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Developing a New Vibration Analysis Calculative Method for Esfahan Subway Train and Railways Design, Manufacturingand Construction

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ABSTRACT

The simulated mass and spring evaluationfor subway or railways construction and installation have wide applications in rail industries. This kind of design should be optimize all related parameters to reduce the amount of vibration in cities, residential areas, historical zones and other critical locations. Finite element method is used too much to analyze such applications with an excellent accuracy but developing some simple, fast and user friendly evaluation always was required in subway industry. In addition, process parameter optimization are required in railways to achieve optimal railways design with maximum safety, reliability and performance. The simple but useful simulated mass and spring evaluation system is developed for Esfahan subway construction. This method is discussed in this paper. Esfahan subway construction has a historical zone. Historical buildings should be protected from harmful vibrations. Polyurethane layer is used to reduce vibrations. This layer completely covered by concrete layers in all directions. It is worthy to know that, all the operation criteria like displacement and stress could be adapted with all vibration criteria like natural frequency, operation frequency and damping. Adaptation is performed by changing in polyurethane layer thickness. The results showed that if 25 millimeter thickness polyurethane layer covered completely by two concrete layers with 12 millimeter thickness,the amounts of vibrations reduce considerably. In addition, it is strongly recommended to increase the polyurethane layer up to 37 millimeter in historical zone to prevent potential harmful effects. The results is confirmed by other commercial methods. The calculative method is successfully performed.Furthermore, it is important to reduce maintenance costs in any potential design.The process parameter like rail ways dimension, rail ways material, cabins loading, cabins quality, cabins dimension and polyurethane layer thickness properly designed to keep the subway natural frequency around 18 Hz (less than allowable 20 Hz).Numerical design results will protect all historical buildings, palaces paintings and old bridges in future subway operation times. In addition, some interesting patent and innovation in rail industry like Suspension mass tuned vibration reducer, short sleeper vibration attenuation fastener and Airtight track vibration noise reducing fastener are discussed in this paper.

Keywords—*Subway construction engineering, natural frequency, operation frequency, vibration analysis, polyurethane layer.*

INTRODUCTION

INPUT values thatused in this paper are types and thickness of rails, foundation characteristics, ground modules, loading parameter and railways geometry It is important to input all the requested information and initial conditions accurately for successful completion of this project. This method has two main sub approaches: Recessive approach and vibration approach. Both of the approaches can evaluate the whole system characteristics.

It is important to identify the bed reaction module accurately before starting both sub approaches. The reaction bed module identification is closed to recessive lamination module identification and that is because of using mass and weight system in subway industries .Both of these modules are a function of different parameter. These parameter consist of polyurethane layer characteristics, installation quality of polyurethane, cabin maximum allowable weight, number of passengers, quality of cabin design and quality of cabin manufacturing. Subway systems could potentially create different types of frequencies. In a city subway system with normal quality of ground soil and acceptable cabin quality like Esfahan subway construction bed reaction module is supposed to be 0.0036 N/mm^2andspring module K is supposed to be 2600 N/mm [1].

It is worthy to know that if L represents the distance between two rails (train main shaft length) and R represents radius of the train main shaft then increasing of the L/R cause to increasing lateral natural frequency [2].

Reducing the train vibrations cause reduce in operation risks. These risks may occur in several kilometer underground tunnels [3].

The outputs of the vibration method should be controlled by bed module characteristics. The occurred displacement should be less than allowable displacement. First ,all modules should be identified. Both dynamic and static analysis is performed. The rails static vibration frequency supposed to be 20 Hz.

A simple and useful mass and spring numerical evaluation is performed in this paper. The results confirmed by laboratory approaches. This method is considered as a parallel way to evaluating the vibrational behavior of subway systems. In addition, this method is parallel to all vendor graphs in damping layers. These graphs are presented in all vendor technical documents and related softwares[4].

MATERIALS AND METHODS

An interesting dynamics model is established using the dynamics software SIMPACK in order to high speed railways wheel rail vibration analysis for vertical sections [5].

Ground vibrations are generated by urban trains especially near rail way lines. The vibrations are so complicated and cannot be measured directly. Inversion genetic algorithm and coupled train track three dimension dynamic model combine to each other in [6]. This Joint inversion design increase the rails efficiency.

An interesting bridge dynamic analysis is introduced for ladder tracks under moving train load [7]. The whole mechanism is simulated for different train speeds.

Rails elastic vibrations parameter are experimentally determined in [8]. Besides, dependence of two rail vibration modes amplitude on misalignment is established.

Railway low frequency ground vibrations are predicted for different roughness in [9]. The results are found beneficial in vibration control.

