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Analiza uslova i podloge za izbor uređaja za zaustavljanje kod zipline-a

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Tema ovog rada su podloge za izbor sistema za zaustavljanje kod zipline-ova. S obzirom da u Srbiji zasad ne postoji zakonska regulativa kojom su definisani uređaji za kočenje i zaustavljanje kod zipline-a, u prvom delu rada je dat izvod iz stranih standarda. Nakon toga sledi pregled nekih od postojećih rešenja sistema za zaustavljanje, kao i primeri patentnih rešenja. Kako je neophodno znati brzinu kojom se putnik kretao pre početka kočenja, u radu su date osnove za određivanje kinematskih parametara putnika. Analiza kinematskih parametara se sastoji iz dva dela – prvog koji uključuje statičku analizu koja se temelji na teoriji lančanice, i drugog koji uzima u obzir inercijalne sile, otpor kotrljanju, otpor vazduha, položaj putnika tokom spuštanja, silu zatezanja užeta i slično. Na kraju su date preporuke za dimenzionisanje sistema za zaustavljanje tako da pri zaustavljanju ne dođe do povrede putnika, kao i jedan računski primer za konkretan zipline koji je izgrađen na Fruškoj Gori.

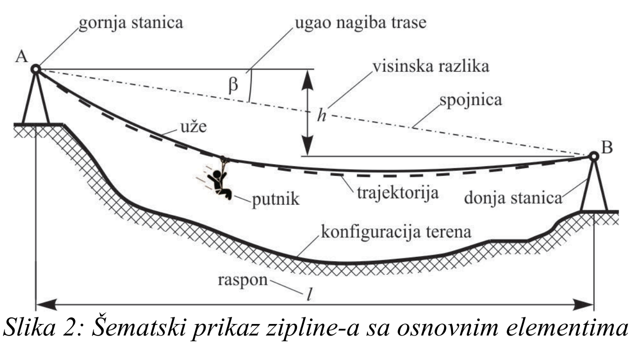
Ključne reči: Zipline, Kočenje, Brzina, Ubrzanje

1. UVOD

Pojam zipline predstavlja sistem zategnutog čeličnog užeta po kojem se velikom brzinom kreću kolica sa putnikom. Kolica i putnik se kreću pod dejstvom sopstvene težine, a glavna namena im je u svrhu razonode, odnosno kao adrenalinski sport. Ekspanziju doživljavaju u poslednje dve decenije sa izgradnjom na različitim mestima kao što su brdoviti predeli, parkovi, jezera, pored mostova u gradskim jezgrima i sl.

Slika 1: Primer zipline-a

Na slici 2 je dat šematski prikaz zipline-a sa osnovnim elementima.



Slika 2: Šematski prikaz zipline-a sa osnovnim elementima

2. PROPISI

Na osnovu ACCT (*Association for Challenge Course Technology*) i ASTM (*American Society for Testing and Materials*) standarda, za zipline-ove kod kojih se postižu brzine veće od 10 km/h, neophodno je obezbediti odgovarajuće sisteme za bezbedno zaustavljanje [1].

ACCT standard razlikuje:

- **Kočioni sistem kod zipline-a:** Sistem za kontrolisanje brzine kretanja i/ili zaustavljanje putnika. Može biti aktivan ili pasivan.
- **Kočioni sistem na kraju trase:** Sistem koji se sastoji od glavne kočnice i kočnice za slučaj opasnosti projektovanih tako da zajedničkim radom obezbede zaustavljanje putnika.
- **Glavna kočnica:** osnovna (glavna) kočnica kod zipline-ova. Koristi se tokom regularnog rada za zaustavljanje putnika. Osnovna kočnica ima dve uloge – da savlada inercijalnu silu od putnika, ali i inercijalne sile od rotacionih i translatornih masa kolica zipline-a.
- **Kočnica za slučaj opasnosti:** Kočnica postavljena na kraju trase koja se aktivira samostalno ukoliko dođe do otkaza glavne kočnice kako bi se sprečile ozbiljne povrede ili smrt putnika.

Gorepomenuti standard navodi da bi sistem za kočenje trebalo da projektuje kvalifikovana osoba i da bi trebalo da uzme u obzir sledeće:

- osnovnu funkciju tj. zaustavljanje;
- statička, dinamička i udarna opterećenja za najnepovoljniji slučaj;
- habanje i zamor;
- faktore radnog okruženja kao što su ekstremne temperature, vetar i drugi vremenski uslovi;
- nivo rizika za učesnika ukoliko dođe do kvara sistema za kočenje ili neke od njegovih komponenata uključujući i mogućnost blokade ili nepravilnog premotavanja savitljivih elemenata.

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Pored toga, standard zahteva i da kvalifikovana osoba izvrši nadzor i proceni rezultate ispitivanja. Svi testovi moraju da pruže dokaz o sledećem:

- kočnica mora biti funkcionalna u svim oblastima od minimalne do maksimalne mase i brzine putnika;
- potvrdu da sistem kočnica funkcioniše kako je i projektovan.

S druge strane, ASTM standard razlikuje:

- **Kočioni sistem:** Kako ovaj standard ne definiše samo zipline, već i druge vidove adrenalinskih sportova koji sadrže uže, kočionim sistemom se smatraju: uzdužne frikcione kočnice, disk ili doboš kočnice bilo da su na kolicima ili van njih. Ukoliko bi defekt kočionog sistema doveo putnika u nebezbednu situaciju, sistem se mora projektovati kao bezopasan.
- **Bezopasan sistem:** Adrenalinski park ili neki njegov deo koji je projektovan tako da se bilo koji vid akcidentne situacije završava bezbedno po korisnika.

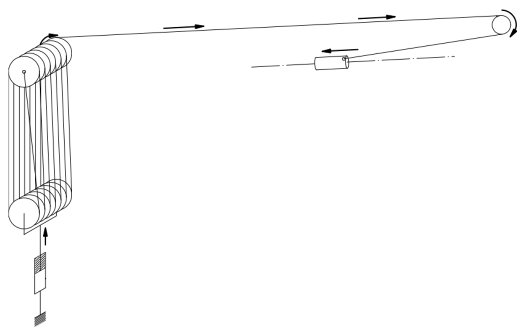
Na osnovu standarda ASTM F2291 projektant je dužan da izvrši i dokumentuje preduzete vidove zaštite. Dokumentacija bi trebalo da sadrži, no nije samo na to i ograničena:

- identifikaciju opasnosti koja uključuje potencijalne uzroke i posledice nezgoda;
- identifikaciju samih nezgoda;
- procenu opasnosti koja uključuje opis na koji način je izvršeno ublažavanje opasnosti na prihvatljiv nivo. Opasnosti se mogu redukovati smanjenjem posledica istih, smanjenjem mogućnosti da do istih dođe ili i jednog i drugog. Opasnosti mogu, ali i ne moraju biti ublažene. Procena opasnosti bi trebalo da uzme u obzir i rizike koji su nastali ili su sprečeni procesom smanjenja. Procena uključuje, ali se ne ograničava samo na analizu otkaza. Analiza otkaza se mora izvršiti na bezbednosnim sistemima koji se koriste u zabavnim parkovima. Analiza otkaza bi trebalo da sadrži istoriju otkaza, režim otkaza ili analize uticajnih parametara ili neki drugi dokaz iz pozitivne inženjerske prakse.

Na osnovu standarda ASTM F2959 usporavanje i zaustavljanje putnika koji je stigao do zaustavne zone se izvodi na kontrolisani način i mora uzeti u obzir i faktore okoline kao što su vlažnost vazduha, padavine, temperature, vetar i sl.

