DEVELOPING AN APPROXIMATE APPROACH FOR VIBRATION AND NOISE ANALYSIS COMBINING FEM AND FTA GUIDELINE

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Abstract: Railway systems are one the most important transportation methods through which many authorities can ensure proper sustainable development in their considered region like an urban area. However, like every other system, this kind of transportation have some drawbacks by which affect the quality of life for neighbor residents. Annoying noise and also train induced vibration are significant problems in urban areas so many efforts are done in order to reduce them. FTA (Federal transportation administration) guideline provides criteria for general assessment based on field experiences to estimate the future vibration levels. Because of various project characteristics and different environments, these criteria are rough and may provide a wrong estimation. In this study, FTA criteria have been simulated using (FEM) finite element method and required soil parameters fro the model were extracted from FEMA (Federal Emergency Management System), ACI (American Concrete Institute) and FHWA (Federal Highway Administration). Dynamic behavior of soil, especially soil damping, is too substantial in this finite element modeling and damping of the soil in the model and real soil must be the same. Using a simple algorithm based on IBC (International Building Code) and ISO (international Organization for Standardization) and by consideration of soil dynamics and dynamics of unbounded media, a finite element model was developed. Using this procedure, it is possible to validate the efficiency of different vibration reduction measures and choose the right alternative. It must be noted using this method, calibration of a model with real situation is possible by varying of model parameters.

Keywords: railway induced vibration, FTA, FEM, Soil dynamics

1   INTRODUCTION

Sustainable development is an inevitable choice for human life and transportation is one of the major component. In a developed area, many kind of transportation modes must be available but railway is the most efficient and also environmentally friend. However, like every system, railway transportation has its own drawbacks. For an urban area, the main problem is noise and vibration produced by trains and transmitted to neighbor buildings which annoy the residents. In order to provide countermeasures, many studies and tests have been performed and some of them were summarized as codes and guidelines. In FTA guideline, vibration assessment and analysis has been provided based on field tests and experiments. By using FTA, misunderstanding in general assessment and detailed analysis may happen. For example, there is no parameter related to dynamic properties of soil in general assessment stage. Based on FTA, it's supposed that soils with clays produces more vibration levels which in many cases is not correct. On the other hand, frequency content of system components is not considered, thus it can affect the efficiency of vibration reduction measures. By comparison of latest studies, FTA vibration damping and resonance

values for different components are too different with measured values. Estimation of ground born noise is based on frequency content, but in general assessment there is no frequency based measures and so a true ground born noise analysis is not possible. FTA guideline doesn't apply numerical methods due to simplifications of soil complex behavior. Instead of FEM, it suggests an experimental method which uses impact load, excites all frequencies at the same level and eventually calculate dynamic response of the soil. By this method, in a railway project, varying of tunnel overburden results in various soil dynamic parameters and so provide different transmission functions which causes significant test numbers and extra costs.

By considering of above mentioned issues, FTA procedure is consistent for low number of points but for vibration estimation of an urban railway project and determination of proper vibration reduction measure, it could cause significant costs. In return, ISO code suggests hybrid method by which numerical method is used for force density calculation and field tests provide transmission measurements or vise versa.

2   LITERATURE REVIEW

Generally, various finite element models for vibration calculation have been provided. These models are as follows:

2.1   Vibration Estimation Based On Elastic Half Space

The most famous procedure for vibration calculation based on this method is PiP. PiP or "Pipe-in-Pipe" is an elastic half space developed by (Hussein et al 2007).

2.2   Vibration Calculation Using 2D Models

In this method effective load must be determined accurately and applied on model. There are two important issues which are not considered this procedure:

- Material damping and geometrical damping which require changing of modeling procedure and shape function.

- Mesh size of the model has direct influence on frequency content of the model so that the length of the model must be not less than five time of wave length and ratio of mesh dimension must be not greater than 1 to 12.