Rail damper role is explained in [10]. Besides, the rails frequency analysis is discussed in detail The concepts related to railway tests is discussed in [11]. Besides, excitation between rail and wheel is simulated. This method is secured the high speed trains stability.

Rails experimental analysis through pulse hammer excitation test is performed in [12]. Influence of rail vibrations on fastener looseness is discussed in details. Finally, the construction and maintenance twist torque ranges are suggested.

Rails physical model is performed through ANSYS. This study is established with Finite element method (FEM). Maximum displacements and vibrations are determined in different directions [13].

Rail track vibrations are measured in [14]. These measurements are performed on slabs. The rails are located in a tunnel and the tunnel were under normal traffic load. In addition, track frequency responses are measured. The influence of track dynamic parameters on track vibrations are discussed. Finally, dynamic characteristics is compared for different types of tracks.

Tuned mass damper is designed to reduce rail noise and vibration. The damper performance is tested in Hong Kong rail lines. Dampers are significantly reduced rail vibration and noise [15].

Multiple motion absorber effects on the rails dynamic behavior is discussed in [16] for the first time. Absorber cause roughness excitation. Roughness excitation cause reduce in vibrations. This reduction are calculated through FEM. Besides, the FEM model compare with traditional beam spring model. Finally, the results show that, the rails noise and vibrations can significantly decrease by using the rail absorber.

Rails recording, simulation, and analysis previously have been developed. These methods was performed in rail industries. Besides, track design and track maintenance were discussed in details through different methods. These methods were obtained significant economic benefits.

The railway track vibration behavior for design and maintenance recently is classified and investigated [17].

Several interesting investigations are recently performed with assist of technical and professional data collectors and related soft wares [18].

The new vertical vibration analysis is performed to analyze periodic rail supports. This method are predicted rail response for both low and high Frequencies[19]. The periodic support model consists of two three-directional Kelvin-Voigt [20] systems for the rail pad and the ballast. This method is successfully performed in rail industries for three directional analysis. In addition, this method can mixed with Maxwell method. This approach is called Kelvin-Voigt/Maxwell [20]. Kelvin-Voigt/Maxwell were successfully performed and analyzed the subgrades condition in rail industries. It is worthy to know that,this method could only analyze stationary harmonic loads.

Wave’s propagation analysis is performed in rail industry [20]. This method is performed by analyzing the trans movement influence in the soil. This analysis is performed before multi storey residential buildings construction. Vibration waves in the ground is determined. The advantages of this method is its simplicity. This method is performed without necessity of soil vibration measurements. These kind of measurements are complex. This method have some disadvantages. The rail and train cabin could not be evaluated in this system .In this paper, the new calculative method for both rotary and stationary harmonic loads is investigated in rail, train cabin and the foundation for the first time. This method is successfully performed in Esfahan rail ways design, manufacturing and construction.

Experimental details

The natural frequency of the railway could calculated with assist of equation (1) or (2) if c' is dynamic module per N/mm, m is spring weights in Kg, E' is dynamic tensile module per N/mm^2, A is load surface per mm^2 and d is recessive layer thickness per mm. In addition, damping quantity K and power transfer I could calculated with assist of equation (3) and (4) respectively. It is worthy to know that, η is related to damping characteristics. Besides, f and $f_\circ$ are related to loading parameter [21].

$$f_0 = 1/2\pi^2 \sqrt[2]{c'/m} \quad (1)$$

$$c' = \frac{E'A}{d} \quad (2)$$

$$K = 20\log\left[\sqrt{\frac{1+\eta^2}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\eta^2}}\right] \quad (3)$$

$$I = 100\left[1 - \sqrt{\frac{1+\eta^2}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\eta^2}}\right] \quad (4)$$

This method is used for Esfahan subway train construction. The results is compared with other traditional evaluations. All different parameter are used. The 25 millimeter thickness polyurethane layer is covered completely by two concrete layers with12 millimeter thickness. The train live stress is tested between 0 and 0.025 N/mm^{2}for different rail material and geometry. Besides, the train live stress is tested for all potential ground characteristics (found in vendor technical document of this kind of train and rail ways).

The wide of the rails is 2.6 meter. The cabins could be loaded up to 0.75 N/mm^2 in high operation times (due to the polyurethane technical document).The system is based on mass and spring approach.This method is previously used both in semi deep and deep constructions. The Esfahan subway construction engineering has40 cm depth for rails. Besides, traverse gap is 70 cm.Moreover,slope is 30/1000. In addition,railstypes are S49.