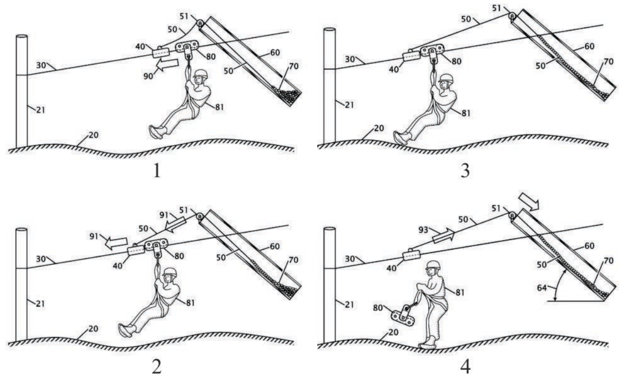
3. PRIMERI SISTEMA ZA ZAUSTAVLJANJE

Zaustavljanje korisnika na kraju trase se najčešće vrši tako što se na noseće uže pričvršćuje odbojnik koji je preko pomoćnog užeta povezan sa određenim uređajem za kočenje. Pomoćno uže se može direktno spajati sa uređajem, ili se njegovim premotavanjem može dobiti odgovarajući prenosni odnos, pa je samim tim potreban manji uređaj.



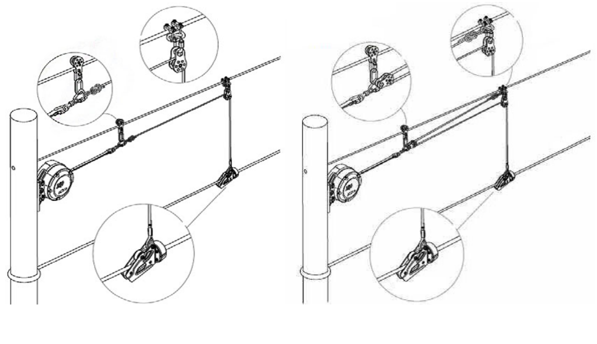
Slika 3: Sistem za kočenje sa hidrauličnom kočnicom

Na slici 3 je dat šematski prikaz jednog sistema za kočenje kod kog kočenje vrši hidrocilindar, dok je na slici 4 dat prikaz sistema gde se usporenje putnika vrši tako što je za odbojnik vezan lanac koji se nalazi u spremištu i koji se nakon naletanja kolica na odbojnik lagano izvlači.



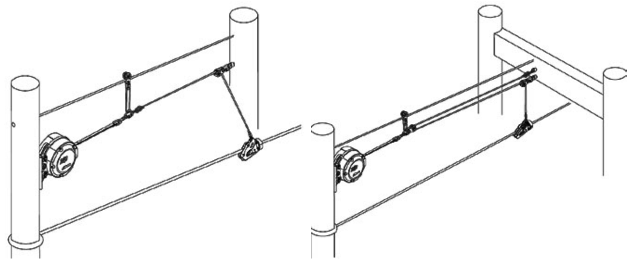
Slika 4: Sistem za kočenje sa lancem

Međutim, pomenuto rešenje sa lancem se može videti u određenim patentnim prijavama [2], ali koliko je autorima poznato, ne i u praksi. U praksi se najčešće sreću rešenja sa oprugama kao što je dato na primeru na slici 5 kod kojeg se usporenje vrši uz pomoć spiralne opruge pri čemu kočiono uže može biti direktno spojeno sa odbojnikom ili se može premotavati preko pomoćne koturače i time povećati prenosni odnos [3].



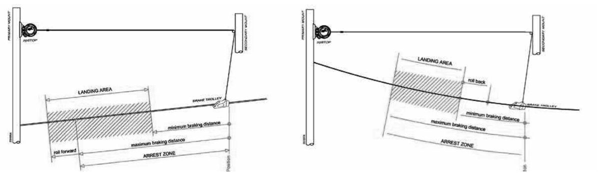
Slika 5: Sistem za kočenje sa spiralnom oprugom

S obzirom da uže koja spaja odbojnik sa kočnicom ne može da lebdi u vazduhu, u okolini donjeg stuba se mora obezbediti i pomoćno noseće uže za koje se na odgovarajućim rastojanjima pridržava kočiono uže. Na slici 6 levo je dat šematski prikaz pričvršćenja sa smaknutim stubom, dok je na slici 6 desno dat prikaz sa portalnim pričvršćenjem [3].



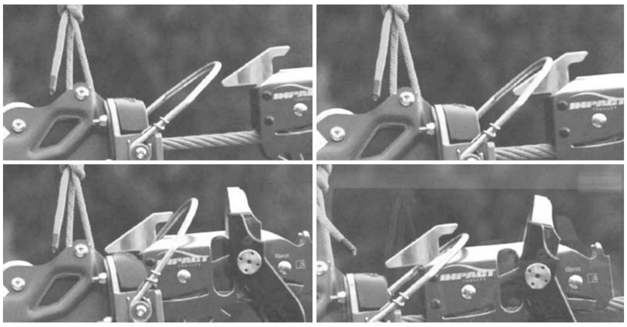
Slika 6: Pričvršćenje pomoćnog užeta

Ukoliko je nagib trase u okolini donjeg stuba takav da slobodno puštena kolica teže da priđu donjem stubu, radi se o pozitivnom nagibu trase [3]. Ukoliko bi se slobodno puštena kolica počela udaljavati od stuba, u pitanju je negativan nagib trase.



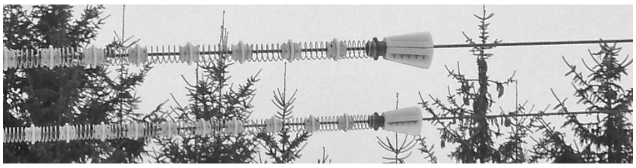
Slika 7: Pozitivan i negativan nagib trase

Za trase sa negativnim nagibom mora se sprečiti mogućnost da se korisnik nehotice vrati na trasu. To se postiže time što na odbojniku postoji ugrađena posebna hvataljka čiji se princip rada može videti na slici 8.



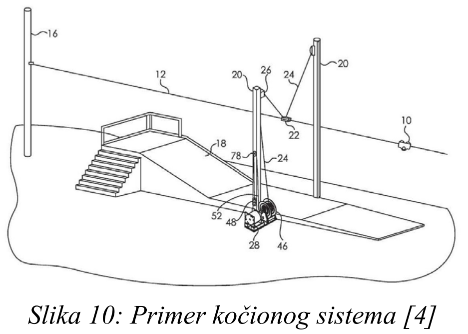
Slika 8: Odbojnik sa hvataljkom

Kao kočnica za slučaj opasnosti se koriste opruge navučene na uže na samom kraju trase.

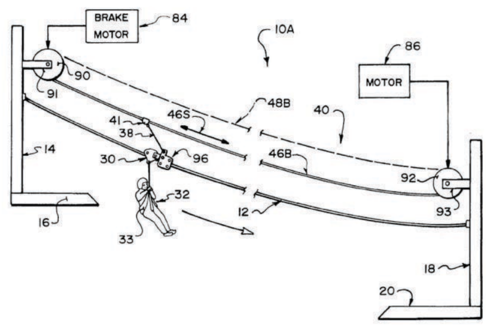


Slika 9: Kočnica u vidu opruga

Primer prikazan na slici 10 ima kočnicu u vidu turbine čije je radno kolo napunjeno viskoznim fluidom, dok primer na slici 11 ima kočnicu u vidu elektromotora.



Slika 10: Primer kočionog sistema [4]



Slika 11: Primer kočionog sistema sa elektromotorom [5]

4. PODLOGE ZA ANALIZU

4.1. Definisanje trajektorije

S obzirom da su teorijske podloge detaljno opisane u preďašnjim radovima kao što su [6]-[12], ovde će se dati samo kratak pregled.

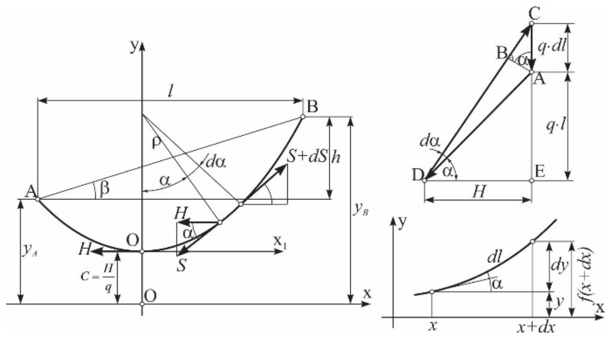
Lančanica predstavlja liniju koja opisuje položaj elastične gipke niti slobodno obešene između dva oslonca koji se nalaze na horizontalnom (*l*) i vertikalnom (*h*) rastojanju i koja je opterećena sopstvenom težinom (*q*).

