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IMPACT ANALYSIS OF ZIPLINE KINEMATIC PARAMETERS

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Abstract: This paper presents analysis of the influence parameters and the procedure for determining kinematic quantities of person traveling along zipline. Zipline is consisted of tightened rope by which the person is carried by high speed travelling trolley with aim of causing increased excitement. At first sight it is a very simple system, where in the case of small lengths the problem is solved by connecting the rope ends to the pylon (e.g. existing trees) and adjusting the inclination and motion parameters on the spot. But, for quality design and safe usage of longer zipline, 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, inclination angle, position during lowering, wheel resistance, wind, etc. This is especially important in case of long span and extreme inclination angle. The calculation itself is based on the catenary theory, while the analysis are made by computer simulations for concrete conditions of zipline whose installation was planned on Fruška Gora, Serbia. The size of above mentioned significant parameters were varied and the analysis results are given through diagrams that shows the person's speed characteristics.
Keywords: zipline, catenary, motion resistance, wind velocity

INTRODUCTION

Zipline represents a system where the anchoring points of carrying rope are at different heights, along which the trolley carrying a person is moving. Their original purpose was bridging of canyon or river, often only for lowering the cargo, while today they are more used for the purpose of entertainment as the so-called adrenaline sport.

Figure 1. Example of zipline

As it is a relatively new system, whose name has not settled yet, beside the mentioned zipline (which will be used in this paper), it is also known under the names such as: *aerial runway, aerial ropeslide, death slide* or *flying fox* in English, *Seilrutsche* in German, *Tirolienne* in French or *Guerillarutsche* in the Austrian.

They expanded over the past two decades, with construction in various locations such as hilly areas, parks, lakes, bridges, the city core, etc. [4].

Ziplines are mainly foreseen for individual lowering of persons, but there are few cases of ziplines where several persons are lowering side by side (never one behind other). Figure 1 shows an example of parallel zipline located in hilly area.

STATE OF THE ART

At the time, the world's longest zipline is *Jebel Jais Flight* in the United Arab Emirates with a length of 2832 m. Longest European zipline is *Stoderzinken* in Austria, which actually consists of two sections with total length of 2500 m. Zipline with the highest drop is *ZipFlyer* in Nepal, with a height difference of 610 m, [8]. However, although this is an imposing altitude difference, the inclination angle of the section (~18.7°) is not the greatest. The zipline with greatest inclination angle is the *Letalnica Bratov Gorišek*, within the same named ski jumping hill in Slovenia, which amounts 38% or 20,8° [7].

According to [8], the highest achieved speed until 2015 amounts 235 km/h.

The most interesting movement parameters which should be determined are the maximum velocity, duration of travel, the travelled distance and the velocity at the end of the section ("velocity at limiter").

The most significant size that influences those parameters is the inclination angle. For inclination angle larger than 10°, high speeds 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.

FUNDAMENTALS FOR ANALYSIS

This chapter shows a short review of significant relations for the theory of so-called "horizontal rope", which was developed for calculations of ropeways, cable cranes, overhead power lines, etc. More detailed can be seen in[2], [9] and [10].

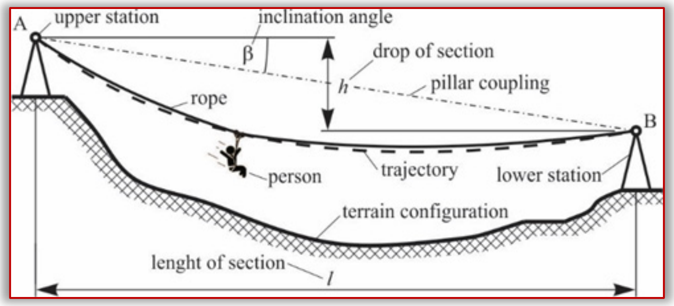

Figure 2. Route and zipline parameters

Figure 2 shows a zipline scheme with basic notations.

–Rope loaded by its own weight

Line that describes the position of the elastic flexible thread freely hanging between two supports located on the horizontal (*l*) and vertical (*h*) distance and loaded with its own weight is called a catenary.

The catenary equation can be obtained by observing the static equilibrium of forces shown in Figure 4.