There is a critical path in this construction engineering. That is because of several historical zones that are located between Takhti and Aza disquare. The zones consist of several beautiful and historical buildings, palaces and bridges. There are some beautiful and priceless paintings on buildings walls. Some of them even painted with natural colors and gold layers. Some of them show historical events. Most of them have more than 500 years old. These buildings and bridges are so sensitive to vibrations. Several photographs from these historical locations can be seen in figures 3 to 7.

The construction group decided to design some kind of light damping system in this area. This system is based on weight and spring evaluations. The idea is originated from technical documents. Several different variants are tested in this project. The results are explained in the next sections .The mentioned method in previous parts is performed successfully in Esfahan subway construction.This method is used for modeling, simulating and evaluation of railways, cabins and foundation.

Recessive layers elasticity module evaluation under dead loads is performed with assist of vendor graphs existed in technical documents .It was estimated 0.012N/mm^2. Frequency supposed to be 20 Hz then the dynamic module is estimated. The density supposed to be 200kg/m3 then all above parameter are adjusted. The static displacement should be less than 4 mm. besides, dynamic displacement should be less than 3 mm. In addition, the lateral share recessive module should be evaluated by the height of lateral recessive profile. Two standards scenarios are tested in this project with plan A.250mm and planB.360mm[22].

RESULT AND DISCUSSION

Tables I to VII are represented the results for recessive vibrations. Table I and II are showed the recessive and reactionary system evaluations. The dynamic and static displacements are reduced by increase in thickness from 40 to 45cm. This phenomenon has two main reasons, the height is increased up to 5cm and polyurethane layer characteristics are changed.

Natural frequency results are presented in Table III. The two main factors are recessive layer dynamic module and spring weight. Natural frequency is decreased significantly by increase in spring weight. That is why the rails natural frequency in operation time decrease too much compare to rails natural frequency without train loading.

It is strongly recommended to adjust recessive layers dynamic characteristics to fix the rail natural frequency. this important item (rails natural frequency) should always kept less than 18 Hz. Rail line natural frequency slightly increase, if lateral profile length increase (that is because of increasing in effective bed dynamic module). Table III shows that by increase in axial load from 12.5 to 14 ton, system natural frequency is not change significantly. This item (system natural frequency)almost constant during increase in axial load.

Vibration damping criteria in operation time is 60 Hz. this item is indicated in Table III. Besides, vibration damping criteria is almost 20 decibel for mentioned historical zone. The results are confirmed the suitability of selected variables for mentioned critical rail line construction [23].

Damping vibrations between band frequencies 0-200 Hz is represented in Tables IV-VII. Damping criteria is calculated with assist of equation (4). Damping characteristics is increased by increasing in vibration frequency. The vibration amplitude is increased considerably by increasing in train loading. This phenomena is occurred in natural frequency ranges. Besides, these phenomena is continued up to resonance frequency. The resonance frequency is equal to 1.414 $f_{\circ}$ (due to the technical documents). Fortunately, line frequency is decreased after passing through resonance. The line frequency always should be passing the natural frequency in an extremely short period of time [24]. In addition, line frequency should be much different from natural frequency to avoid resonance.

It is strongly recommended to keep the line and train natural frequency under 18 Hz (due to the results explained in Tables IV-VII). It is worthy to know that, this is possible to keep these parameters around 15 Hz [25].

Line and train operation frequency is around 25 Hz (as mentioned before). The Line and train operation frequency is much different from designed natural frequency (15 Hz). It is worthy to know that, all the operation criteria like displacement and stress could be adapted with all vibration criteria like natural frequency, operation frequency and damping. Adaptation is performed by using polyurethane layer [26].

In addition, it is strongly recommended to increase the polyurethane layer up to 37 millimeter in historical zone to prevent potential harmful effects [27].Schematic figures 1 and 2 shows designed polyurethane layer thickness in historical and residential areas.

One of the new patent and innovation in subway industry is Suspension mass tuned vibration reducer (SMTVR). This method is applied in china railways successfully in 2011. SMTVR sometimes is called Suspension mass tuning shock absorber and has lower suspension spring connected with main piston. SMTVR is connected with main piston lug. Cylinder body is discontinuously penetrated to the box walls. SMTVR is filled with damping liquid. SMTVR is designed with simple and compact structure. Manufacturing, assembly and installation costs is low .Some other advantages are eases of maintenance, system reliability during operation and eases of assembly. Besides, the effect of vibration reduction can be adjusted through an external hydraulic or gas pressure control system [28].

