2. Literature Survey

2.1 Human deceleration specification literature survey

2.1.1 Introduction

Man, as a mechanical system, is extremely complex and his mechanical properties readily undergo changes under dynamic conditions. Information quantifying the magnitude of forces which produce physical and psychological damage to the human body, is scarce [9]. The study of positive longitudinal short duration acceleration is closely linked to the development of upward ejection seats used for escape from aircraft.

The term impact describes the force applied to a body coming into sudden contact with a second body where momentum transfer then takes place. Impact forces by nature are of considerable magnitude, with no exception during the scenario where a human body decelerates independently from a rapidly decelerating cage.

In the literature survey conducted, it has been noted that the duration of the impact, combined with its magnitude, form the crux in defining the degree to which human injury would occur. The magnitude of the acceleration alone without the time duration of the force exposure is not enough information to draw any conclusion [9], [10]. Another defining characteristic is the level to which the human body is supported while being subjected to the deceleration. A person who is seated and strapped down can withstand greater vertical accelerations than a person who is free-standing, such as someone standing in an elevator or a mine cage [9], [10]. A wide range of literature concerning automobile as well as aircraft crashes, has also been perused. Experiments with dummies or manikins, and live subjects reveal that complete body support and restraint of the induced motion extremities, provides maximum protection against acceleration induced, impact forces and offers the subject the greatest chance of survival [11].

In summary, specifically concerning freestanding vertically ascending acceleration, the human body can survive large decelerations for short durations (roughly 200Gs for 2Msec). Based upon the minimal research undertaken for longer duration exposure, the survivable limit is estimated to be in the region of 20Gs for 200Msec [10]. The G-loading decreases as the time exposure increases further from the estimated values above (refer: Table 1). Control or prevention of injury is critically dependant on body positioning and restraint to minimise unwanted, forceful flexion of the spinal column. The fracture tolerance limit is influenced by age, physical condition, clothing, bodyweight and many other factors. All can greatly alter the stress that the subject can or cannot survive. When limits are exceeded, fractures of the lumbar and thoracic vertebrae occur first (injuries of the lower back and back). While in itself this injury is not classified as severe, small changes in orientation are enough to involve the spinal cord, which is extremely sensitive and susceptible to problems with forced posture disturbance. Neck injuries occur at considerably higher levels of vertical accelerations than back injuries [10].

2.1.2 Human deceleration specifications

Deceleration specifications are scarce and usually incomplete, with certain degrees of uncertainty involved with the application thereof. This study highlights four applicable criteria found in literature, which serve as comparisons for the two mining specifications, to validate and compare their order of magnitude.

2.1.2.1 Deceleration criteria 1 [10]

The envelopes of deceleration listed in Table 1 below have been set up from extensive experiments conducted in the field under operational conditions. The limits which indicate possible death, have been based on the post crash analysis of experts estimating the conditions of exposure experienced by the occupants, or victims.

Type of operation.	Acceleration, G's	Duration, sec
Man:		
Parachute opening, 40 000ft (vertical)	33	0.2 to 0.5
6 000ft (vertical)	8.5	0.5
Parachute landing (vertical)	3 to 4	
Fall onto firemans net (vertical)	20	0.1
Approx limit of survival with well distributed forces (fall into deep snow bank)	200	0.015 to 0.03
Aircraft: (Horizontal)		
Ordinary take-off	0.5	>10
Catapult take-off	2.5 to 6	1.5
Crash landing (survivable)	20 to 100	<0.1
Seat ejection (vertical)	10 to 15	0.25
Automobiles: (Horizontal)		
Comfortable stop	0.25	5 to 8
Very undesirable	0.45	3 to 5
Maximum obtainable	0.7	3
Crash (survivable)	20 to 100	<0.1
Public transport: (Horizontal)		
Normal acceleration and deceleration	0.1 to 0.2	5
Emergency stop from 70 mph	0.4	2.5
Elevators: (vertical)		
Average (fast service)	0.1 to 0.2	1 to 5
Comfort limit	0.3	
Emergency deceleration	2.5	

Table 1 Approximate Duration and Magnitude of Some Short-Interval Acceleration Loads [10].

2.1.2.2 Deceleration criteria 2 [9]

Arthur E. Hirsch considered all the available data published by a variety of experts in the field and combined it into a single figure with three defining axes (refer: Figure 7). The three defining axes are firstly, the exposed Gs rating, secondly the time of exposure and lastly the condition or injury that is likely to be encountered at that stage (refer: Figure 7). This information is currently extensively used in industry as a guideline for acceptable human deceleration limits.