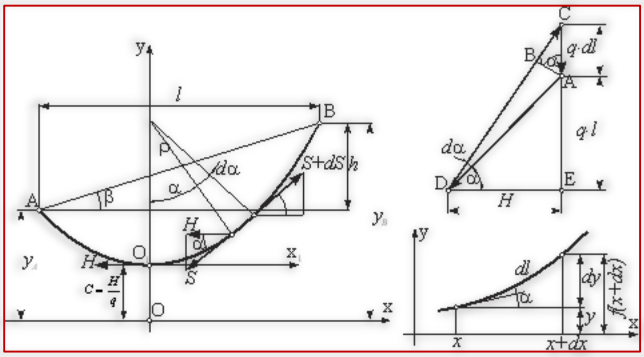

Figure 3. Catenary parameters [11]

Based on the static equilibrium equations that can be written for the elementary section of the rope, and after their rearrangement, the catenary equation is obtained as:

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

where the catenary parameter can be defined as:

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

where:

H - horizontal component of tension rope force,

q - own weight of rope.

The difference of forces between any two points of rope can be determined by the expression:

$$\Delta S = S_B - S_A = q \cdot (y_A - y_B) = q \cdot h \qquad (2)$$

The use of the catenary theory provides the correct solutions, but as the use of hyperbolic functions is relatively complicated, in the engineering practice the catenary is replaced by the appropriate parabola.

Figure 4 shows the possibility of replacing the catenary with a parabola. The errors in the size of the deflections which are made by this approximation are 2 ÷ 3% (the deflections are smaller in case of parabola than in the case of a catenary). Accuracy can be increased by introducing a correction coefficient (*k*).

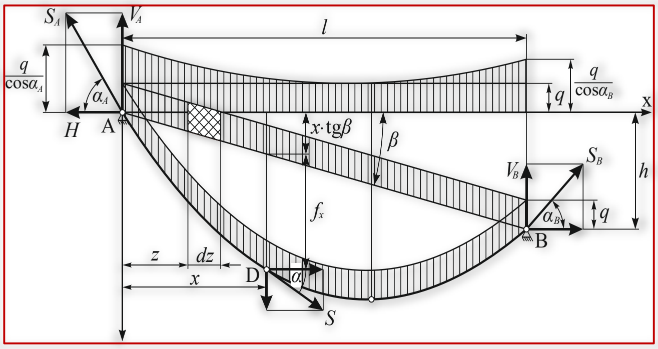

Figure 4. Parabola method [9]

Parabola method, obtains the equation of the curve as:

$$y = \frac{q \cdot x \cdot (l - x)}{2 \cdot H \cdot \cos\beta} \cdot k + x \cdot tg\beta \qquad (3)$$

where f_x represent deflection which is calculated as:

$$f_x = \frac{q \cdot x \cdot (l - x)}{2 \cdot H \cdot \cos\beta} \cdot k \qquad (4)$$

where:

$k = 1 + \frac{\cos^2\beta}{p} \cdot \left[\frac{1}{p} \cdot \left(x^2 - l \cdot x + \frac{l^2}{2}\right) - 2 \cdot (l - 2x) \cdot tg\beta\right]$ - correction coefficient,

$p = \frac{H}{q} \cdot \cos\beta$ - parabola parameter.

–Rope loaded by its own weight and concentrated load

Unlike most of metal constructions like beams, frames or grids, where the influence of deformation on the static equilibrium is neglected, that is not the case for the "horizontal rope", so the second-order theory must be applied.

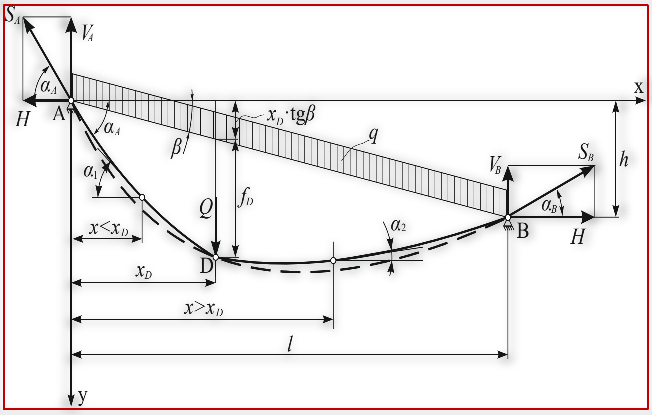

Figure 5. Rope loaded with its own weight and concentrated load [1], [9]