Na osnovu slike 12 i određenih matematičkih transformacija, dobija se jednačina lančanice u obliku:

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

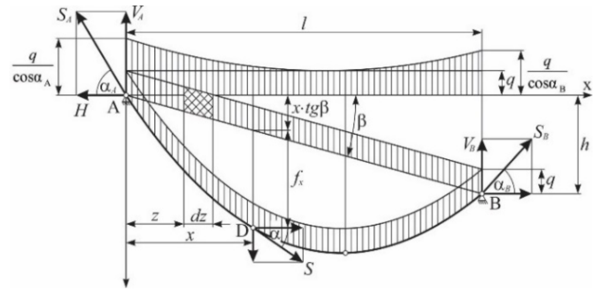
gde je parametar lančanice (*C*) funkcija sile u užetu (*H*) i njegove sopstvene težine (*q*):

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



Slika 12: Primer lančanice

Teorija lančanice daje tačna rešenja, no s obzirom da je upotreba hiperboličkih funkcija relativno komplikovana u inženjerskoj praksi, lančanica se zamenjuje odgovarajućom parabolom. Ova aproksimacija dovodi do greške u ugibima od oko 2 ÷ 3%. Tačnost se može povećati korišćenjem korekcionog koeficijenta (*k*). Na slici 13 su prikazane neke od mogućnosti za zamenu lančanice parabolom.



Slika 13: Primeri parabole

Jednačina parabole se može zapisati kao:

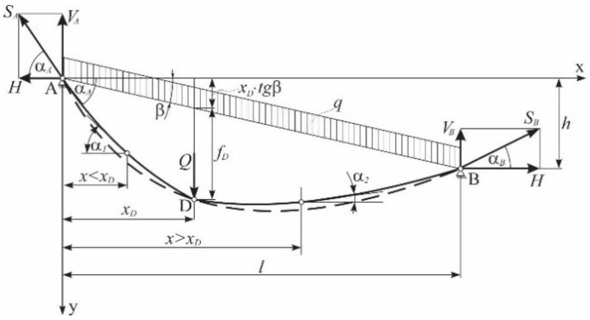
$$y = \frac{q \cdot x \cdot (l - x)}{2 \cdot H \cdot \cos\beta} \cdot k + x \cdot tg\beta \qquad (3)$$

gde se korekcioni koeficijent računa kao:

$$k = 1 + \frac{\cos^2\beta}{p} \cdot \left[\frac{1}{p} \cdot \left(x^2 - l \cdot x + \frac{l^2}{2} \right) - 2 \cdot (l - 2x) \cdot tg\beta \right] \qquad (4)$$

a parametar parabole (p) kao:

$$p = \frac{H}{q} \cdot \cos\beta \qquad (5)$$



Slika 14: Uže opterećeno sopstvenom težinom i koncentrisanim opterećenjem

Slika 14 prikazuje slučaj užeta čiji su oslonci na različitim visinama i koje je opterećeno ne samo sopstvenom težinom, već i koncentrisanim opterećenjem. Jednačina trajektorije kretanja putnika tokom spuštanja se može predstaviti kao:

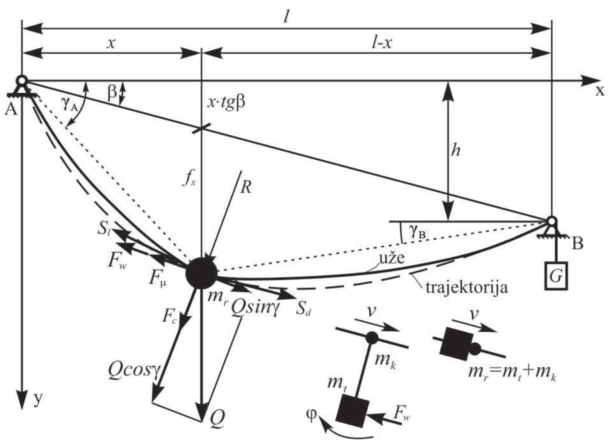
$$y = x \cdot \mathrm{tg}\beta + f_x \qquad (6)$$

gde se ugib na rastojanju x_D na kom deluje koncentrisano opterećenje računa kao:

$$f_D = \frac{x_D}{l \cdot H} \cdot \left[Q \cdot (l - x_D) + \frac{q \cdot (l - x_D)}{\cos\beta} \cdot \frac{l}{2} \right] \qquad (7)$$

4.2. Proračunski model

Formiranje relevantnog proračunskog modela će se izvršiti zanemarivanjem malih veličina višeg reda. Takozvana statička trajektorija je određena izrazima (6) i (7). Osoba koja je uz pomoć pojaseva vezana za kolica, formira sa kolicima matematičko klatno, no ako je dužina pojaseva mala, efekat njihanja se može zanemariti. Isto važi i za centrifugalnu silu usled velikog poluprečnika zakrivljenja.



Slika 15: Proračunski model zipline-a

U skladu sa tim, proračunski model zipline-a, koji je prikazan na slici 15, se može posmatrati i kao kretanje koncentrisane mase po trajektoriji definisanoj za statičke uslove.

Otpor vazduha i otpor kotrljanju dejstvuju na koncentrisanu masu tokom kretanja i to u smeru suprotnom od smera kretnja.

$$F_w = c_w \cdot A \cdot \frac{\rho \cdot (v \pm v_v)^n}{2} \qquad (8)$$

Na osnovu jednačine (8), otpor vazduha zavisi od:

- koeficijenta opstrujavanja (c_w),
- površine izloženoj dejstvu vazduha (A),
- gustine vazduha (ρ),
- relativne brzine između putnika i vazdušne struje (vetra), i
- bezdimenzionog koeficijenta (n), koji za vrednosti brzina od 1 m/s do 300 m/s ima vrednost 2.

S obzirom da se gustina vazduha ne menja mnogo za neke standardne uslove, i s obzirom da se brzina kretanja češće izražava u km/h nego u m/s, jednačina (8) se može napisati i u obliku:

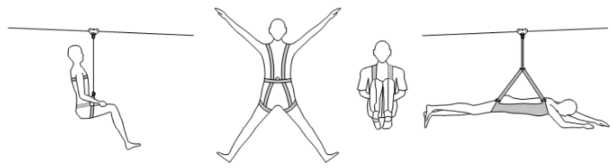
$$F_w = 0.0473 \cdot c_w \cdot A \cdot v^2 \qquad (9)$$

pri čemu je usvojeno da je gustina vazduha ρ=1.225 kg/m^3, vlažnost vazduha w=60 %, i temperatura vazduha t=15^0 C. Ukoliko temperatura vazduha ili atmosferski pritisak odstupaju od uobičajenih vrednosti, gustina vazduha se može tačnije definisati putem:

$$\rho = 1.25 \cdot \frac{B}{1.015} \cdot \frac{293}{T} \qquad (10)$$

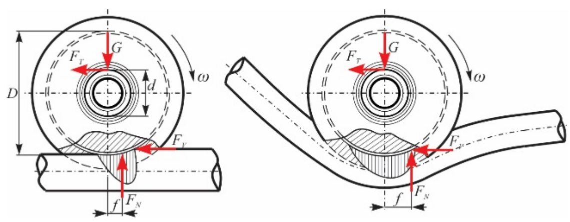
gde je pritisak (B) izražen u barima, a temperatura (T) u kelvinima.

Slika 16 prikazuje različite položaje spuštanja koji imaju uticaja na površinu izloženu dejstvu vazduha kao i na koeficijent opstrujavanja.