This procedure was introduced by (Minsili et al 2013) for vibration investigation in a building. (Nejati 2012) developed a finite difference model for vibration investigation of Tehran metro line 4 by focusing on material damping and soil parameters in dynamic analysis.

2.3   2.5 D Model

This model includes a 3D model for tunnel and soil parameter determination. Results of this model are considered as inputs of two another 2D model for vibration propagation. This method developed by (Gardin 2003).

2.4   Hybrid Models

The concept on hybrid models was introduced by (Verbakan 2014). This method is a combination of finite element modeling and field tests. In this procedure, a finite element model is provided and verified by field tests. This method has high accuracy (considering calibration of the model) comparing with just FEM and low cost in comparison of extensive filed tests.

3   PRINCIPLES OF MODELING

The mechanism of induced noise and vibration in a building is totally dependant to wheel-rail interaction. By moving of train on rail and through of interaction between rail and wheel a vibration energy is created. This vibration can be increased Depending on rolling stock type and rail surface quality. The produced vibration in superstructure is transferred to tunnel structure and then to the surrounding soil. Depending on type of the soil, two kind of vibration will be considered: soil vibration and tunnel vibration. Due to the fact that dynamic parameters of the soil is much less than tunnel structure, most of the vibration energy transmitted by soil. Soil itself consists of various layers in which have different dynamic properties. According to (Kramer 1996), transferred vibration depends on Impedance constant and on the other hand longitudinal and transverse wave speed. Attenuation effects can increase or decrease soil amplitude by soil depth (Figure 1). When vibration waves reach ground surface, they reach to building foundation and through soil-structure interaction, significant vibration reduction happens which is called coupling lost (FTA). Vibration transmission into walls and building segments can cause vibration reduction or amplification which is depend on structure type and building material. Vibration of walls and floors produced structure born noise which is annoying for residents.
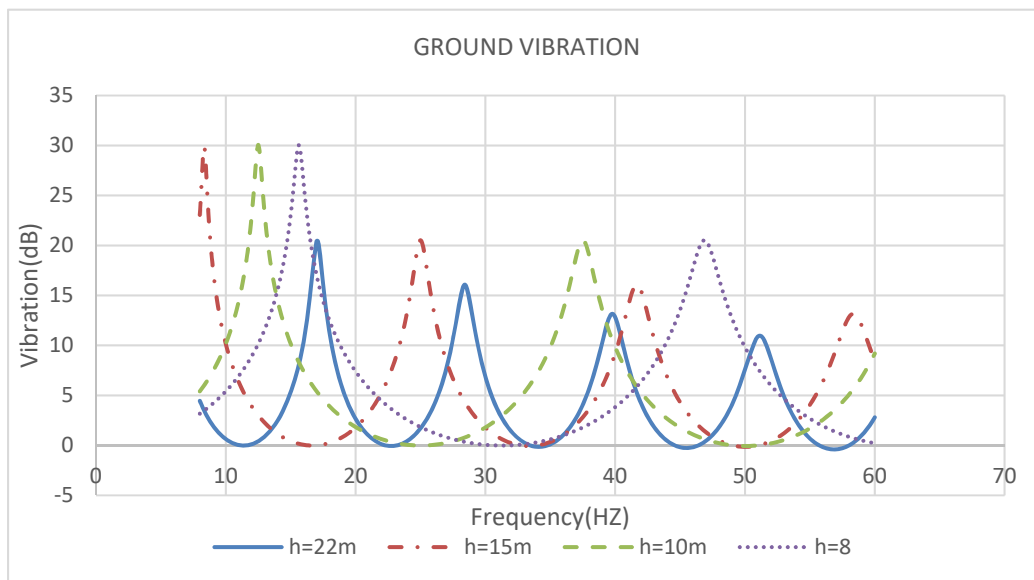

Figure 1: Effect of depth on frequencies and vibration magnitude

The aforementioned procedure is the normal mechanism for train induced vibration and transmission. In underground urban railway and during tunnel construction, soil plastic behavior occurred in construction. It means there was a ground settlement in surface due to soil plastic deformation in excavation process. In plastic soil, damping properties is considerable. On the other hand, most of the vibration test are performed before construction stage so this important issue may be ignored. It must be noted increasing the damping of lower soil layers cause increase of wave speed in the surface.

