EXPERIMENTAL DETERMINATION OF AIR RESISTANCE IN THE TUNNEL AT HIGH – SPEED RAILWAYS

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Summary: *This paper discusses a very complex problem at high speed rails, which is the resistance of the air in the tunnel. Shows the procedure for experimental determination of the resistance. Air circulations caused by the passage of a train through the tunnel are tested experimentally and numerically with the intention of aerodynamic occurence for better understand and determination of their sizes. Experimental techniques for measuring the position and the value of air pressure are extremely complex. The original research related to determining the form of diagrams pressure, depending from the moving speed and distance of train forehead from the entrance in the tunnel. Experimentally was established the manner in which the pressure occurs during train entering in the tunnel and when it continues movement along the tunnel. Depending on the method for measuring air resistance in the tunnel, results of ekspreimental research are shown on prototype. In this paper are shown the results of experimental measurements in the tunnel Linkou (given in the work of Yung-Yen Ko-a [2]).*

Key words: *high-speed railway, tunnel, air resistance, measuring, prototype*

1. INTRODUCTION

Contemporary railway in addition to more modern and upgraded means of transport, implies also a reconstruction, ie construction of a new modern railway infrastructure. The most important demand is the increase of train speed. Condition that must be fulfilled in order to increase the speed is harmonization of driving speed with constructive elements of the road (radiuses of curvatures, cambers and inclination of vertical alignment). Principle that was respected during projecting of traffic line objects was as little earth works as possible. However, when we talk about contemporary railway, the primacy in requirements is the higher speed, and then higher cost of earth works, tunnels and bridges is something that implies. It means that on the railways for higher speeds would be a lot

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of bridges and tunnels, more than it would be in earlier case. This causes more serious studying of air resistance in tunnels.
Aerodynamic problems at high-speed trains are closely connected with air circulation around the vehicle. It took a lot of time to realize that a lot of energy is lost on overcoming these resistances and that vehicles abilities are reduces. Under vehicle abilities are considered increased air resistance with increase of speed, noise and vibrations. Detail research confirmed that air resistance directly depends from speed of driving. Problem of studying of air resistance significantly complicates during the passing of the train through the tunnel. Carried out were researches considering size and characteristics of air resistance in tunnel during passing of trains of small speeds. From known researches exist research on model in tested tunnels and measurements that are carried out on realistic constructions and at real conditions. Besides experimental research are carried out numerical simulation of occurrence of resistance around the train, after which those sizes and occurrences are compared to those obtained with experimental research.
Experimental measuring determined that resistance and air circulation near vehicle depend from its shape, so it I has been began with upgrading of frontal part and sides of transport means. Also, existence of vertical ventilation shafts in tunnels affects the value of air resistance.

2. THEORETICAL BASIS

In research, theoretical or experimental it is began from defining the turbulent flow. When the train passes through the tunnel, it is created vortex field and turbulent flow. Equation of continuity for turbulent flows has the following shape [3]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho\, u_j)}{\partial x_j}=0, \quad j=1,2,3 \tag{1}$$

where: t – is time, ρ –density, x_j – coordinates, u_j – speed in direction of coordinates
Equation of movement

$$\frac{\partial(\rho\, u_i)}{\partial t}+\frac{\partial(\rho\, u_i u_j)}{\partial x_j}=\rho\, f_i-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where: p – is a static pressure, u_i – speed in direction x_{ij}, f_i – force in direction x_i, τ_{ij} – voltage tensor
Voltage tensor is determined in the following way:

$$\tau_{ij}=\mu\left[\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right] \tag{3}$$

where: μ – is a coefficient of air viscosity
Base on equation (2) is obtained kinetic energy equation (k) of turbulent movement:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]}{\partial x_j}+G_k-\rho\varepsilon+G_b-Y_M+S_k \tag{4}$$

Equation of turbulent dissipation (ε) is given with the equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]}{\partial x_j}+C_{\varepsilon 1}\frac{\varepsilon}{k}\left(G_k+C_{\varepsilon 3}G_b\right)-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{5}$$

3. DETERMINATION OF AIR RESISTANCE IN THE TUNNEL ON PROTOTYPE

Within measuring of air resistance on prototype, here would be presented cases of measurement in tunnel *Linkou*. Measurements were carried out under customary circumstances and with realized commercial speeds.