Short sleeper vibration attenuation fastener (SSVAF)is improved structure reliability. SSVAF is performed by replacing elasticity short sleeper. The invention is related to the technical field of rails. This method brings economic advantages compare to traditional approaches. The technology is simple and rapid. SSVAF is decreased the line frequency. The maintenance and manufacturing costs are low [29].

Airtight track vibration and noise reducing fastener for railway track is provided with a bolt between support plate and airtight bases. Anchor bolt is fixed with sleeper through bolt hole. This brilliant idea is successfully performed in China railways in 2010. It is worthy to know that, Vibration isolating rubber works in a closed space to prolong the service life. When the performance is reduced after long term use, only the rubber pad plate needs to be replaced. The replacements are performed according to schedules. These schedules are provided by technical documents. The mentioned design saves maintenance costs. Besides, safety are ensured [30].

Wheel sensor was previously located for streetcars. Car wheel sensors are produced magnetic field. These sensors work on basic principles of Hall Effect detectors. Subway train wheel sensor is recently located. These Vibration sensors are sensing vibrations. These vibrations are caused by railway vehicle motions. The vibrations are influenced by several factors. These factors are previously discussed in this paper. These vibrations are indicated by signals. These signals are measured by data collectors. These data collectors are designed for rail industry and are equipped with high quality options.

Subway train wheel sensors comprises first and second Hall Effect devices. Rail way vehicle wheel motion changes the magnetic field in the Hall Effect devices. This phenomena produces wheel indication signals. The circuit is located to receive these signals. The circuit is calibrated to produce an output signal. This output signal is received by data collector [31].

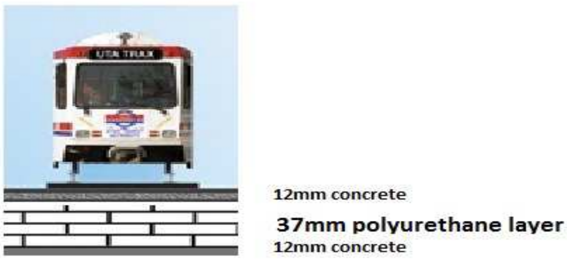

Fig 1. Polyurethane layer thickness in historical zone (between Azadi and Takhti station)

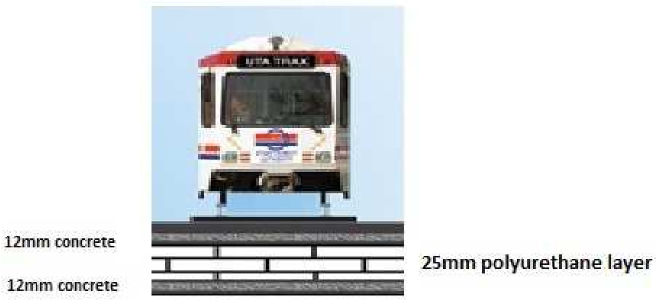

Fig 2. Polyurethane layer thickness in other areas

Fig 3. Wall painting in Chehelsotoun Palace

Fig 4. Chehelsotoun Palace

Fig 5. SiosepolBridge

Fig 6.Chaharbagh School

Fig 7. Chehelsotoun Palace

TABLE I

LINEARDISPLACEMENT AND OTHER SUBWAY INSTRUCTION CHARACTERISTICS OF DEEP TUNNELS - POLYURETHANE LAYER THICKNESS EQUAL TO 25MM

Upper thickness cm	Spring coefficient lateral elastic layer KN/mm	Bed module static N/mm^3	static Spring coefficient KN/mm	Dynamic Basic bending index mm	Static Basic bending index mm	DynamicRail displacement mm	StaticRail displacement mm	Static pressure on recessive Layer N/mm^2 Operation condition	Static pressure onrecessive Layer N/mm^2 Only rails	Axial load Ton
40	1.433	3650	2.85	3476	3639	2.94	3.39	0.0243	0.012	12.5
45	1.433	3790	2.96	3762	3937	2.65	3.08	0.0237	0.012	12.5
40	1.433	3500	2.73	3515	3679	3.41	3.93	0.0257	0.012	14
45	1.433	3550	2.77	3824	4002	3.13	3.65	0.025	0.012	14

TABLE II

LINEARDISPLACEMENT AND OTHER SUBWAY INSTRUCTION CHARACTERISTICS OF SEMI DEEP TUNNELS - POLYURETHANE LAYER THICKNESS EQUAL TO 25MM