Observing the rope, whose supports are at different highs, which is loaded with its own weight and concentrated load (*Q*), the equation of the load trajectory, shown on Figure 5, can be presented as:

$$y = x \cdot tg\beta + f_x \quad (5)$$

where the deflection at the distance x_D where the load is acting can be calculated as:

$$f_D = \frac{x_D}{l \cdot H} \cdot \left[Q \cdot (l - x_D) + \frac{q \cdot (l - x_D)}{\cos\beta} \cdot \frac{l}{2} \right] \quad (6)$$

while the maximal deflection is calculated by:

$$f_{\max} = \frac{l^2}{8H} \cdot \left(\frac{q}{\cos\beta} + \frac{2Q}{l} \right) \quad (7)$$

ANCHORING ROPE ENDS

There are two ways to achieve anchorage of the rope ends:

- both sided anchorage,
- anchorage at one end and tightening with the weight at other.

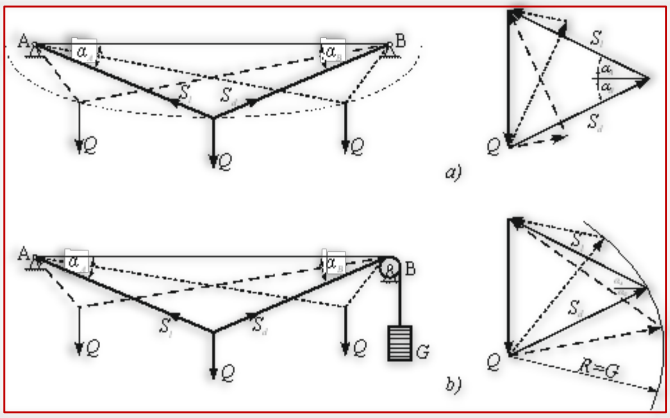

Figure 6. The rope force change in case of a both sided anchored rope (a) and in the case of tightening with a weight (b)

Case of a both-sided anchored rope is a statically indeterminate system with a significant change in the rope force when the load is moving. Besides that, there is significant impact of temperature and rope elasticity. On the contrary, this case is easy to perform, which is reason why it is often applied for short ziplines (so-called "from tree to tree").

The case of a rope that is anchored at one and tightened with weight at other end is considerably more favorable, because the rope forces aren't changing much and there aren't influences of the temperature and rope elasticity, but the system is more expensive and solution requires more space on the pillar.

Change of rope force for three characteristic load positions are notable on Figure 6.

This paper will further be based only on case of rope anchored at one and tensioned with weight at other end.

COMPUTATIONAL MODEL FORMING

The adequate computational model will be formed by neglecting small quantities of high order. The terms (5) and (6) are determining the so-called static trajectory of movement. In the case of tensioning with weight and "shallow" catenary, according to [9] and [10], the oscillation of the rope in the vertical plane is relatively small and can be neglected. A person connected with trolley forms a mathematical pendulum, but if the start is smooth and the belt length are short, the effect of swinging can also be ignored. According to that, the computational model which is shown on Figure 7, can be represented as the concentrated mass that is moving along trajectory determined for static conditions, [5].

Air resistance and rolling resistance are acting onto concentrated mass during the movement, [1], [5] and [13]. The direction of resistances is always opposite to the direction of the movement.

