Theoretical backgrounds for zipline analysis

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This paper defines theoretical backgrounds for the zipline analysis. Considering that these systems are relatively new, and that there are still no valid regulations or drafts for them, the production of such systems is still left to the enthusiasts. For quality design it is necessary to perform a detailed analysis of persons kinematic parameters dependence from a range of influential sizes such as person's weight, tensile rope force, position during lowering, wheel resistance, wind, etc. Procedure for computational model forming is based on the catenary theory. The analysis are made by computer simulations for concrete conditions of zipline whose installation was planned on Fruška Gora. Conditions for mentioned zipline are characteristic due to the relatively large length (≈1500 m), small inclination angle (≈3.50°) and the "shallow" terrain. Analysis results are given through diagrams that shows the person's reach, velocity or acceleration in dependence of time or travelled distance.

Keywords: *Zipline, Catenary, Computation Model, Computer Simulation, Motion Resistance, Velocity, Deflection, Wind.*

1. INTRODUCTION

The term "zipline" represents a system of tightened steel rope by which the person is carried by high speed travelling trolley. The trolley and person are moving under the influence of their own weight. The main aim is causing increased excitement, so-called adrenaline sport. They expanded over the past two decades, with construction in various locations such as hilly areas, parks, lakes, bridges, the city cores, etc, [1].

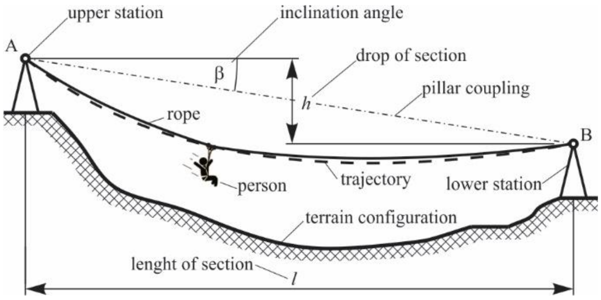

Figure 1. Schematic representation of zipline

From usage and safety viewpoint, the most interesting kinematic parameters are maximum velocity and acceleration, travelling time, range and velocity at the end of the section (velocity at limiter). The most significant size that influences those parameters is the inclination angle (β). For inclination angle larger than 10°, high velocities are achieved at the section, but also at the entry of lower station which is a significant problem for safe stopping of the person. In cases of inclination angles lower than 5°, there is a problem with arriving to the lower station, especially in cases of unfavorable wind direction or changes of the area exposed to the air flow (body position, spreading of hands, etc) during movement. For such cases, there is often a need for "pulling out" the person from the section.

2. THEORETICAL BACKGROUND AND COMPUTATIONAL MODEL FOR ZIPLINE ANALYSIS

Figure 2 shows a schematic representation of zipline with main notions and convenient mechanical model as background for computational model defining, [2], [3].

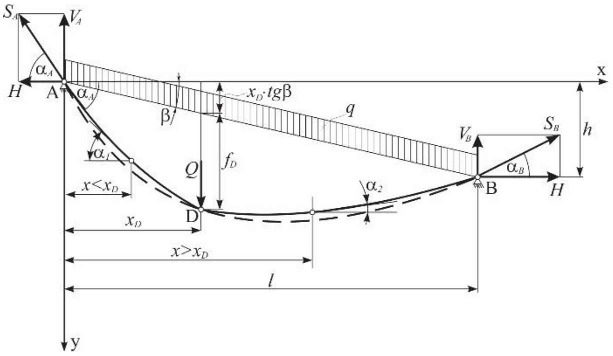

Figure 2. Mechanical model of zipline

The computational model is based on the catenary theory which represents an elastic flexible thread freely suspended between two supports located on the horizontal (l) and vertical (h) distance and loaded with its own weight [4].

The catenary equation, in a well-known form, is:

$$y = C \cdot \mathrm{ch}\left(\frac{x}{C}\right) \tag{1}$$

where catenary parameter:

$$C = \frac{H}{q} \tag{2}$$

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The usage of hyperbolic functions is relatively complicated, so the catenary is replaced by the appropriate parabola in the engineering practice. Errors which are made by this parabola are about 2 ÷ 3%.