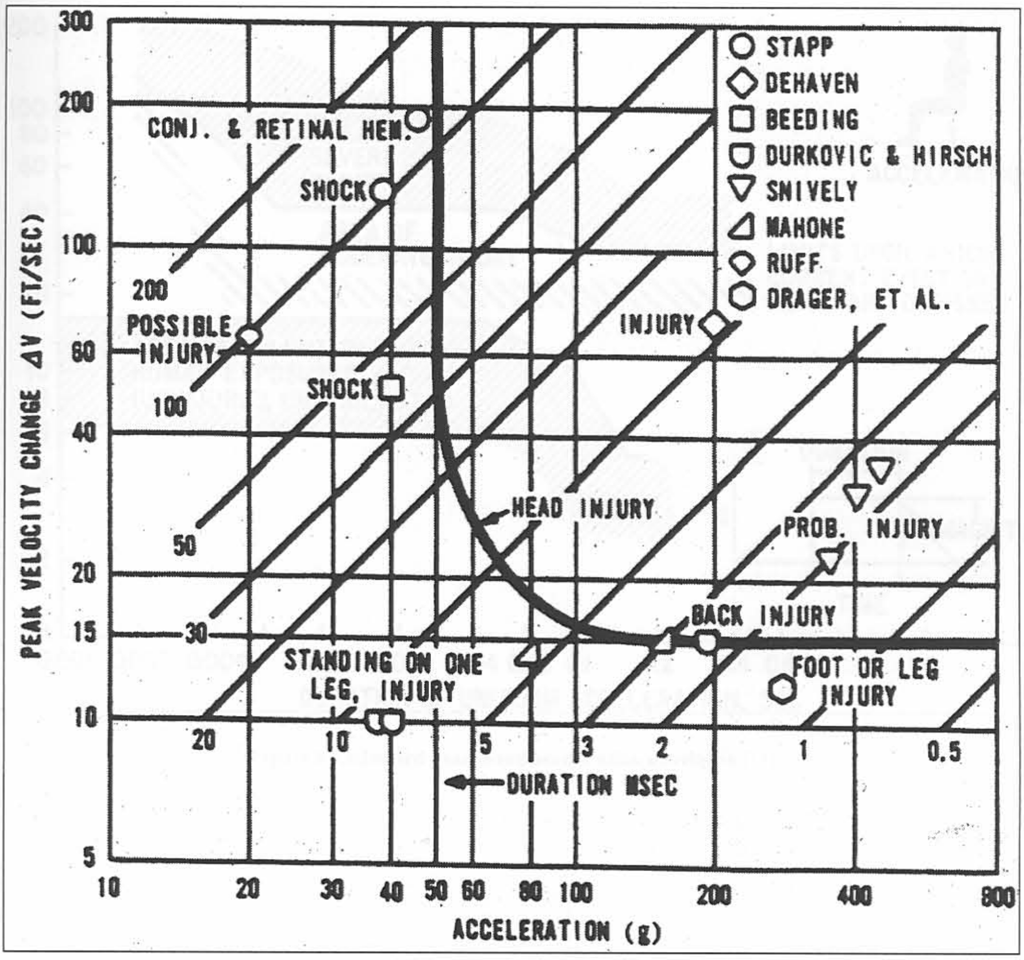

Figure 7 Acceleration tolerance limits [9].

2.1.2.3 Deceleration criteria 3 [11]

The human tolerance for vertically seated ascending acceleration for various exposure intervals was investigated by Arthur Eiband. The research was performed for the National Aeronautics and Space Administration (NASA). His findings are summarised in a figure depicting various limits of comfort (refer: Figure 8).