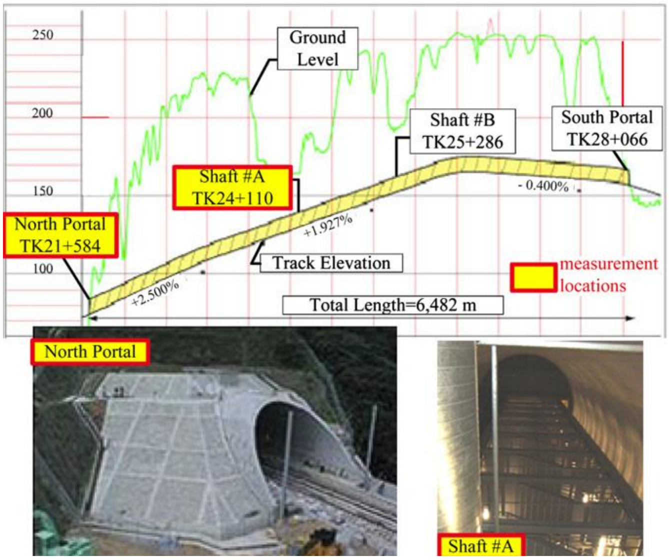

Figure 1 – Tunnel Linkou – portal, longitudinal intersection and position of measuring points [2]

Length of *Linkou* tunnel is 6482 m with cross section of 74 m^2. Position of measuring points is located near north portal of the tunnel and shaft A (figure 2). Shaft A is on position 2562 m from north portal. *Linkou* tunnel is located on the north Taiwan. It should be mentioned that both entrance portals are vaulted towards tunnel, approximately around 20 m, which increases 1,5 times a cross section of the tunnel. Appearance of entrance portal, cross section of the tunnel and position of measuring points are shown on figure 1.

4. MEASURING POINTS AND THE CHARACTERISTICS OF THE MEASURING

Measurings were carried out for precisely determined train speeds. What is certain is that the speed of other trains that would traffic through the tunnel would not always coincide with measured. For that purpose was set optical switch, so voltage signals on switches synchrinously recorded together with pressure sensors direction of train movement and evaluated current speed of the train. Pressure sensors are set on height of 2,5m and 4,0 m and are placed along tunnel, so they can register wave pressure spreadings and their spatial deviation from the pressure amplitude.

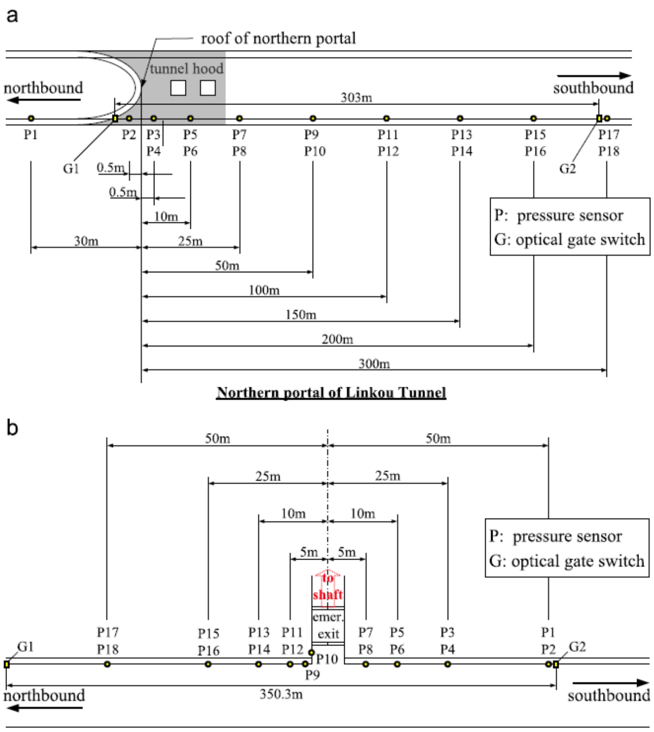

Figure 2 – Position of measuring points in Linkoutunnel - a) north portal b) shaft A [2]

Exact positions of measuring points are given in figure 2, shown are north portal and shaft A. For measuring in shaft and connecting hall were set additional sensors at passenger emergency exits. Optical switches are set on both ends of measuring section. During measuring in *Linkou* tunnel speeds of trains were: 270 km/h, 230 km/h, 170 km/h and 120 km/h. For every mentioned speed were carried out measurings with 6 trains. From that, three trains were from direction of north portal, and remaining three from direction of south portal. In order the measurements more reliable on part between both ends of the tunnel, measurings were measurements were continued for five minutes after the passing of the train.