According to soil dynamics, fine grained soils have good damping properties in high frequencies and poor damping in low frequencies. Figure 2 shows the different between soft soils and rock for various frequencies.
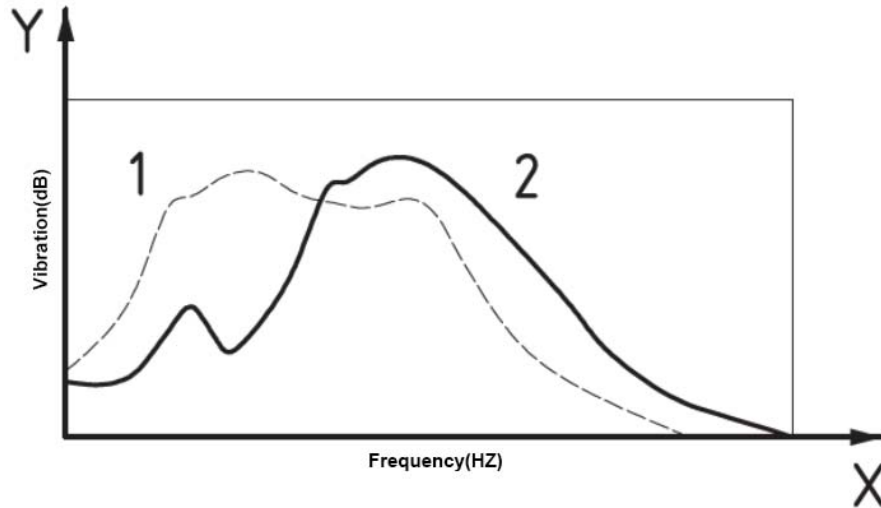
Figure 2: Differences between soft ground [ISO 14837-1 2005] (1) and rock (2)

On the other hand, based on IBC 2012, soils are classified in 6 categories. For soil classes D to F curve no. 1 will be used and for the other soil classes curve no 2 (Figure 2) should be used. So in soil- structure interaction, hard soils must filter low frequencies and amplify high frequencies and soft soil must amplify low frequencies and filter high frequencies.

Table 1: Soil classifications according to IBC 2012

Site class	Shear wave velocity	Rock and soil category
A	>1500 m/s	Hard rock
B	760 to 1500 m/s	Rock
C	360 to 760 m/s	Soft rock
D	180 to 360 m/s	Stiff soil
E	<180 m/s	Soft soil

If materials are elastic, there is only geometrical damping. But considering this fact that material like soil and rock are not totally elastic, some small deformation will be happened during transmission of vibration which means vibration energy absorption. (Watan and Sassa 1996) and (Gutowski 1976) suggested following equations for vibration amplitude calculation considering material damping and distance from vibration source:

[1] $A = A_0 e^{-\alpha \ (r - r_0)}$

[2] $\alpha = \dfrac{\pi \ f}{C} \eta$

C: wave speed (initial or secondary wave) (mm/s)

f: frequency (based on table 2) (Hz)

r: distance from vibration source(m)

A: vibration amplitude(dB)

Table 2: loss factor for each soil category

Soil Class	Wave Speed[1][m/s]	Loss factor (η)	Density [Kg/m3]
Rock	3500	0.01	2.65
Sand, silt, gravel, loess	600	0.1	1.6
Clay, clayey soil	1500	0.1-0.22[2]	1.7

1) Longitudinal wave velocity
2) That is a conservative value and the factor can be up to 0.5, but such a high value should be used with caution.

4 SUGGESTED MODEL

Based on above mentioned issues two models developed in SAP program:

4.1 3D models for effective length of the track consisting following components:

- Rail which modeled by beam component

- Fastening system by spring component

- Concrete slab which is modeled by SHELL component and cracking factor is supposed to 0.5 according to ACI for service mode.