Slika 16: Različiti položaji spuštanja

Preporuke za određivanje koeficijenta opstrujavanju i površina izložene dejstvu vazduha za različite položaje tokom spuštanja su detaljnije objašnjene u [6], [10], [13] i [14].



Slika 17: Model točka zipline-a

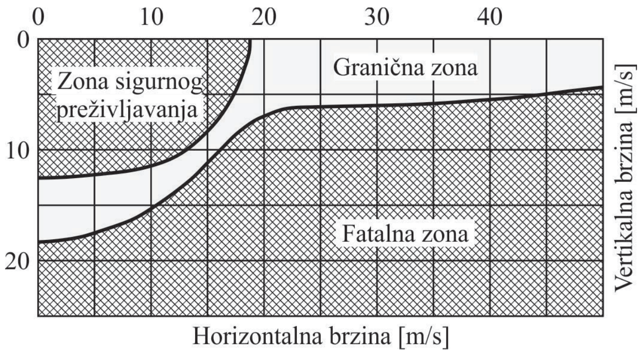
Za razliku od točkova koji se kotrljaju po deformabilnoj podlozi i koji imaju komponentu otpora usled trenja u ležaju i usled deformacije kontaktnih površina, točak koji se kreće po užetu ima i dodatni otpor koji se javlja kao posledica krutosti užeta. Za razliku od idealno savitljivog užeta, realno uže neće zauzeti položaje

tangenti ispred i iza točka što se može posmatrati kao nabiranje užeta ispred točka.

5. ODREĐIVANJE SILE PRI ZAUSTAVLJANJU

U studiji NASA-e pod nazivom *Human Tolerance to Impact Velocities* može se pronaći dijagram dat na slici 18 koji prikazuje mogućnost preživljavanja pri udaru o čvrstu prepreku pri kretanju određenom brzinom [1]. Na dijagramu se razlikuju tri zone:

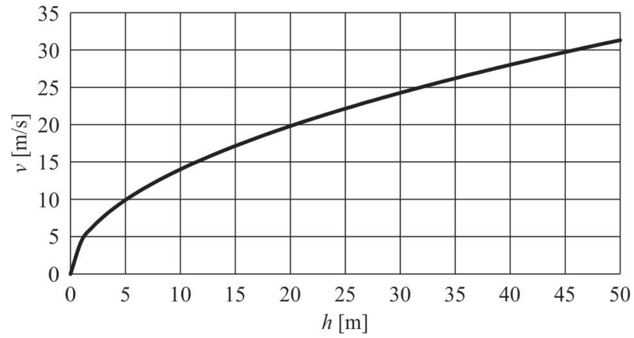
- zona sigurnog preživljavanja,
- granična zona, i
- fatalna zona.



Slika 18: Različite zone preživljavanja

Zona sigurnog preživljavanja se ne sme smatrati za prihvatljivu odnosno u potpunosti bezbednu. Ukoliko se kinematski parametri putnika nalaze u toj zoni, putnik će sigurno preživeti, no to ne znači da su ozbiljnije povrede nemoguće.

Kako bi se lakše shvatili uslovi o kojim brzina je reč kod zipline-ova, daje se dijagram prikazan na slici 19. Znajući da se krajnja brzina pri slobodnom padu sa određene visine izračunava kao $v = \sqrt{2 \cdot g \cdot h}$, na dijagramu je prikazana ekvivalentna visina sa koje bi telo pušteno da se kreće slobodnim padom udarilo o tlo određenom brzinom. Npr. osoba koja se kreće brzinom od 30 m/s zapravo ima brzinu kao osoba koja bi padala sa 45 metara visine.

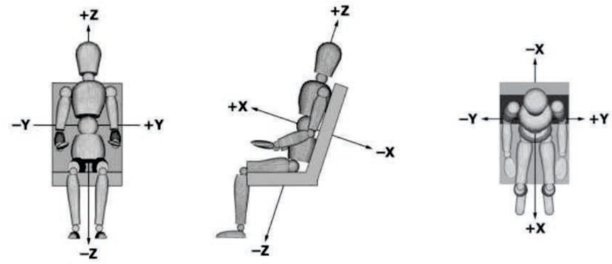


Slika 19: Zavisnost krajnje brzine od visine slobodnog pada

Dijagram prikazan na slici 18 daje podatak o mogućnosti preživljavanja pri momentalnom zaustavljanju tela koje se kretalo određenom brzinom. Međutim, kako kod regularne upotrebe zipline-a ne dolazi do momentalnog zaustavljanja, znatno je praktičnije posmatrati ubrzanje, odnosno usporenje putnika.

Samo ubrzanje ili usporenje se manifestuje opterećenjem na telo putnika, te se neće posmatrati vrednost ubrzanja, već sile koje je to ubrzanje, odnosno usporenje, izazvalo. Sila se najčešće ne izražava svojim intenzitetom već odnosom prema težini putnika, tzv. G-silom.

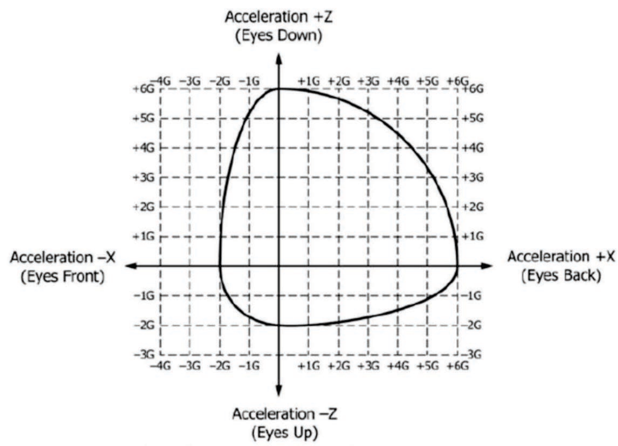
S obzirom da ljudski organizam ne prima određenu G-silu u svim pravcima podjednako [15], uveden je koordinatni sistem kao na slici 20.



Slika 20: Koordinatni sistem putnika

Prema standardu ASTM F2291, najveća vrednost G-sile se dopušta pri kočenju putnika u sedećem položaju (+X) i to sila intenziteta 6g.

Međutim, s obzirom da je putnik sa kolicima vezan pomoću pojaseva, tako da je omogućeno njihanje u pravcu kretanja, u najvećem broju slučajeva sila intenziteta 6g bi dovela do toga da putnik udari u uže. Empirijski je utvrđeno da sila pri kočenju ne bi trebalo da prelazi intenzitet od 2.5g.



Slika 21: Dozvoljene vrednosti ubrzanja u X i Z pravcu

Iz jednačine za rad sledi da sila u slučaju zaustavljanja tela koje se kretalo brzinom *v* na dužini *l* iznosi:

$$\frac{1}{2} \cdot m \cdot v^2 = F \cdot l \quad \Rightarrow \quad F = \frac{m \cdot v^2}{2 \cdot l} \tag{11}$$

Kao što je već rečeno, G-sila se može definisati kao odnos sile koja na to telo deluje i njegove sopstvene težine, te sledi:

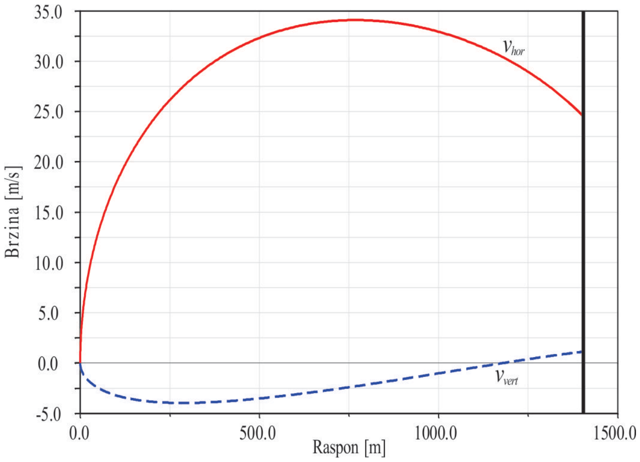
$$G = \frac{F}{m \cdot g} = \frac{\frac{m \cdot v^2}{2 \cdot l}}{m \cdot g} = \frac{v^2}{2 \cdot l \cdot g} \tag{12}$$

Iz jednačine 12 se može uočiti da se na intenzitet G-sile, za određenu početnu brzinu kočenja, može uticati putem, odnosno dužinom na kojoj će se usporavanje izvršiti.