Upper thickness cm	Spring coefficient lateral elastic layer KN/mm	Bed module static N/mm^3	static Spring coefficient KN/mm	Dynamic Basic bending index mm	Static Basic bending index mm	Dynamic Rail displacement mm	Static Rail displacement mm	Static pressure on recessive Layer N/mm^2 Operation condition	Static pressure on recessive Layer N/mm^2 Only rails	Axial load Ton
40	2.006	3650	2.85	3476	3639	2.94	3.39	0.0243	0.012	12.5
45	2.006	3600	2.91	3742	3995	2.55	3.13	0.025	0.012	12.5
40	2.006	3500	2.73	3515	3679	3.41	3.93	0.0257	0.012	14
45	2.006	3550	2.77	3824	4002	3.13	3.65	0.025	0.012	14

TABLE III

NATURAL FREQUENCY AND VIBRATION DAMPING CRITERIA IN 60 HZ ESFAHAN SUBWAY CONSTRUCTION CHARACTERISTICS

considerations	Vibration reduction dB	Natural frequency Hz for dynamic train	Natural frequency Hzfor static train	Dynamic Rail displacement mm	Static rail displacement mm	Axial load Ton
Lateral profile height equal to 350mm	-20.2	17.7	20.8	2.65	3.08	12.5
Lateral profile height equal to 250mm	-20.6	17.2	20.4	2.65	3.08	12.5
Lateral profile height equal to 350mm	-20.0	17.9	20.8	3.13	3.65	14
Lateral profile height equal to 250mm	-20.2	17.6	20.4	3.13	3.65	14

TABLE IV

NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 250 MM WITH AXIAL LOAD EQUAL TO 12.5 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-101	6.1	12.5	17.2	20.4
-299	12	16	17.2	20.4
-137	7.5	20	17.2	20.4
9	-0.9	25	17.2	20.4
55	-7	31.5	17.2	20.4
75	-12.2	40	17.2	20.4
85	-16.5	50	17.2	20.4
91	-20.6	63	17.2	20.4
94	-24.5	80	17.2	20.4
96	-28	100	17.2	20.4
97	-31.3	125	17.2	20.4
99	-40.8	250	17.2	20.4

TABLE V

NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 250 MM WITH AXIAL LOAD EQUAL TO 14 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-103	6.2	12.5	17.6	20.4
-306	12.2	16	17.6	20.4
-130	7.2	20	17.6	20.4
11	-1	25	17.6	20.4
56	-7.1	31.5	17.6	20.4
76	-12.3	40	17.6	20.4
85	-16.6	50	17.6	20.4
91	-20.7	63	17.6	20.4
94	-20.6	80	17.6	20.4
96	-28.1	100	17.6	20.4
97	-31.4	125	17.6	20.4
99	-40.8	250	17.6	20.4

TABLE VI
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF SEMI DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 360 MM WITH AXIAL LOAD EQUAL TO 12.5 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-93	5.7	12.5	17.2	20.4
-271	11.4	16	17.2	20.4
-167	8.5	20	17.2	20.4
2	-0.1	25	17.2	20.4
52	-6.5	31.5	17.2	20.4
74	-11.7	40	17.2	20.4
84	-16.1	50	17.2	20.4
90	-20.2	63	17.2	20.4
94	-24.1	80	17.2	20.4
96	-27.7	100	17.2	20.4
97	-31	125	17.2	20.4
99	-40.5	250	17.2	20.4

TABLE VII
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF SEMI DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 360 MM WITH AXIAL LOAD EQUAL TO 14 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-95	5.8	12.5	17.6	20.4
-278	11.5	16	17.6	20.4
-159	8.3	20	17.6	20.4
4	-0.3	25	17.6	20.4
53	-6.6	31.5	17.6	20.4
74	-11.8	40	17.6	20.4
84	-16.2	50	17.6	20.4
90	-20.3	63	17.6	20.4
94	-24.2	80	17.6	20.4
96	-27.7	100	17.6	20.4
97	-31.1	125	17.6	20.4
99	-40.5	250	17.6	20.4

CONCLUSION

Current and Future Development

Calculative method is introduced for subway construction engineering and vibration analysis. Related formulations and equations are introduced (I or K=f(f(Hz)). Besides, a case history related to Esfahan subway construction is explained in details. Esfahan subway construction has a historical zone. Historical buildings should be protected from harmful vibrations. The results is confirmed by other commercial methods. The calculative method is successfully performed. The process parameter like rail ways dimension, rail ways material, cabins loading, cabins quality, cabins dimension and polyurethane layer thickness should be properly design to keep the subway natural frequency around 18 Hz(less than 20 Hz).

Numerical design will protect all historical buildings, palaces and bridges in future operation times .Results only valid for vibration generated by future subway operation. The vibration generated by construction machinery or explosive activities must be redesign and control.

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