- Modeling of connection between slab and tunnel invert defined as spring per area unit in two conditions:
  - Mass spring system in which mechanical properties of vibration mats introduced to model (figure 3a).
  - Stiff subgrade which is based on AREMA (American railway engineering and maintenance association) subgrade modulus in order to provide maximum rail deflection or modeling of soil and substructure are incorporated with superstructure such as figure 3b.

- Dynamic loads applied on model. It is possible to apply various load pattern like CopperE80 according to AREMA.

- Considering of maintenance effects on vibration levels, these effects will be added to results of the model according to FTA.

Based on the model, base shear versus time can be extracted and RMS (Root Mean Square) calculated according to FTA. That means excitation density function can be determined.

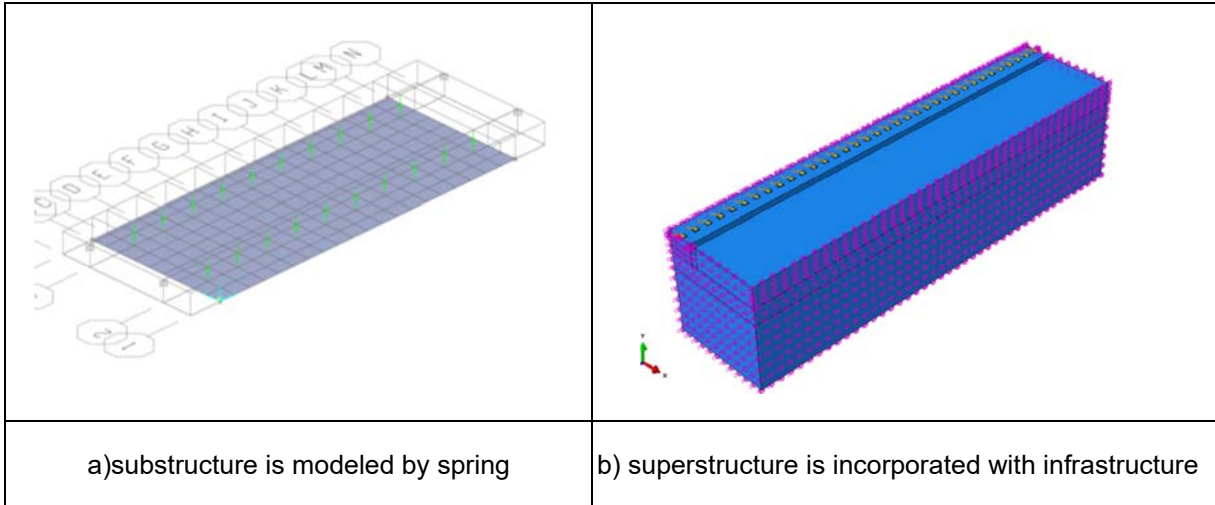| a)substructure is modeled by spring | b) superstructure is incorporated with infrastructure |

