Impact of ground transport on pedestrian undercrossings and shallow subways

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Abstract. This article presents the obtained theoretical solutions for determining the degree of impact of ground transport vehicles on pedestrian undercrossings and shallow subways. Frequency characteristics of the transport impact on underground engineering structures are determined, and the maximum vertical load at high speed is found to equal 50 km/hour. With the increase of the speed of vibrational frequency the lateral vibrations of maximum amplitude occur and spike. However, the vibrational frequencies spike at the increase of speed, which may lead to resonant vibrations with underground structures, what will cause serious damage as a consequence. Studying of vibrational processes as the effect from the moving transport on underground structures it is easy to calculate that their impact is equivalent to seismicity, and can be deemed as grade 3-4 of a real earthquake intensity. The research reveals that if an engineering structure exposed to external effects of moving transport does not feature relevant protection of seismic isolation, it may be destroyed in case of a grade 4-5 earthquake since the accumulated effect will manifest itself as grade 8-9.

1. Introduction

The railways rolling stock and heavy-duty ground motor vehicles not only create significant additional load for engineering structures located under roads, but are also a source of a system of vibrational processes similar to seismic activity. It is easy to understand that this will have a negative effect on the condition of the engineering structures and will actually reduce their standard service life, and may even bring them to the ultimate limit state.

The analysis of the aftermath of the Gazli earthquakes in Uzbekistan became the grounds for studying the impact of transport vehicles on the seismic resistance of underground culvert pipes and communications since with identical structures and soil conditions the destructions were of different degree of severity. The research performed by I.Ya [1-4], Dorman allow to conclude that at the sections of various intensity and load-bearing capacity of the moving transport vibrations similar to seismic activity can be created, which at some road sections may overlap with seismic activity and could cause different damages of pipes in the road bed [5-10]. These scientific conclusions were used by Professor A.Kh. Abduzhabarov with determining of the frequency characteristics and the degree of impact load from transport on the road culverts [11-13].
2. Calculation of concrete pavement vibrations

The vibrations of concrete pavement on earth road bed were considered as beams of endless length lying on modified Fuss-Winkler foundation under impact of immobile and changing-over-time force, and are described by a linear differential equation in partial derivatives:

\[
EI_y \frac{\partial^4 I_p}{\partial x^4} + N \frac{\partial^2 I_p}{\partial x^2} + m_I \frac{\partial^2 I_p}{\partial t^2} + f_I \frac{\partial I_p}{\partial t} + u_0 I_p = 0
\]

(1)

where \( E \) is the module of elasticity of concrete pavement; \( I_y \) is the moment of inertia of the pavement relative of the main transverse horizontal axis \( Y \); \( I_p \) is the vertical deflection of the pavement; \( x \) is the abscissa of the pavement cross-section, from the fixed coordinates origin; \( t \) is time; \( N \) is the axial force in the pavement; \( m_I \) is the length-distributed equivalent mass of the concrete pavement and the foundation in case of the road vertical vibrations; \( f_I \) is the length-distributed road damping in case of vertical vibrations; \( u_0 \) is the module of elasticity of concrete pavement foundation.

Equation (1) is true for everything, except for the point for force \( Q(t) \), where the third derivative of the pavement vertical deflection is discontinuous in coordinate \( x \).

In case of load moving with permanent speed \(- V\) it is necessary to switch to new variables \( u, t \), where \( u \) is the abscissa of the pavement cross-section from the mobile coordinates origin combined with the moving force (Figure 1).

![Figure 1. System of coordinates for calculation of the concrete pavement vibrations.](image)

A shallow subways was constructed in Tashkent, Baku, and Almaty. Similar subways are probably soon going to be constructed in Dushanbe, Bishkek, and Ashkhabad [14-16]. Apart from the fact that these cities are located in the seismic zone, one shall not disregard the impact of heavy-duty ground transport as an additional and permanent source of seismic effects [17,18].

3. Calculation and discussion

Spatial vibrations of transport in part of the wheels-support generate vertical and lateral vibrations which are translated to the road beds and underground structures located under them [19].

With the increase of the speed of the moving transport the frequency characteristics change. It is necessary to determine the range of the frequency change depending on the transport speed and transport weight.

To determine the interaction between transport and road surface in case of vertical vibrations, let us consider a two-mass system (Figure 2) [20].