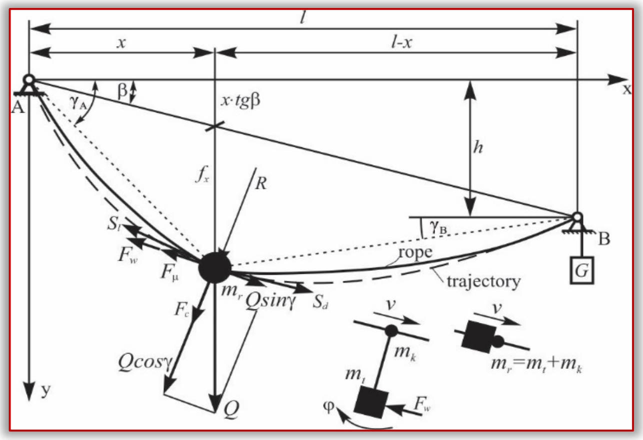

Figure 7. Computational model

As the load is moving along curved path, there is an influence of the centrifugal force. If it is assumed that generally the maximum velocity doesn't exceed 120 km/h (~33,33 m/s), the maximum possible impact of the centrifugal force in relation to the component of person's weight is:

$$\frac{F_{c,\max}}{Q \cdot \cos\beta} = \frac{v_{\max}^2}{g \cdot R_{\min} \cdot \cos\beta} = \frac{33{,}33^2}{9{,}81 \cdot 4982} \sim 0{,}02$$

where $\cos\beta \approx 1$, and the radius of the trajectory curve for given conditions is:

$$R_{\min} \approx \frac{G}{q + \frac{2Q}{l}} = \frac{62500}{10{,}5 + \frac{2 \cdot 1500}{1467}} = 4982 \text{ m}$$

As seen, the maximum impact of the centrifugal force is less than 2%, so it can be ignored.

–Determination of rolling resistance

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 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 which is shown on Figure 8.

This effect can be included by the relation (8), where the lever arm of rolling torque includes the influence of contact surfaces deformation and the "wrinkling" of the rope, so the value is higher than in case of "standard" wheel.

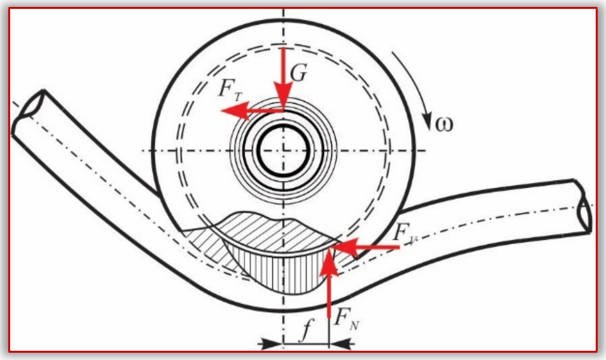

Figure 8. Wheel model

Resistance of wheel that is rolling along steel rope is calculated as:

$$F_\mu = \mu \cdot \Sigma G = \left(\mu_0 \cdot \frac{d}{D} + 2 \cdot \frac{f}{D}\right) \cdot \Sigma G \qquad (8)$$

where:
μ - total resistance coefficient,
μ_0 - bearing friction coefficient,
d – bearing diameter
D – wheel diameter,
f – lever arm of rolling torque,
$\sum G$ - sum of vertical forces.

Based on expression (8) it can be seen that the total resistance coefficient depends on the geometric size of the wheel (d, D), as well as the rolling resistance coefficient in the bearing (μ_0) and the rolling resistance between the wheel and rope (f). The bearing friction coefficient and lever arm of rolling torque are determined experimentally.

–Determination of air resistance

As person travelling along zipline typically generates high velocity, air resistance has a significant impact on all driving parameters. Air resistance is influenced by a large number of dimensions, such as the type of flow (laminar or turbulent), area exposed to the air, the shape of the body, velocity etc.

Air resistance is, according to [3], calculated:

$$F_W = c_W \cdot A \cdot \frac{\rho \cdot (v \pm v_v)^n}{2} \qquad (9)$$

where:
c_W – drag coefficient,
A – frontal area,
ρ – air density,
v – person velocity,
v_v – component of wind velocity in the direction of movement,
n – dimensionless exponent depending on velocity, according to [3]:
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.

As the air density doesn't change much for some standard conditions, and the velocity is more often expressed in km/h than in m/s, formula (9) can be written in the form:

$$F_w = 0,0473 \cdot c_w \cdot A \cdot v^2 \qquad (10)$$

whereby the velocity (v) is expressed in km/h, the specific air density is taken as ρ=1,225 kg/m³, medium air humidity as w=60% and medium air temperature as t=15 °C.