5. RESULTS ANALYSIS OF EXPERIMENTS

In paper will be presented some of the measuring in Linkou tunnel with individual interpretations. In order to obtain comprehensive data on the pressure of air during train entering / exiting from the tunnel at high speed, ie during passing of the train through a tunnel, a relatively long-term variations of pressure during passing of train from the direction of the south portal at the site of shaft A in Linkou tunnel are given on diagrams 3(a) and 3(b), expressed by time intervals. On shown diagram 3(a) are given measuring of sensor P1, which was located south from exit for emergency situations at a distance from 50м (hereinafter S-50). Optical switch was at the same place so it was possible to determine current position of the train. Other optical switch was set 300 m north from emergency exit. Measured train speed during passing on location of shaft A was 212,72 km/h.

Looking at the diagram 3(a), can be noted that time interval, where maximum positive pressure follows maximum negative, is between 200. and 210. seconds. On next diagram 3(b) are shown measuring values of pressure with smaller intervals of measuring, measured on sensor P17. Position of sensor P17 is 50 m north from emergency exit (hereinafter N-50). It can be concluded that change of pressure in interval 200-210 s is caused by the south wave of pressures, based on small time difference of pressure amplitude between S-50 and N-50. It is assumed that these waves of pressure (compression and expansion) are caused by rain entrance on north side of the portal.

On figure 3(b) is noted that time difference of pressure amplitude until the arrival of the front part of the train in S-50 is around 37 s. Distance of S-50 to the north portal is 2576 m. Theoretically, the pressure waves are spreading with the speed of sound of 346 m/s at air temperatures of 25ºC. This implies that time of spreading of buoyancy wave, because of entrance of frontal part of train in tunnel, on side of north portal to S-50 is 2576/346=7,4 s. Time that passes between passing of frontal part of the train through north portal to position S-50 is 37+7,4=44,4 s, so average speed on that part is 2576/44,4=58,0 m/s= 208,8 km/h. This speed is approximate to the speed measured at shaft A.

According to diagram 3(a), top of negative pressure followed by positive is noted on position from 225-230 s. It is assumed that waves induced with train entry on south portal, by reflecting, cause waves that spread to the northern portal. Since distance of position S-50 to south portal is 3906 m, time interval between S-50 waves formed during entering of frontal part of train from south side of portal and reflecting wave from north on place S-50 is 22,5 s. This means that waves speeded on length of 3906x2=7812 m, and speed wave was7812/22,5=346,4 m/s, which is approximately equal to the sound spreading on temperature of 25ºC. According to diagram from figure 3(a) and 3(b) is clearly noted that when the frontal part of train reached to S-50 in 240 s, a sudden and pronounced drop in pressure occurred. After the train passes through S-50 is noted flickering of diagram. When the end of the train is moved from S-50, is noted first positive pressure. In N-50 is noted identical occurrence with small difference in time, because the train from south side arrived before in N-50 than in S-50. This pressure spreading is directly connected with train movement and is caused by aerodynamic resistance train during movement. If diagrams of air resistance during passing of train at speed higher than 200 km/h, on open and in tunnel are compared, can be noted the same trend of line pressures. It can only be explained that during train resistance on open railway, pressure increase on frontal part of the train is to small comparing to local drop of pressure directly next to frontal part of the train. On figure 3(a) is noted one more relatively big amplitude of positive pressure followed by negative on interval 315-320 s. According to time of drive, ie speed of the train, can be concluded that this occurrence happens at moment when train leaves the tunnel. Immediately after is noted occurrence of negative pressure followed by positive, as a consequence of existing of aerodynamic waves and after the train leaves the tunnel. It is time interval 330-335 s, figure 3(a).