6. RAČUNSKI PRIMER

Posmatrajući spuštanje kolica sa dva putnika u sedećem položaju (jedan iza drugog) na konkretnom zipline-u raspona 1404 metra koji je izgrađen na Fruškoj Gori, za slučaj kretanja sa minimalnim otporima vazduha i

kotrljanja (a samim tim i maksimalno postignutom brzinom), dobija se dijagrami promene horizontalne i vertikalne komponente brzine koji je prikazan na slici 22.



Slika 22: Horizontalna i vertikalna komponenta brzine

Sa dijagrama se može uočiti da brzina u horizontalnom pravcu na kraju trase ima vrednost od 24.6 m/s, a vertikalna od 0.5 m/s. Na osnovu pomenutog, ukoliko bi došlo do momentalnog zaustavljanja, zašlo bi se u graničnu zonu.

Na osnovu formule (12), ukoliko se želi zadržati u području do 6g, neophodan bi bio put kočenja od:

$$l = \frac{v^2}{2 \cdot G \cdot g} = \frac{24.6^2}{2 \cdot 6 \cdot 9.81} = 5.1 \text{ m}$$

Odnosno ukoliko se želi ostati u području do 2.5g zaustavni put bi trebalo da bude:

$$l = \frac{v^2}{2 \cdot G \cdot g} = \frac{24.6^2}{2 \cdot 2.5 \cdot 9.81} = 12.4 \text{ m}$$

7. ZAKLJUČAK

S obzirom da zipline predstavlja relativno nov sistem, koji je ekspanziju doživeo poslednjih dvadesetak godina, još uvek ne postoje odgovarajući domaći propisi za njihovu izgradnju i korišćenje.

Kod zipline-ova malih raspona koji se sreću na dečijim igralištima ili tzv. „s drveta na drvo“, na kojima se ne postižu velike brzine kretanja, a kakvi su uglavnom izrađivani do sada, nije postojala veća opasnost ozleđivanja putnika. Međutim, kako je u poslednje vreme izgrađen veći broj zipline-ova velikog raspona na kojima je moguće postići i velike brzine kretanja, tema kočenja postaje znatno interesantnija. U okviru ovog rada je ukazano na značaj adekvatnog izbora kočionih, odnosno zaustavnih uređaja.

Proizvođači zaustavnih uređaja daju preporuke za izbor i ugradnju odgovarajućeg sistema za kočenje, ali za određene ulazne podatke kao što je brzina kretanja pri početku kočenja koju projektant zipline-a mora prethodno da odredi. Isto tako, na projektantu je da definiše intenzitet kočenja, a jedna od vodilja mu mogu biti, za sada, propisi ACCT i ASTM koji su analizirani u radu.

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Condition Analysis and Basis for Selection of Zipline Arresting Devices

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This paper defines the basis for zipline arresting devices. Considering that there is currently no legal regulation in Serbia that defines devices for zipline braking and arresting, an excerpt from foreign standards are given in the first part of the paper. This is followed by an overview of existing solutions of arresting systems, as well as examples of patented solutions. As it is necessary to know the velocity of the passenger at the beginning of braking, the paper gives a basis for determining the kinematic parameters of the passenger. The analysis of kinematic parameters consists of two parts - the first one, which includes static analysis based on catenary theory, and the second, which takes into account inertial forces, movement resistance, air resistance, the position of a passenger during lowering, tightening force, etc. Finally, recommendations for the selection of zipline arresting system are given, as well as an example of concrete zipline which was built on Fruška Gora.

Keywords: Zipline, Braking, Velocity, Acceleration

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.

Figure 1: An example of zipline

Figure 2 shows a schematic representation of zipline with main notions.

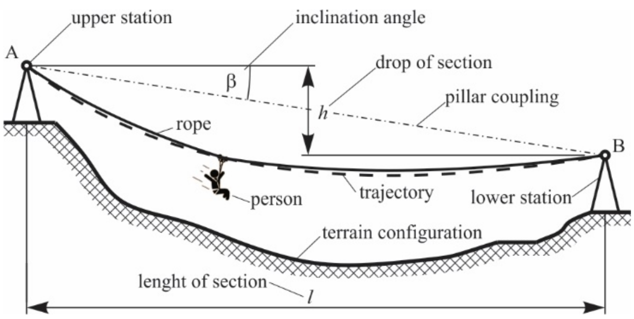

Figure 2: A schematic representation of zipline with main notions

2. REGULATIONS

Based on the ACCT (*Association for Challenge Course Technology*) and ASTM (*American Society for Testing and Materials*) standards, for ziplines at which velocities above 10 km/h are achieved, it is necessary to provide adequate systems for safe stopping [1].

The ACCT standard distinguishes:

- **Zip Line Brake System:** A system that controls and/or arrests the motion of a person along a zip line. Brake systems can be active or passive.
- **Brake System:** An arrangement of primary and emergency brakes that are designed to function together to arrest the motion of a person.
- **Primary Brake:** The principal brake in a zip line brake system, engaged during normal operation to arrest a user's motion. Primary brakes include both gravity-assisted brakes and other brake force-generating devices.
- **Emergency Brake:** A brake located on a zip line that engages without any participant input upon failure of the primary brake in order to prevent serious injury or death.

The above-mentioned standard provides that brake systems shall be designed by a qualified person. The design shall address the following:

- arrest as a critical function;
- static, dynamic, and impact loads in worst-case scenario;
- resistance to wear and fatigue with consideration given to the anticipated use;
- environmental factors such as extreme temperatures, wind, and weather conditions;
- the level of risk to the participant posed by the failure of the brake system or any of its components, including potential for pinching, binding, entanglement, etc

Additionally, the standard requires that a qualified person shall design the methods, oversee the performance,

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and assess the results of operational tests. All tests shall provide proof of the following:

- brake system operational characteristics at the extremes of the design continuum for participant weight and arrival speed;
- confirmation that the brake system performs reliably and as designed.

On the other hand, the ASTM standard differs:

- **Brake System:** As it applies to aerial adventure courses, examples of braking systems include, but are not limited to: longitudinal friction brakes, disc or drum brakes, motor end brakes, either onboard or off-board of the patron-carrying vehicle or device. If the failure of the braking system results in an unsafe condition, then the braking system shall be fail-safe.
- **Fail-Safe:** Characteristic of an aerial adventure course, or component thereof, that is designed such that the normal and expected failure mode results in a safe condition.

Based on the standard ASTM F2291 the designer/engineer shall perform and document a ride analysis that illustrates how hazards to persons have been managed. The documentation shall include but not be limited to the following:

- an identification of hazards that includes potential sources and consequences of harm;
- an identification of hazardous scenarios;
- an assessment of hazards that includes a description of how identified hazards are mitigated to an acceptable level. Hazards are mitigated by reducing the severity of the hazard, reducing the probability of occurrence of related hazardous scenarios, or both. Hazards may or may not require mitigation. The assessment of hazards shall consider hazards that are created or aggravated by the means of mitigation and the potential for failure of the means of mitigation. This assessment shall include but not be limited to the Failure Analysis. A failure analysis shall be performed on the safety related systems of the amusement ride or device. The failure analysis shall include either a Fault Tree Analysis, a Failure Mode or Effect Analysis (FMEA), or other accepted engineering practice.

Based on the standard ASTM F2959 the deceleration and arrest of patrons arriving at landing zones shall be performed in a controlled manner and environmental factors such as humidity, precipitation, temperature and the wind effects on patron velocity should be included.

3. EXAMPLES OF ZIPLINE ARRESTING SYSTEMS

The passenger is usually stopped at the end of the section by a bumper which is attached to the rope which is connected via an extension line with a certain braking device. The extension line can be connected directly to the arresting device, or a suitable mechanical advantage can be obtained by rewinding it, so a smaller device is needed.