In case of steel rope, whose supports are at different heights, loaded with its own weight and concentrated loads, the equation of the trajectory of person can be represented as:

$$y = x \cdot tg\beta + f_x \tag{3}$$

where the deflection at a distance x_D at which the load is acting is represented as:

$$f_D = \frac{x_D}{l \cdot H} \cdot \left[Q \cdot (l - x_D) + \frac{q \cdot (l - x_D)}{\cos\beta} \cdot \frac{l}{2} \right] \tag{4}$$

Usually, for short ziplines, both ends of the rope are anchored, but for ziplines with larger spans, the ropes are anchored at one end and tightened with weight at other.

Realization of zipline with both-sided anchorage is easy, which is the reason why it is often applied for short ziplines (from "tree to tree") but it represents a statically indeterminate system. For such case, the tension rope force changes considerably with the load moving, and additionally depends on the rope elasticity and current temperature [5]. This are main reasons why the case of a rope that is anchored at one end, and tightened with weight at other is generally more favourable, but the solution requires more space on the pillar and the system is more expensive which is justifiably only for large span ziplines.

The relevant computational model will be formed by neglecting small quantities of high order. The so-called static trajectory of movement is determined by expressions (3) and (4). Rope oscillation in vertical plane is, according to [6], [7] and [8], relatively small and can be neglected in case of "shallow" terrain and a system where the rope is anchored at one end and tensioned with weight at other.

Person connected with trolley forms a mathematical pendulum. If the length of the connecting belts is small, the effect of the swing can also be neglected as well as the influence of the centrifugal force due to the large radius of the trajectory curvature.

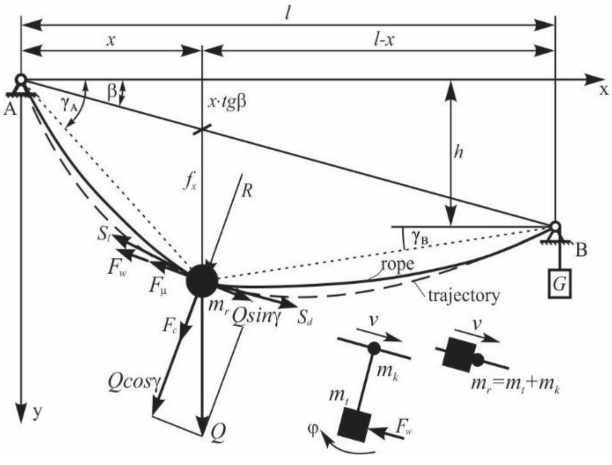

Figure 3. Computational model of zipline

In accordance to that, the computational model, shown on figure 3, can be represented as the movement of a concentrated mass along the trajectory determined for static conditions, [9] and [10]. The air resistance and rolling resistance are acting on the concentrated mass while moving. The direction of resistances is always opposite to the direction of movement.

Every wheel that is rolling along deformable surface has a resistance component due the friction in wheel bearings and due to deformation of contact surfaces. Wheel that is rolling along the rope (Figure 4) has additional resistance component due the rope stiffness. Unlike the perfectly flexible rope, the real rope will not take the position of the tangents behind and in front of the wheel, which can be seen as a "wrinkling" of rope in front of the wheel.

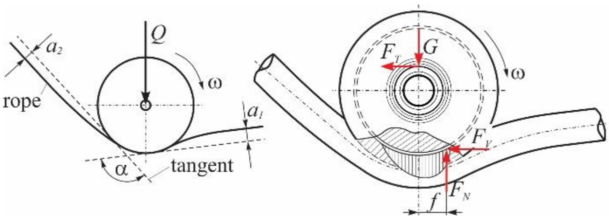

Figure 4. Model of wheel rolling along steel rope

Movement resistance of wheel that is rolling along steel rope can be determined by the expression:

$$F_\mu = \mu \cdot \Sigma G = \left(\mu_0 \cdot \frac{d}{D} + 2 \cdot \frac{f}{D} \right) \cdot \Sigma G \tag{5}$$