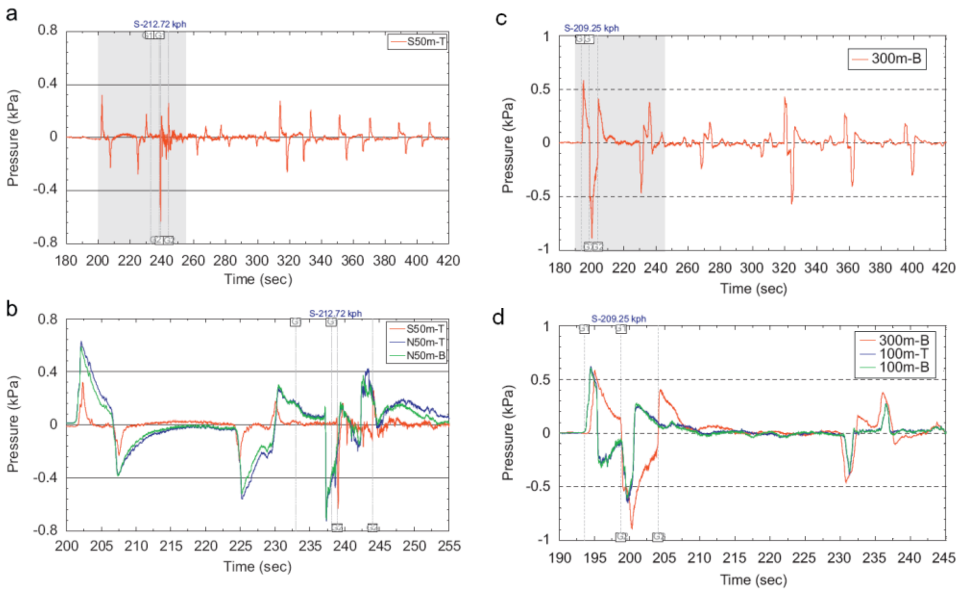

Figure 3 - a) Development of pressure in moment of measuring at shaft A, Linkou tunnel (train speed is 212,72km/h) on place S-50 (180-420s); b)ie on place S-50 and N-50 (200-255s); c) Development of pressure values at north portal of Linkou tunnel (train speed 209,25km/h) on position 300m (180-420s) ; d) ie on places 300m and 100m (190-245s). Mark B represents recording of sensor places on height of 2,5m, T on height 4m[2].

For discussion of pressure measuring on north portal were taken measuring of sensor P18. Graphically, measurements are shown on diagrams, figures 3(c) and 3(d). This sensor is positioned 300 m south from the highest point of north portal (hereinafter point on position 300 m). Optical switch G2 is installed on same place as P18, while switch G1 is positioned exactly on north portal, which is clearly seen on figure 2(a). This enables precise recording of train movement, notation of passing of frontal and end part of train. According to notes of optical speed switches train speed during entering the tunnel through north portal is 209,25 km/h. By diagram analysis from figure 3(c) frontal part of the train was in the tunnel at 195 s, and positive pressure was noted on position of 300 m exactly 1s after that. It is clearly noticeable that the top arrived first on position of 100 m, and some time later on 300 m. Soon after the passing of frontal part of the train through position 300 m, almost simultaneously the end of the train passed the portal. In that moment negative pressure was noted on 300 m which caused pressure of frontal part of the train passing and expansion wave of train end during entrance. While train passed the position of 300 m, negative pressure gradually decreased to the moment of 240 s when the end of the train passes 300 m. In that moment positive pressure overcomes, which is a consequence of resistance from effect of the end of train. At about 230 s, 270 s and 310 s, top of negative pressure followed by one positive is noted on place of position of 300 m. Also, top of positive pressure followed by negative is recorded in moment 320-325 s. This happens in moment of train leaving through south portal.

6. CONCLUSION

Results of measured pressures show that entry / exit of frontal part of train from tunnel cause buoyancy wave along entire tunnel and causes significant decrease of pressure, while the end of the train causes occurrence of expansion wave with pressure drop.

- Waves caused by train movement through tunnel spread with the speed close to speed of sound spreading.
- Current local drop of pressure is noted during passing of train through tunnel and by absolute value is equal to pressure jump caused by entrance of frontal part of the train in tunnel at the same speed.
- On locations distant from tunnel entrance, in presented example that is 50 m, pressure amplitudes become constant for characteristic train.
- Maximal positive pressures measured in tunnel are result of air resistance during entrance of frontal part of the train and are approximately proportional to the square of the speed of train movement.
- Amplitudes of positive and negative pressures are around 1kPa for speeds.
- Intensity of pressure is inversely proportional to the size of the cross section of the tunnel. The bigger the cross section of the tunnel is, the positive pressure is of smaller intensity.

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ЕКСПЕРИМЕНТАЛНО ОДРЕЂИВАЊЕ ОТПОРА ВАЗДУХА У ТУНЕЛУ КОД БРЗИХ ЖЕЛЕЗНИЦА

Резиме: *У раду се разматра један веома сложен проблем код брзих железница, а то је отпор ваздуха у тунелу. Приказује се поступак експерименталног одређивања отпора. Ваздушне струје изазване проласком воза кроз тунел се испитују експериментално и нумерички са намером да се аеродинамичке појаве што боље упознају и утврди њихова величина. Експерименталне технике мерења положаја и вредности притиска ваздуха су изузетно сложене. Првобитна истраживања су се односила на одређивање облика дијаграма притиска у зависности од брзине вожње и удаљености чела воза од улаза тунела. Експерименталним путем је утврђено на који начин се притисак јавља при уласку воза у тунел и када настави са кретањем дуж тунела. Зависно од начина мерења отпора ваздуха у тунелу, приказују се резултати експреименталних истраживања на прототипу. У оквиру овог рада се приказују резултати експерименталних мерења у тунелу Linkou (дати у раду Yung-Yen Ko-a [2]).*

Кључне речи: *брзе железнице, тунел, отпор ваздуха, мерење, прототип*