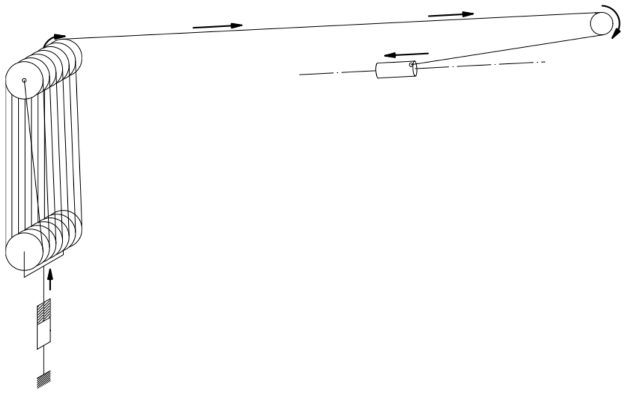

Figure 3: Arresting system with hydraulic brake

Figure 3 shows a schematic representation of arresting system where the braking is performed by a hydraulic cylinder, while Figure 4 shows a system where the deceleration of passenger is done by attaching a bumper to a chain.

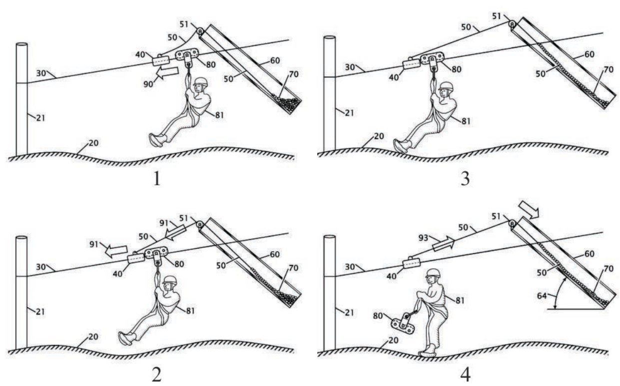

Figure 4: Arresting system with chain

However, the mentioned solution with a chain can be seen in certain patent applications [2], but as far as the authors know, not in practice. In practice, the most common solution is with springs as given in the example shown in Figure 5. In this solution, the deceleration is performed by helical spring where the extension line can be directly connected to the bumper or it can be rewinded [3].

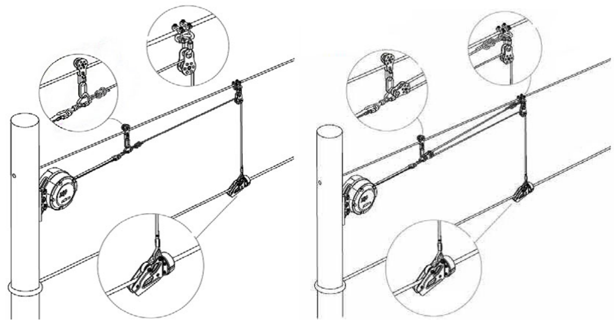

Figure 5: Arresting system with a spring

Since the extension line which connects the bumper with the brake can’t float in the air, an auxiliary rope must be provided. The extension line is at certain distances connected with auxiliary rope. Figure 6 (left) shows a solution with an auxiliary rope fastened to the pillar (so-called offset redirection), while Figure 6 (right) shows beam mounted pulley [3].

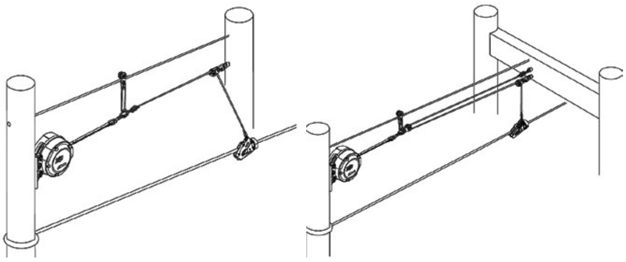

Figure 6: Offset Redirection Pulley and Beam Mounted Pulley

If the slope of the rope at the lower pillar is such that the freely released trolley tends to approach the lower pillar, it is a positive slope [3]. If the freely released trolley tends to move away from the pillar, it is a negative slope.

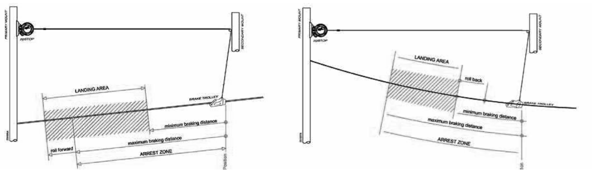

Figure 7: Positive and negative slope line

For a section with a negative slope, it must be prevented that the trolley with passenger moves backward. This is achieved by using a brake trolley with catch mechanism. The working principle of those mechanisms can be seen in Figure 8.

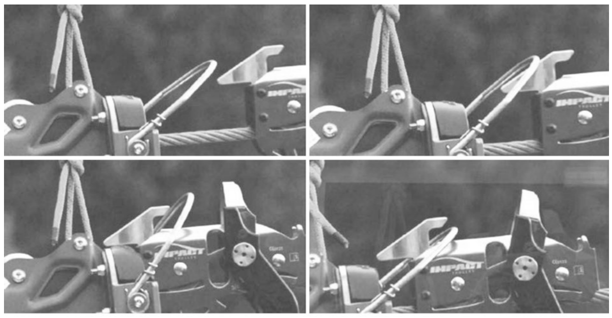

Figure 8: Brake trolley with catch mechanism

Springs as shown in Figure 9 are most often used as an emergency brake at the end of zipline section.

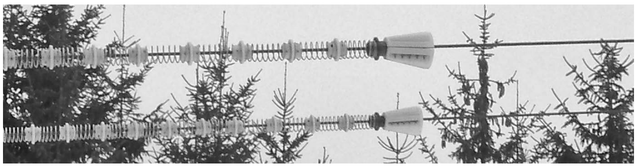

Figure 9: Springs as an emergency brake

Solution shown in Figure 10 has brake in the form of a turbine filled with viscous fluid, while solution shown in Figure 11 has a brake in the form of an electric motor.

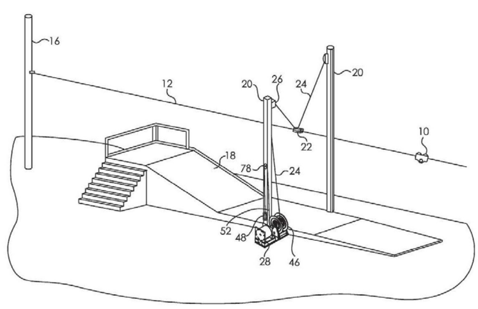

Figure 10: An example of a braking system [4]

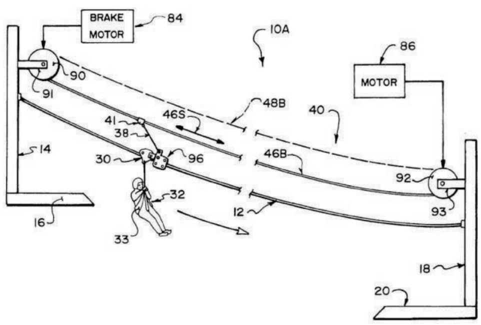

Figure 11: An example of a braking system with an electromotor [5]

4. FUNDAMENTALS FOR ANALYSIS

4.1. Trajectory defining

As the theoretical background is detailed described in previous papers such as [6]-[12], only a brief overview will be given here.

The line 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 (*q*) is called catenary.

