0.0005	~
No. 2	15.0	22	30	-	23	3300	0.56	0.9	0.109	0.00058	~
No. 3	16.0	20	-	28	-	20000	0.53	1.2	2.353	5.38E-05	~
No. 4	15.8	20	40	-	8.5	4000	0.46	1.1	0.365	0.000278	~
No. 5 Sta.	19.7	~	600	30	~	80000	1.00	-	-	-	~
No. 5 dyn.	19.7	~	600	30	~	883600	1.00	~	8.00E-03	8.30E-04	~
Sherkat Naft station (N2)											
No. 1	15	~	-	25	2000	0.57	1.2	0.190	5.00E-04	1.00E-05	
No. 2	15.6	24	35	-	4500	0.48	1	0.161	5.60E-04	5.00E-06	
No. 3	16.5	20	-	32	10000	0.47	1.2	1.300	9.70E-05	6.00E-06	
No. 4	15.4	25	30	-	5500	0.48	1	0.535	1.69E-04	5.00E-06	
No. 5 Sta.			600	15	80000	1.00	-	-	-	~	
No. 5 Dyn.			600	30	883600	1.00	~	0.008	0.0083	~	
Darvazeh station (N3)											
No. 1	15	~	-	25	-	2000	0.57	1.2	0.190	0.0005	~
No. 2			50	-	16	13000	0.51	1.0	0.142	0.00056	~
No. 3 Sta.	19.7	~	600	30	~	80000	1	-	-	-	~
No. 3 Dyn.	19.7	~	600	30	~	883600	1	~	8.00E-03	8.30E-04	~
Daneshgah SQ. station (N4)											
No. 1	15	~	-	25	-	2000	0.57	1.2	0.190	0.0005	~
No. 2	16.1	22	55	-	25	4000	0.58	0.8	0.112	0.000541	5.00E-06
No. 3	16.5	20	-	35	-	14200	0.43	1.2	0.777	0.000163	6.00E-06
No. 4	16.5	21	60	-	8	8300	0.46	1.1	0.229	0.00045	5.00E-06
No. 5	16.5	20	-	35	-	16600	0.43	1.2	0.254	0.000497	8.50E-06
No. 6	17.4	19	200	-	21	20000	0.55	0.9	0.296	0.00023	9.75E-06
No. 7	16.5	22	-	42	-	40000	0.33	1.2	0.435	0.00029	4.50E-06

Appendix continued:

Layer	γ_d (kN m^{-3})	ω_n (%)	C_u (kN m^{-2})	ϕ (deg)	I_p	E (kN m^{-2})	K_0	(Damping parameters) D	α	β	K (cm sec^{-1})
Dormitory station (N5)											
No. 1	15.0	~	-	25	~	2000	0.57	1.2	0.19	0.0005	~
No. 2	16.7	18	40	-	24.5	7700	0.57	0.9	0.204	0.000301	5.00E-06
No. 3	16.2	22	-	32	-	10000	0.47	1.2	0.906	0.00014	7.00E-06
No. 4	16.5	21	60	-	15.0	8300	0.50	1.2	0.289	0.000284	5.00E-06
No. 5	16.8	18	-	35	-	12500	0.42	1.2	1.221	0.000104	5.00E-06
No. 6	17.2	19	90	-	22.0	8300	0.55	0.9	0.141	0.000465	4.50E-06
No. 7	16.7	20	-	38	-	25000	0.38	1.2	2.101	6.02E-05	4.00E-06
No. 8	17.2	19	170	-	19.0	25000	0.53	0.9	0.119	0.000607	3.00E-06

Layer	γ_d (kN m^{-3})	ω_n (%)	C_u (kN m^{-2})	ϕ (deg)	E (kN m^{-2})	K_0	(Damping parameters) D	α	β	K (cm sec^{-1})
Ab va Bargh station (N6)										
No. 1	15.0	~	-	25	2000	0.57	1.2	0.19	5.00E-04	1.00E-05
No. 2	18.0	~	32	5	10000	0.50	1.2	0.118	7.40E-04	~
No. 3	19.7	~	600	30	80000	1.00	-	8.00E-03	8.30E-04	~
Oloom Pezeshki station (N7)										
No. 1	15.0	~	-	25	2000	0.57	1.2	0.19	0.0005	~
No. 2	16.4	22	60	-	4000	0.54	0.9	0.147	0.00047	3.00E-06
No. 3	16.6	20	-	32	7700	0.47	1.2	2.11	5.00E-05	3.00E-05
No. 4	16.3	22	65	-	5555	0.50	1.0	0.184	0.0004	3.00E-05
No. 5	1.61	23	45	-	6666	0.46	1.1	0.253	0.00036	8.00E-05
No. 6	16.6	21	-	35	33300	0.43	1.2	0.73	0.00014	5.00E-05
No. 7	16.8	20	-	37	25000	0.40	1.2	1.90	5.68E-05	1.00E-05
No. 8	17.7	17	200	-	33300	0.52	1.0	0.579	0.00013	5.00E-06
Kargar station (N8)										
No. 1	15.0	~	-	25	2000	0.57	1.2	0.190	5.00E-04	1.00E-05
No. 2	16.0	23	35	-	4000	0.55	0.9	0.320	2.03E-04	1.00E-06
No. 3	17.0	20	-	30	20000	0.50	1.0	0.869	1.45E-04	1.00E-05
No. 4	16.1	23	45	-	6600	0.50	1.0	0.328	0.00025	2.00E-06
No. 5	16.4	21	75	-	6600	0.50	0.9	0.472	0.0001	1.00E-06
No. 6	16.0	21	-	35	20000	0.42	1.0	0.073	0.0017	1.13E-05

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