The vibrations of such system from the dynamic force impact \( Q_g \) are described by the system of differential equations.

\[
\begin{aligned}
M_1 \frac{d^2 z_1}{dr^2} + r_1 \frac{dz_1}{dr} + c_1 z_1 - r_1 \frac{dz}{dr} - c_1 z &= 0 \\
-M_0 \frac{d^2 z}{dr^2} - c_1 z_1 + M_0 \frac{dz}{dr} + r_1 \frac{dz}{dr} + c_1 z &= -Q_g
\end{aligned}
\]

(2)
Performing Laplace transformation of equations (2) and taking the initial conditions as zero, we will obtain a system of two first-degree algebraic equations.

\[
\begin{align*}
&z_i \left( M_i s^2 + rs + c_i \right) - z \left( r_s s + c_i \right) = 0 \\
&-z_i \left( r_s s + c_i \right) + z \left( M_o s^2 + r_s s + c_i \right) = -Q_g
\end{align*}
\]

\[ z = -\frac{M_i s^2 + r_s s + c_i}{M_i M_o s^4 + r_i \left( M_i + M_o \right) s^3 + c_i \left( M_i + M_o \right) s^2} Q_g \] (4)

Now the transfer function relating the vertical displacement of the wheel to the dynamic force in the point of contact of the wheel and the road surface, or rail in case of a railroad, may be expressed as follows (Figure 2):

\[
W^0 (s) = -\frac{M_i s^2 + r_s s + c_i}{M_i M_o s^4 + r_i \left( M_i + M_o \right) s^3 + c_i \left( M_i + M_o \right) s^2} \] (5)

The impulsive admittance function of the system \( h^0 (t) \) can be determined through the inverse Laplace transformation of the transfer function \( W^0 (S) \) (Figure 5,6).

\[
W^0 (S) = \frac{A}{s^2} + \frac{B}{\left( s + r_\gamma / 2 \right)^2 + c_\gamma - \left( r_\gamma / 2 \right)^2} \] (6)

where: \( \gamma = (M_1 + M_0) / (M_1 - M_0) \); \( A = -1 / (M_1 + M_0) \); \( B = M_1 / (M_0 (M_1 - M_0)) \).

This results in:

\[
h^0 (t) = At + B \frac{1}{\beta} \exp \left( -\frac{r_\gamma \beta t}{\beta^2} \right) \sin (\beta t) \] (7)

where: \( \beta = (c_\gamma + r_\gamma / 2)^{1/2} \).

The impulsive admittance function \( h^0 (t) \) allows to obtain the value of the wheel’s movement through the vertical plane \( z(t) \):

\[
z(t) = \int_{-\infty}^{t} h^0 (t - \tau) Q_g (\tau) d\tau \] (8)

Movement of one unsprung mass is \( M_0 \), and the impulsive admittance function \( h^0 (t) \) equals:
If $M_1=0$ from (7) wheel displacement, we will obtain:

$$z(t) = \frac{1}{M_0} \int (t-\tau)Q_x(\tau)d\tau$$

(9)

If (9) is twice differentiated for $t$, we will obtain:

$$-M_0 \frac{d^2 z}{dt^2} = Q(t)$$

(10)

To determine the dynamic parameters of the moving transport influence on ground structures, it is better to use the frequency characteristics $W^0(i\omega)$, which may be obtained from (5) by replacing $s$ with $i\omega$:

$$W^0(i\omega) = \frac{M_1\omega^2 - ir_1\omega - c_1}{M_0\omega^4 - ir_1(M_1 + M_0)\omega^3 - c_1(M_1 + M_0)\omega^2}$$

(11)

Let us determine the vertical forces occurring in case of joint vibrations of the transport moving at the speed of $\vartheta$ and road surface, or rails for railroads.

$$z(t) - z^0(t) - \eta^0(t) = \xi^0(\vartheta t)$$

(12)

Performing Fourier transformation for (12) and taking into account the equation

We will obtain:

$$W^0(i\omega) - W^0_z(0,i\omega) - \frac{1}{C_k^0} Q = \xi$$

Now:

$$Q = W_p(i\omega) \xi$$

(13)

where:

$$W_p(i\omega) = \frac{1}{W^0(i\omega) - W^0_z(0,i\omega) + 1/C_k^0}$$

(14)

is the frequency characteristics.

In the Fourier transformations the differentiation is equivalent to multiplying by $i\omega$, and we will obtain the value of the frequency characteristics:

$$W_\xi(i\omega) = \frac{1}{\omega^2 \left[ W^0_z(0,i\omega) - W^0_\eta(i\omega) + 1/C_k^0 \right]}$$

(15)

From formulas (11) and (15) we will obtain:

$$W_\xi(0) = \lim_{\omega \to \infty} \frac{M_1M_0\omega^3 - ir_1(M_1 + M_0)\omega^2 - c_1(M_1 + M_0)\omega - c_1(M_1 + M_0)\omega^2}{M_1\omega^4 - ir_1(M_1 + M_0)\omega^3 - c_1(M_1 + M_0)\omega^2} = M_1 + M_0$$

(16)

The graphs (Figure 3) and (Figure 4) were plotted for the following weights of transport $M_1 = 10000$ kg, wheels $M_0 = 1000$ kg; $C_1 = 2 \times 10^6$ N/m; $r_1 = 9000$ N·s/m; deflection rate in the point of contact of the wheel and surface $C_k^0 = 5 \times 10^8$ N/m.
Figure 3. Arguments of the frequency characteristics $W_Q(i\omega)$ at frequencies $\omega=0\div300$ c$^{-1}$.