Based on Figure 12 and after certain mathematical transformations, a catenary equation can be written as:

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

where the catenary parameter (*C*) is function of tension rope force (*H*) and the own weight of rope:

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

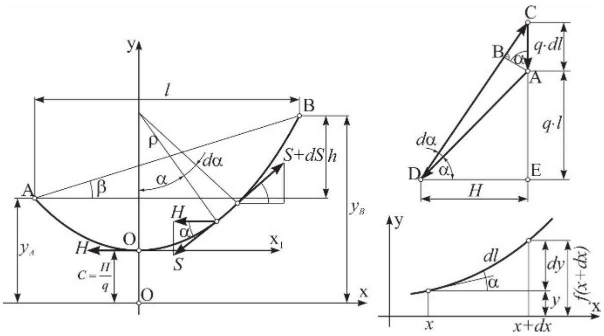

Figure 12: Parameters of catenary

The catenary theory provides accurate solutions, but the usage of hyperbolic functions is relatively complicated for engineering practice, so the catenary is replaced by the appropriate parabola. This approximation leads to errors in the size of the deflections which amounts 2 ÷ 3%. Accuracy can be increased by introducing a correction coefficient (*k*). Figure 13 shows some possibilities for replacing the catenary with a parabola.

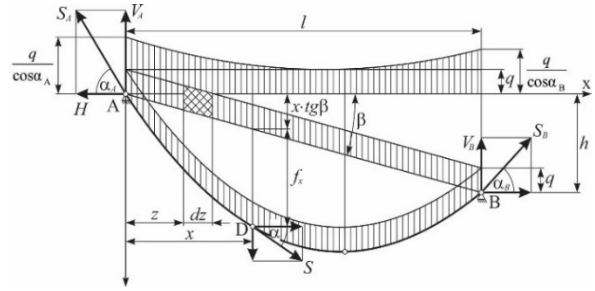

Figure 13: Parameters of the parabola

Equation of parabola can be written as:

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

where the correction coefficient is calculated as:

$$k = 1 + \frac{\cos^2\beta}{p} \cdot \left[\frac{1}{p} \cdot \left(x^2 - l \cdot x + \frac{l^2}{2} \right) - 2 \cdot (l - 2x) \cdot tg\beta \right] \quad (4)$$

and the parameter of the parabola (p) as:

$$p = \frac{H}{q} \cdot \cos\beta \quad (5)$$

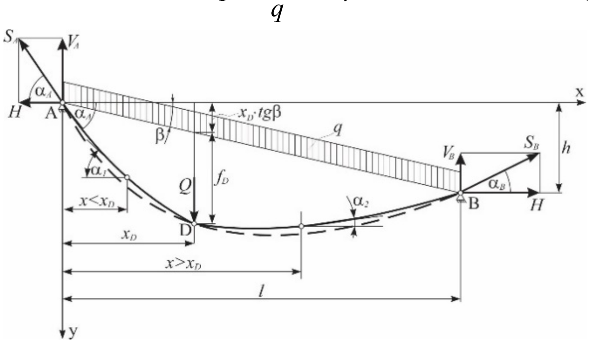

Figure 14: Model of rope loaded with own weight and concentrated load

Figure 14 shows a case of a rope, whose supports are at different heights, and which is loaded not only with its own weight but with a concentrated load too. The equation of the trajectory of a person which is lowering can then be represented as:

$$y = x \cdot \text{tg}\beta + f_x \quad (6)$$

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

$$f_D = \frac{x_D}{l \cdot H} \cdot \left[Q \cdot (l - x_D) + \frac{q \cdot (l - x_D)}{\cos\beta} \cdot \frac{l}{2} \right] \quad (7)$$

4.2. Computational model

The relevant computational model will be formed by neglecting small quantities of a high order. The so-called static trajectory of movement is determined by expressions (6) and (7). A person connected with trolley forms a mathematical pendulum, but if the length of the connecting belts is small, the effect of the swing can be neglected as well as the influence of the centrifugal force due to the large radius of the trajectory curvature.

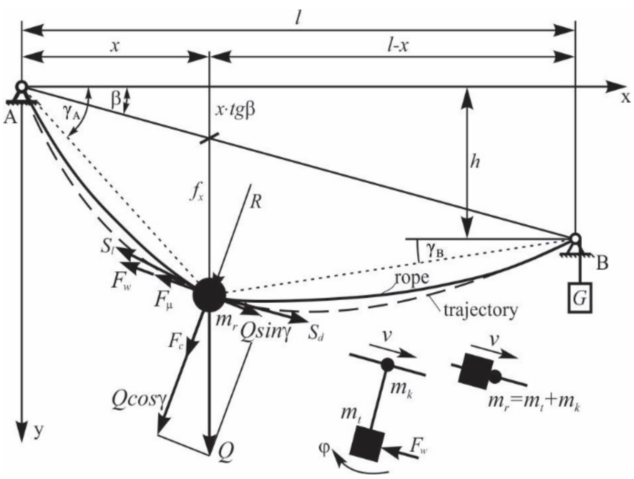

Figure 15: Computational model of zipline

According to that, the computational model of the zipline, which is shown in Figure 15, can be represented as the movement of a concentrated mass along the trajectory determined for static conditions.

The air resistance and rolling resistance are acting on the concentrated mass while moving in the direction which is always opposite to the direction of movement.

$$F_w = c_w \cdot A \cdot \frac{\rho \cdot (v \pm v_v)^n}{2} \quad (8)$$

According to equation (8), the value of air resistance depends on:

- drag coefficient (c_w),
- area exposed to the air-flow (A),
- air density (ρ),
- relative velocity between the object and airflow (wind), and
- dimensionless coefficient (n), which has value of 2 for velocities between 1 m/s and 300 m/s

As the air density changes relatively little for some standard conditions, and the velocity is more often expressed in km/h than in m/s, the equation (8) can be written in the form:

$$F_w = 0.0473 \cdot c_w \cdot A \cdot v^2 \quad (9)$$

whereby the specific air density is taken as ρ=1.225 kg/m^3, medium air humidity as w=60 %, and medium air temperature as t=15^0 C. If the temperature or atmospheric pressure vary from ordinary, air density can be calculated as:

$$\rho = 1.25 \cdot \frac{B}{1.015} \cdot \frac{293}{T} \quad (10)$$

where the pressure (B) is expressed in bar, and the temperature (T) in kelvin.

Figure 16 shows various lowering positions which have an impact on the area exposed to air and drag coefficient.

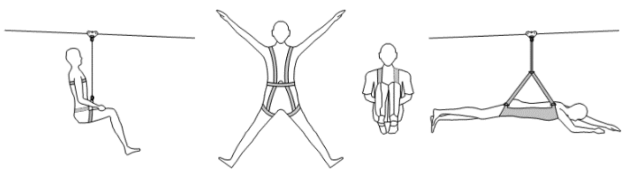

Figure 16: Various lowering positions

Recommendations for the determination of drag coefficient and areas exposed to airflow for various lowering positions are detailed explained in [6], [10], [13] and [14].

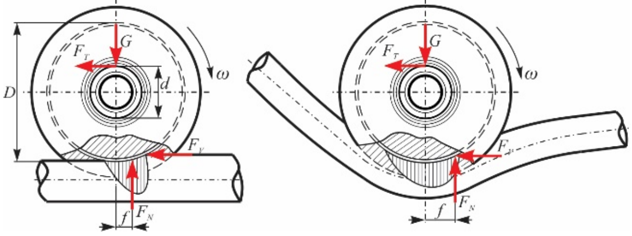

Figure 17: Zipline wheel model

Unlike every other wheel that is rolling along a deformable surface which has a resistance component due to the friction in wheel bearings and due to deformation of contact surfaces, the wheel that is rolling along the rope has an additional resistance component due to rope

stiffness. Unlike a 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.

5. BRAKING FORCES DETERMINATION

In the NASA study titled *Human Tolerance to Impact Velocities*, can be found a diagram shown in Figure 18 that shows the chances of survival when hitting a hard flat surface at different velocities [1]. There are three zones on the diagram:

- zone of certain survival,
- zone of marginal survival, and
- fatal zone.