When temperature or pressure vary from ordinary, a corrected term for density is used:

$$\rho = 1,25 \cdot \frac{B}{1,015} \cdot \frac{293}{T} \qquad (11)$$

where:
B – pressure (bar)
T – temperature (K)

The orientational values of the drag coefficient (c_W) are obtained experimentally and according to [6] approximately amount:
- standing person ~0,78,
- cyclist in an upright position 0,53÷0,69,
- cyclist in bent position ~0,4.

COMPUTER SIMULATIONS

Within this point the procedure and the results of the analysis for a concrete example of zipline whose construction was planned on Fruška Gora will be presented. Figure 11 shows the geometry of the route with section length of 1467 m and a drop of 99 m. Hence, the inclination angle amounts:

$$\beta = \text{atan}\frac{h}{l} = \text{atan}\frac{99}{1467} = 3,86^0$$

This represents a limiting case because of the small inclination angle

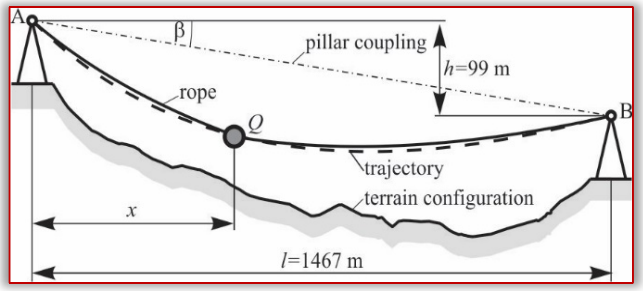

Figure 9. Example zipline, size 1: 2.5

The selection of the rope type and its diameter, as well as the foreseen tensile rope force, are detailed elaborated in [12]. The simulation results will be shown for the steel rope of Warrington 6x19+IWRC construction with diameter of 16 mm.

Determination of motion parameters was performed using computer simulations in the MSC Adams program package. As mentioned in previous section, the system was modeled as a concentrated mass that moves along a trajectory defined by equation (5). Air and rolling resistance are acting on the concentrated mass which is moving under the influence of its own weight. The direction of resistances is always opposite to the direction of movement.

Simulations were performed by varying the persons weight from 50 to 150 kg. Areas exposed to air are depending on the persons size (weight) and the lowering position, which can be sitting, half-sitting and lying. For case of lowering in a sitting position, those areas can be aproximated by the average dimensions of the persons given on Figure 10:

- A = 0,25 m2 - for persons weighting less than 60 kg,
- A = 0,3 m2 - for persons weighting between 60 kg and 100 kg,
- A = 0,4 m2 - for persons weighting between 100 kg and 140 kg,
- A = 0,5 m2 - for persons weighting more than 140 kg.

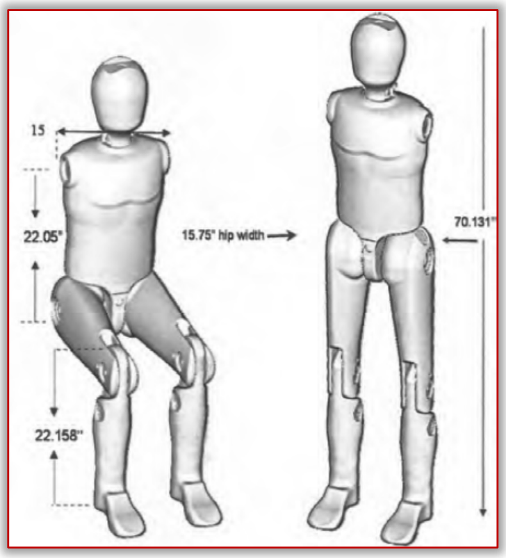

Figure 10. Determining the areas exposed to air (wind), [12]

Areas exposed to air flow for lowering in half-sitting and lying position are smaller and amounts 0,18 m^2 and 0,1 m^2 respectively.

The drag coefficient depends on the lowering position:

— c_w = 0,6 - for sitting,

— c_w = 0,4 - for the half-sitting and

— c_w = 0,2 - for lying position.