As the person traveling on zipline typically generates high velocity, the air resistance has a significant impact on all driving parameters. The air resistance is calculated according to [11]:

$$F_W = c_W \cdot A \cdot \frac{\rho \cdot (v \pm v_v)^n}{2} \tag{6}$$

where the dimensionless exponent depending on velocity (n) has values of:

n=1 for velocities smaller than 1 m/s,
n=2 for velocities between 1 m/s and 300 m/s,
n=3 for velocities greater than 300 m/s,

and values of drag coefficient (c_w) are determined experimentally. According to [12], the values for different lowering positions are:

c_w=0,6 - for sitting position,
c_w=0,4 - for half-sitting position,
c_w =0,2 - for lying position.

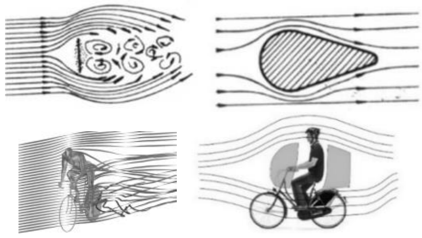

Figure 5. Turbulent or laminar flow cases

Areas exposed to air (A) are depending on the persons size and the body position. For person weighting 100 kg, they are approximately defined as:

A=0,4 m^2 for sitting position,
A=0,3 m^2 for half-sitting position,
A=0,2 m^2 for lying position.

Areas are proportional larger or smaller for persons weighting more or less than above mentioned mass.

3. RESULTS OF THE ANALYSIS

This heading presents analysis results for a concrete example of a zipline with a section length of 1467 m and drop of 99 m (therefore with inclination angle of 3,86°). Following diagrams shows the dependence of range, velocity and acceleration on person's weight, tensile rope force, position during lowering and wind direction.

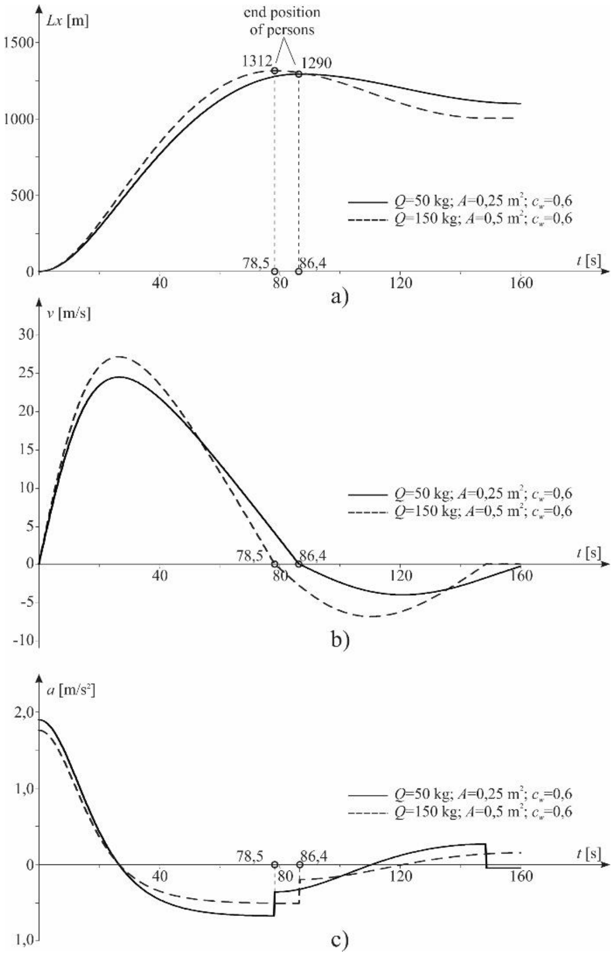

Figure 6. Diagram of the change in reach, velocity and acceleration for different values of person's mass

Diagram shown on figure 6 represents reach, velocity and acceleration as function of time for persons weighting 50 kg and 150 kg.