Figure 3: boundary condition of soil model

Modeling was performed based on Figure 3b and figure 4 shows comparison of modeling and result of field test from Tehran existing metro line.
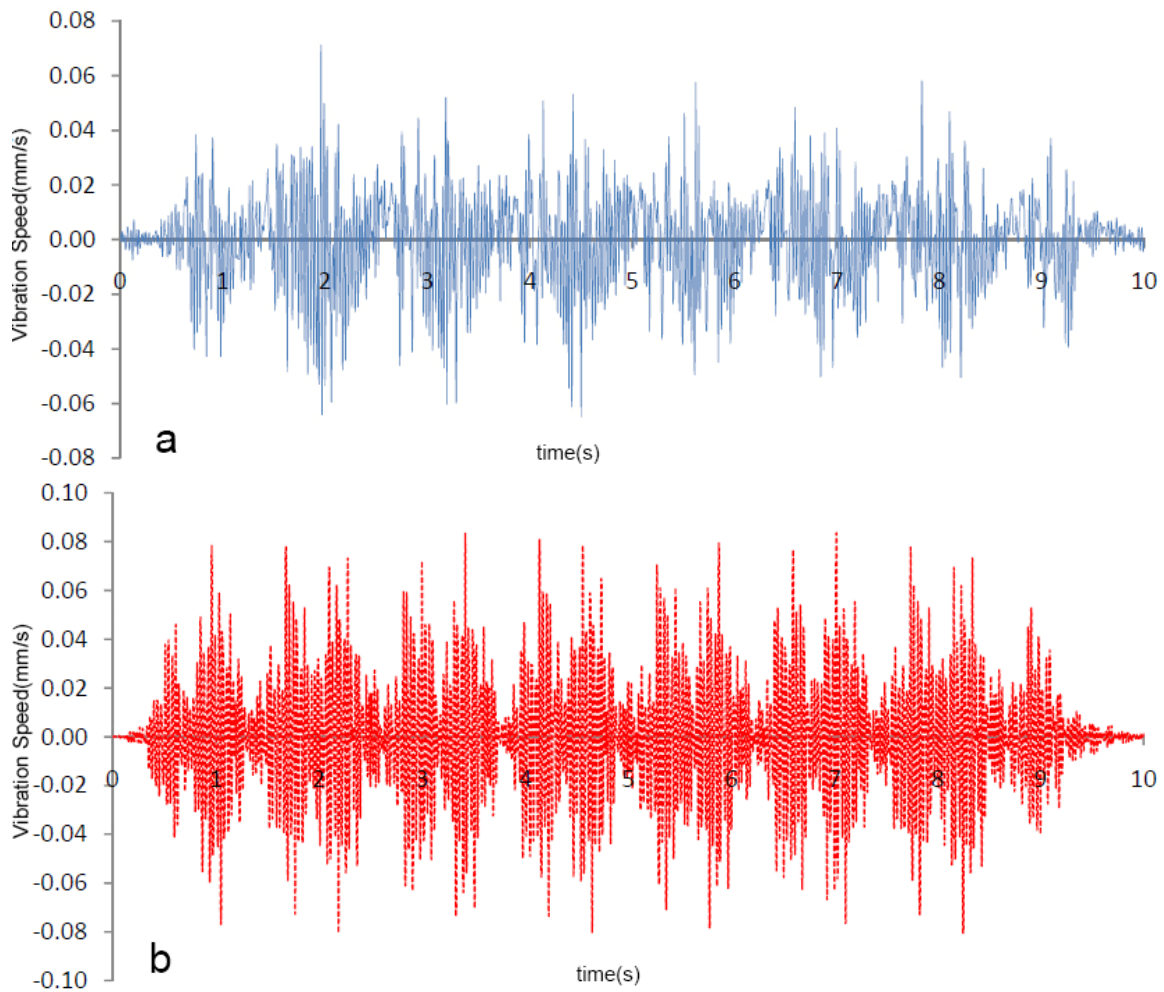

Figure 4: velocity versus time for test(a) and modeling(b)

Comparison of results show a good coordination between test results and model outputs.

4.2   Transmission model based on 3D model

This modeling are as follows:

- E (Elasticity modulus), v (poison ratio) and G (Shear modulus) parameters regarding longitudinal and transvers wave speed can be estimated based on soil properties. It must be noted, based on studies of Tehran metro line 4, soil cohesion and soil friction angle has no effects on responses and thus elastic parameters is selected.

- Cracking factor of the tunnel has been determined based on ACI. Train induced vibration occurs in service mode and tunnel lining has a bending behavior in which creep and shrinkage cracks occur. So the suggested cracking factor is 0.75. tunnel was modeled using SHELL component and soil-structure components were considered in two to three layers in order to proper vibration damping modeling.