The total resistance coefficient of movement, based on the bearing and wheel diameter for concrete trolleys (d = 22 mm and D = 100 mm) and literature based bearing friction coefficient μ_o = 0,01 and lever arm of rolling torque f=0,7 mm, is calculated as:

$$\mu = \mu_0 \cdot \frac{d}{D} + 2 \cdot \frac{f}{D} = 0{,}01 \cdot \frac{22}{100} + 2 \cdot \frac{0{,}7}{100} = 0{,}016$$

This average value of the moving resistance coefficient can significantly deviate depending on the d_o/D ratio, bearing type, rope type or H/q ratio.

Above mentioned parameters were varied during simulations within limits up to 25%.

RESULTS OF SIMULATION

Presentation of characteristic results is shown below.

–Impact of persons mass

Diagram of velocity for different values of person's mass is shown on Figure 11.

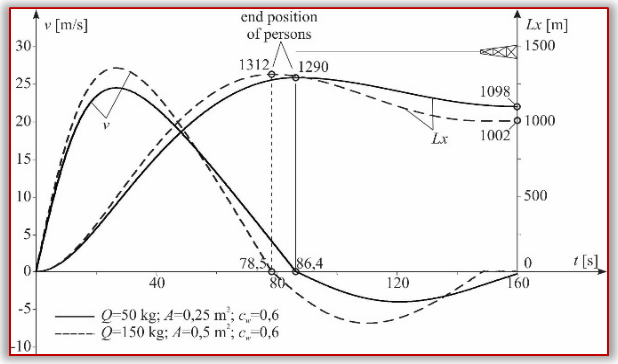

Figure 11. Diagram of velocity for different values of person's mass

From Figure 11, it is notable that persons do not reach the lower station.

–Impact of lowering position

The diagram shown on Figure 12 represents the simulation results for the different lowering positions, where it is notable that the seating position can not be applied for the given conditions.

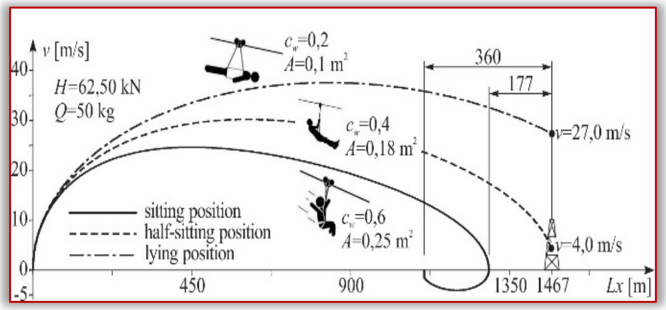

Figure 12. Diagram of velocity for different lowering positions

However, even the "half-sitting" and "lying" positions should be carefully analyzed, because these positions are significantly more "sensitive" to changes such as spreading of the hand for "selfi" (a larger area), which significantly changes the conditions of the person's arrival in the lower station.

–Impact of wind

Previous paragraphs show only the case of the body moving through the "quiet" air. The following analysis will show the effect of changeable wind direction. Velocity of moderate breeze (intensity 4 on Beaufort scale) amounts between 5,5 m/s and 7,9 m/s, so the average values of 6,5 m/s was taken in simulation.

The diagram given on Figure 13 shows the influence of the wind in the direction of movement in the case of the tailwind and headwind for person weighting 50 kg.

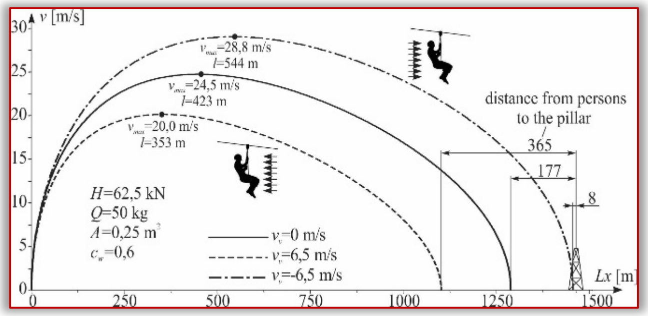

Figure 13. Diagram of velocity for different wind directions

CONCLUSION

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 such as person's weight, tensile rope force, inclination angle, position during lowering, wheel resistance, wind, etc. It is essential to form adequate computational model which allows the simulation and determination of so-called "driving characteristics" for concrete conditions.

Note:

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