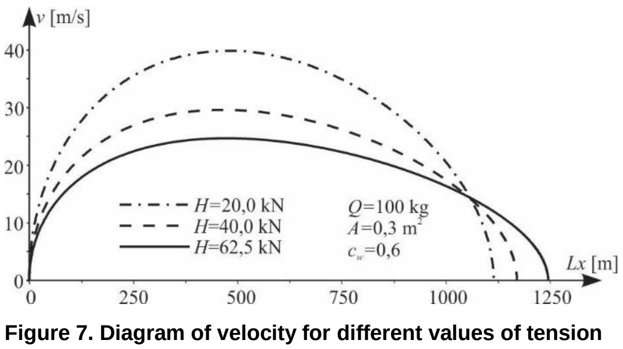

Figure 7. Diagram of velocity for different values of tension rope force

Diagram shown on figure 7 represents velocity as function of the horizontal distance between pillars for different values of tensile rope force. It is notable that the reach is increasing with tension rope force increasing.

Diagram shown on figure 8 represents velocity as function of the horizontal distance between pillars for different lowering positions, where it is notable that lowering in sitting position can't be applied. On the other hand, case of lowering in lying position requires caution due the high velocity of arrival at lower station.

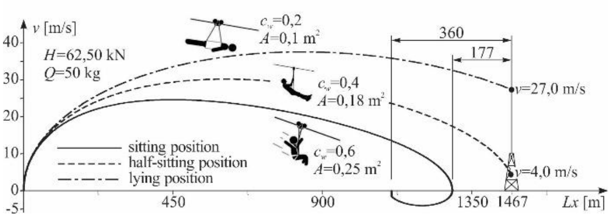

Figure 8. Diagram of velocity for different lowering positions

Diagram shown on figure 9 represents velocity as function of the horizontal distance between pillars for different directions of wind.

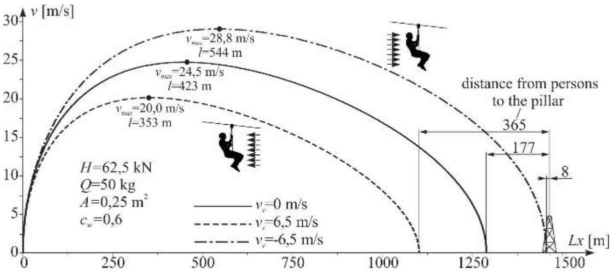

Figure 9. Diagram of velocity for different wind directions

4. CONCLUSIONS

For quality design, production and safe use of zipline, it is necessary to perform a detailed analysis of persons kinematic parameters dependence from a range of influential sizes. It is essential to form a relevant computational model which allows the simulation and determination of so-called "driving" characteristics" for concrete conditions.

For small inclination angles, the problem with person's arrival to the lower station occurs, especially in the case of "headwind" for light persons, which requires an appropriate solution for "pulling out" from the line. It is necessary to minimize movement resistance for such cases. Reducing trolley movement resistance can be achieved by an appropriate selection of wheels, rope construction and larger rope tension. In real conditions, air resistance can be reduced by reducing the area exposed to obstruction, or by correct selection of person's lowering position. The "half sitting" and "lying" lowering positions ensures arrival of persons to the lower station even for small inclination angles, whereby it is necessary to determine the arrival velocity and selection of appropriate safe stopping equipment.

Here are presented the analysis results by variating person's weight, tensile rope force, position during lowering, and wind direction. More detailed results are given in [13].

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NOMENCLATURE

β	inclination angle /◦/
h	section drop /m/
l	section length /m/
H	horizontal component of rope force /N/
q	own weight of rope /$^{kg}/_{m}$/
μ	total resistance coefficient /-/
μ_0	bearing friction coefficient /-/
d	bearing diameter /mm/
D	wheel diameter /mm/
f	lever arm of rolling torque /mm/
$\sum G$	sum of vertical forces /N/
c_w	drag coefficient /-/
A	frontal area /m^2/
ρ	air density /$^{kg}/_{m3}$/
v	person velocity / $^{m}/_{s}$ /
v_v	component of wind velocity in the direction of movement /$^{m}/_{s}$/;
n	dimensionless exponent depending on velocity