Estimation of soil damping is based on mentioned references. For a situation in which tunnel overburden is twice of tunnel diameter, the first layer has more damping. The boundary condition is defined as figure 5.
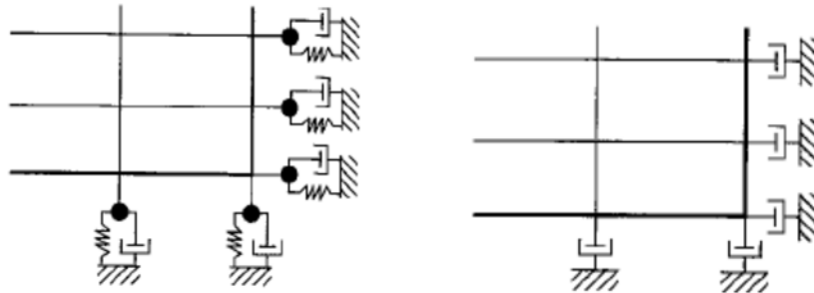

Figure 5: Boundary condition of soil model included dampers and springs

Damping equations are as follows:

[3] $f_x = -\rho C_p \frac{\partial u}{\partial t}$

[4] $f_y = -\rho C_s \frac{\partial v}{\partial t}$

ρ= soil density (Kg/m^3)

C_s= shear wave velocity(m/s)

C_p=longitudinal wave velocity (m/s)

u= horizontal displacement (m)

v= vertical displacement (m)

t= time(sec)

According to FEMA code, soil transmission constant considered as 0.65 and applied on model.

The required moment of inertia for TBM tunnel can be calculated using following formula (FHWA):

[5] $I_e = I_y + I \left(\frac{4}{n}\right)^2$

I_e= effective moment of inertia(mm^4)

I_y= the joint moment of inertia(mm^4)

I= the moment of inertia of the gross lining section(mm^4)

n= the number of joints in lining rings

Soil lateral load is an important parameter and it was model by static loads. However, calculated base shear by modeling of superstructure-tunnel interaction is applied on the model. In order to proper damping modeling, Rayleigh damping is applied considering the factor of mass and stiffness matrix which is different in each layer. This factor is calculated using table 2.

5   CONCLUSION

As described above, an algorithm based on codes and studies related to soil dynamics and FEM was presented. This method can be used instead of full vibration analysis in a project with a very low cost, with much lower vibration test points, and good criteria for vibration verification considering soft or hard soils. It is also possible to calibrate soil-structure interaction characteristics and provide more reliable results. On the other hand, because of the lower cost, this method can investigate various vibration reduction measures and its efficiency before construction.

References

2006, FTA (Federal Transient Administration). *Transit noise and vibration impact assessment. Department of Transportation*, United State of America.

Hussein et al H, M.F.M., 2007. A numerical model for calculating vibration from a railway tunnel embedded in a full-space. *Journal of Sound and Vibration*, Elsevier, 305: 401–431.

Nejati et al H..,2012, Numerical analysis of ground surface vibration induced by underground train movement, *Journal of Tunnelling and Underground Space Technology*, Elsevier, 29 (2012): 1–9

Gardien et al, W.,2003, Modelling of soil vibrations from railway tunnels, *Journal of Sound and Vibration*, Elsevier, 267 (2003): 605–619

Minsili et al, 2013, Analytical Model of Underground Train Induced Vibrations on Nearby Building Structures in Cameroon: Assessment and Prediction *Journal of Practices and Technologies,* Leonardo, 23(2013):63-82

T.G.GutowskiC.L.Dym.,1976. Propagation of ground vibration: A review, *Journal of Sound and Vibration,* Elsevier, 49: 179-193

Lombaert et a, G,2014, Numerical, experimental and hybrid methods for the prediction of railway-induced ground vibration, *Proceedings of the 9th International Conference on Structural Dynamics*, EURODYN, Porto, Portugal,1, 91-99.

Kramer, S,1996, *Geotechnical Earthquake Engineering*, second Ed., Prentice Hall., New York, USA.