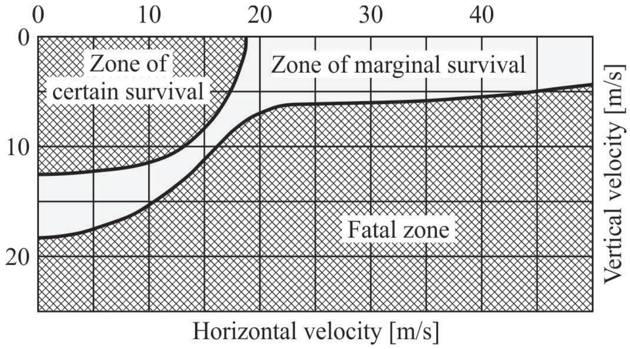

Figure 18: Different survival zones

The "zone of certain survival" still carries significant potential for serious injury, so do not mistake that zone as an acceptable, safe, or desirable outcome.

Knowing that the final speed of the free fall from a certain height is calculated as $v = \sqrt{2 \cdot g \cdot h}$, the diagram given in Figure 19 shows a comparison of arrival velocities to their equivalent free fall distances. These values can be used to assess ziplines arrival speeds and to get an understanding of how far a patron is "falling" when they arrive at a terminal platform. For example, rider traveling at 30 m/s has the same velocity as someone falling from 45 meter.

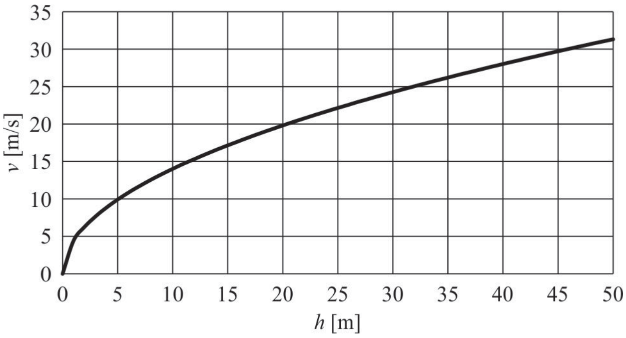

Figure 19: Comparison of arrival velocities to their equivalent free-fall distances

The diagram shown in Figure 18 gives information about the possibility of survival when the body moving at a certain speed stops instantly. However, since there is no instantaneous stop at regular usage of zipline, it is much more practical to observe the acceleration or deceleration of passenger.

The acceleration or deceleration is manifested by the load on the passenger's body, so the value of the acceleration will not be observed, but the force that the acceleration, ie deceleration, caused. The force is usually not expressed by its intensity but by the relationship to the weight of the passengers, the so-called G-force.

Since the human body does not receive a certain G-force in all directions equally [15], a coordinate system has been introduced as in Figure 20.

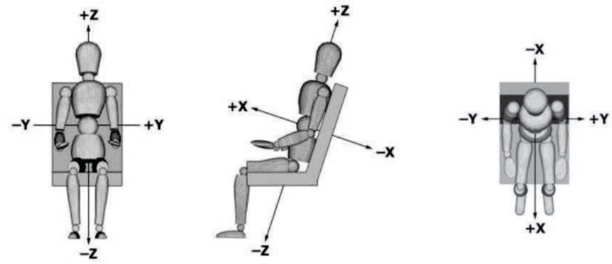

Figure 20: Passenger coordinate system

According to the ASTM F2291 standard, the maximum value of G-force during braking for sitting position is allowed in + X direction and has intensity of 6g.

However, since the passenger is connected to the trolley by belts which allow swinging in the direction of movement, a braking force of 6g will cause an upward swing and the passenger may hit the zipline cable. It has been empirically determined that the braking force should not exceed the intensity of 2.5g.

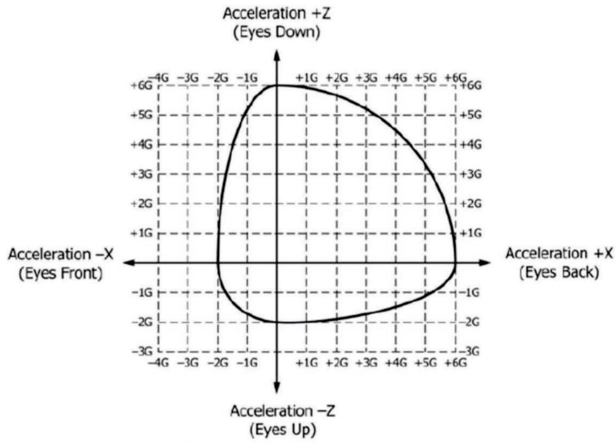

Figure 21: Allowable combined magnitude of X and Z accelerations

From the equation of work it follows that the force in the case of stopping a body which was moving at a velocity v on the length l is:

$$\frac{1}{2} \cdot m \cdot v^2 = F \cdot l \quad \Rightarrow \quad F = \frac{m \cdot v^2}{2 \cdot l} \tag{11}$$

As already mentioned, the G-force can be defined as the ratio of the force acting on that body and its own weight, so it follows:

$$G = \frac{F}{m \cdot g} = \frac{\frac{m \cdot v^2}{2 \cdot l}}{m \cdot g} = \frac{v^2}{2 \cdot l \cdot g} \tag{12}$$

It can be noticed from (12) that the intensity of the G-force, for a certain initial braking velocity, can be influenced by the path, ie the length at which the deceleration will take place.

6. AN EXAMPLE

Observing the lowering of a trolley with two passengers in a sitting position (one behind the other) on a concrete zipline which is built on Fruška Gora, which has a range of 1404 meters, for a case with minimal air and rolling resistances (and thus with maximal velocity), following diagrams of changes in horizontal and vertical velocity components are obtained.

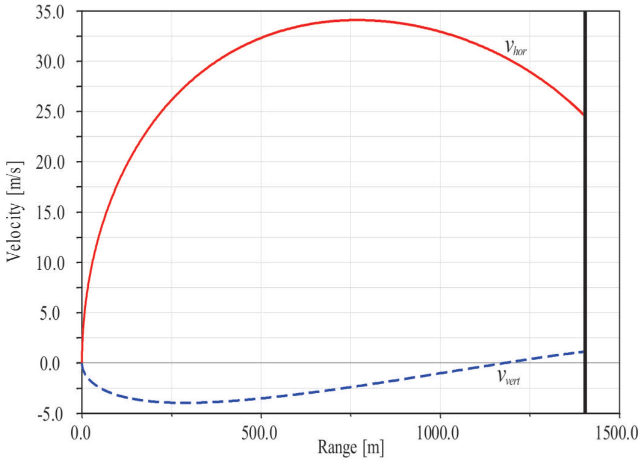

Figure 22: Horizontal and vertical velocity components

According to the diagram shown in Figure 22, it can be noticed that the horizontal component of velocity at the end of a section has a value of 24.6 m/s and a vertical of 0.5 m/s. Based on that, if there would be an immediate stop, it would be in the zone of marginal survival.

Based on (12), if we want to stay in the range up to 6g, a braking distance of:

$$l = \frac{v^2}{2 \cdot G \cdot g} = \frac{24.6^2}{2 \cdot 6 \cdot 9.81} = 5.1 \text{ m}$$

is needed, and if we want to stay in the range up to 2.5g, the braking distance should be:

$$l = \frac{v^2}{2 \cdot G \cdot g} = \frac{24.6^2}{2 \cdot 2.5 \cdot 9.81} = 12.4 \text{ m}$$

7. CONCLUSION

Considering that ziplines are a relatively new system, which has expanded in the last twenty years, there are still no appropriate regulations for their construction and usage.

For small range ziplines which can be seen on children's playgrounds or so-called “from three to three” ziplines, on which high velocities cannot be achieved, there was no greater danger of injuring. However, as a large number of high-range ziplines have recently been built on which it is possible to achieve high velocity, the topic of braking has become much more interesting. Within this paper, the importance of the adequate selection of braking or arresting devices is pointed out.

Recommendations for the selection and installation of an appropriate braking system are given by manufacturers of arresting devices, but for certain input data such as the velocity at the beginning of braking which must be determined by zipline designer. The designer must also define the braking intensity, and one of his guidelines may be, for now, the ACCT and ASTM regulations which have been analysed in this paper.

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