Figure 4. Arguments of the frequency characteristics $W_Q(i\omega)$ at frequencies $\omega=0\div3000$ c$^{-1}$.

Figure 5. Impulsive admittance function.

Figure 6. Impulsive admittance function of the force in the contact of wheel and road surface.

4. Conclusion

Determining the frequency characteristics of the transport’s impact on underground engineering structures, using formulas (10,14,15), one may reveal that the maximum vertical loads occur at the speed of up to 50 km/hour. With the increase of the speed of vibrational frequency the lateral vibrations of maximum amplitude occur and spike. The vibrational frequencies spike at the increase of speed, what may lead to resonant vibrations with underground structures, what will cause serious damage to the latter as a consequence.

Analysing the oscillation processes as the effect from the moving transport on underground structures it is easy to calculate that their impact is equivalent to seismicity, and can be deemed as grade 3-4 of a real earthquake intensity. These calculations reveal that if an engineering structure exposed to external effects of moving transport does not feature relevant protection of seismic isolation, it may be destroyed in case of a grade 4-5 earthquake since the accumulated effect will manifest itself as grade 8-9.

References

[1] Abduzhabarov A Kh 1996 Seismic Resistance of Motor and Rail Roads Bulletin of KASI (Bishkek) p 226
[2] Kogan A Ya 1968 Vibrations of Rails under the Impact of Moving Variable Load Bulletin of VNIIZHT (Railway Research Institute) 1 pp 7–11
[3] Abduzhabarov A Kh and Khasanov N M 2013 Seismic Resistance of Road Pipe Culverts and Undercrossings Bulletin of KGUSTA (Bishkek) 3 pp 101–104
[4] Abduzhabarov A Kh and Khasanov N M 2001 Construction Solutions for Concrete Pavements of Roads and Airfield Landing Strips in Seismic Conditions NiNT Science and New Technologies (Bishkek) 9 pp 91–93
[5] Imanaliev T B 2010 Seismic Resistance of Artificial Structures (Bishkek: KUSTA) p 211
[6] Abduzhabarov A Kh, Khasanov N M and Yakubov A O 2017 Calculation and Construction Solutions for Seismic Resistance of Undercrossings and Underground Utilities Bulletin of KUSTA (Bishkek) 3 pp 127–131
[7] Khasanov N M and Abduzhabarov A Kh 2016 Calculation of the Strain-stress State of Road Pavement in Case of Seismic Activity Bulletin of TIU (Industrial University of Tyumen) (Tyumen) p 267
[8] Khasanov N M 2017 Seismic Resistance of the Structures of Pipe Culverts and Undercrossings, Scientific-technical journal “Vestnik grazhdanskikhingenerov” (Bulletin of Civil Engineers) (Saint Petersburg) 2 (55) pp 205–209
[9] Suleimanova M A and Saidov F Yu 2015 Qualitative Assessment of the Strain-stress State of Structures Foundations in Case of Seismic Load Bulletin of TTU (Tajik Technical University named after academician M. Osimi) (Dushanbe) 4(40) pp 135–141
[10] Sagdiev Kh S and Yunusaliev E M 2010 Vibrations of Soil and Structures during Industrial Explosions in Difficult Mining and Geological Conditions (Tashkent: Publishing House FAN) p 160
[11] Khozhmetov G Kh, Abduzhabarov A Kh and Omelyanenko V A 1988 Assessing Seismic Hazard of Special Engineering Structures Proceedings of the 21st World Congress of the General Assembly (Sofia) pp 73–75
[12] Khasanov N M and Zaripov S S 2014 Design of Concrete Pavement of Roads and Airfields with Consideration to Seismic Forces Bulletin of the Tajik National University (Dushanbe) pp 98–104
[13] Khasanov N M and Dzhalladinov M M 2015 Calculation of the Strain-stress State of a Culvert Structure Bulletin of the Tajik National University (Dushanbe) 3 pp 98–104
[14] Bathe K J, Ozdemir H and Wilson E L 1974 Static and Dynamic Geometric and Material Nonlinear Analysis Report UC SESM 74-4 College of Engineering University of California (Berkeley)
[15] Negmatullaev S Kh 2015 Maps of Epicentres of Earthquakes in Tajikistan for 2007-2015 (Dushanbe) p 196
[16] Baklashov I V and Kartoziya B A 2012 Mechanics of Underground Structures and Design of Supports (Moscow: Student 3-rd ed.) p 542
[17] Newmark N M 1959 A Method of Computation for Structural Dynamics ASCE Journal of Engineering Mechanics Division (New York) 85 pp 69–94
[18] Bathe K J 1975 Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis (Cambridge)
[19] Khasanov N M and Yakubov A O 2017 Strain-stress State of Unfixed Mine Openings. Problems and Prospects of Development International Science-to-practice Conference (Vologda) pp 113–122
[20] Khasanov N M and Yakubov A O 2017 Parameters of Assessing Slope Stability International Science-to-practice Conference on Integration Processes of the World Scientific and Technological Development (Belgorod) pp176–180

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