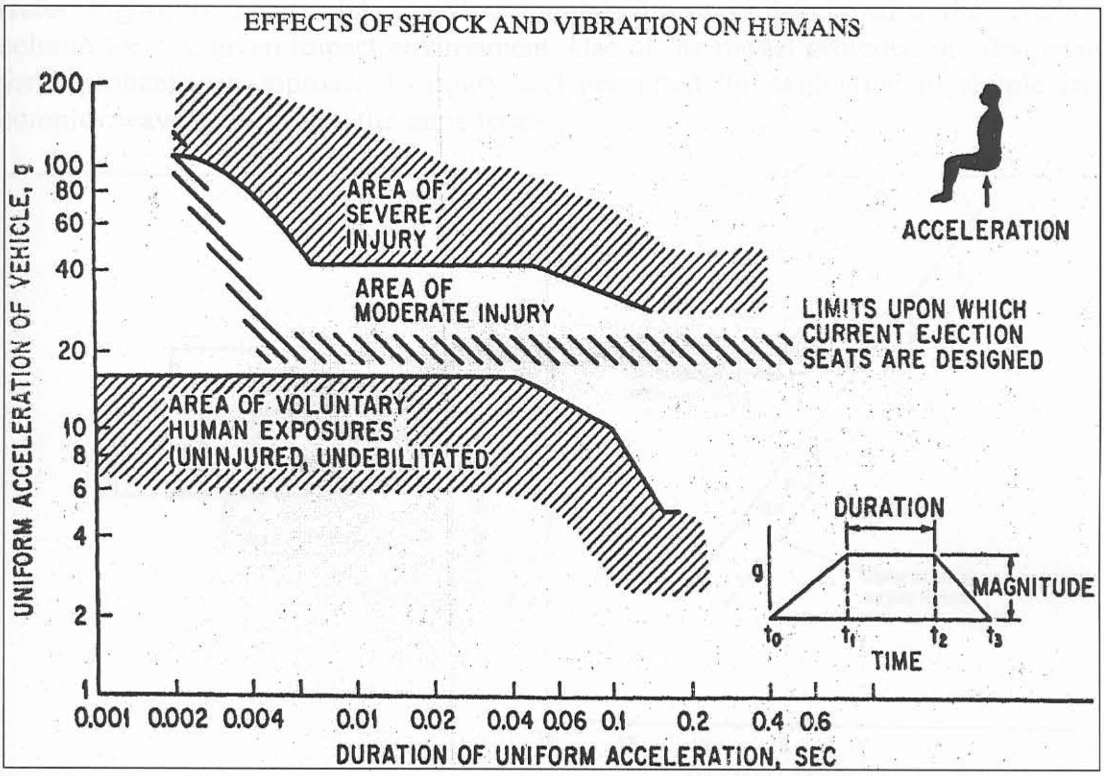

Figure 8 Estimated head ward acceleration envelopes [11].

2.1.2.4 Deceleration criteria 4 [13]

Investigations indicate that the human body's ballistic response can be predicted by means of analogue computations by making use of the frequency response characteristic of the body. The simplest analogue model used for the study of positive vertical accelerations, is the single degree of freedom mechanical resonator composed of the lumped parameter with elements comprising of a mass, spring and damper (refer: Figure 9). The model is used to simulate the stress developed in the vertebral column for any given impact environment. Use of the model provided the first basis for a probabilistic approach to injury and permitted the evaluation of simple and complex waveforms within the same terms.

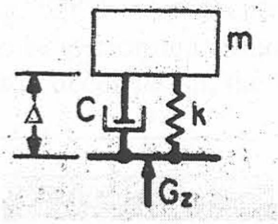

Figure 9 Ballistic model of human body.

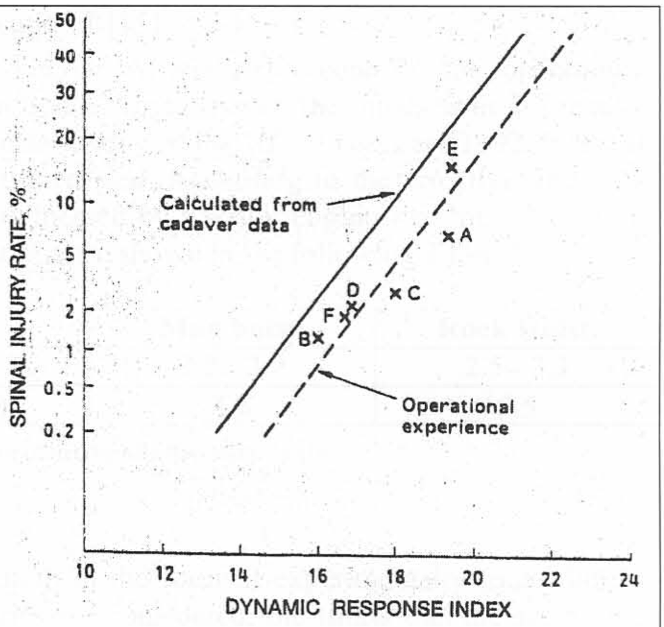

Figure 10 Spine injury probability % vs. DRI.

The maximum dynamic deflection of the spring, Δ_{max}, may be calculated for a given input acceleration-time history to the model. The potential for spinal injury was then estimated by forming the *dynamic response index* (DRI),

which is defined as $DRI = \dfrac{\omega^2{}_n \Delta_{\max}}{g}$,

where the natural frequency of the model is $\omega_n = \sqrt{\dfrac{k}{m}}$,

and the damping ratio $\dfrac{c}{2}\sqrt{km} = 0.224$.

Experience with 361 non-fatal ejections from military aircraft, shown by the crosses and dashed line in Figure 10, suggests a 5% probability of spinal injury from exposure to a dynamic response index of 18. An estimate of the rate of spinal injury from cadavers is shown in the same figure as the solid line. The success of the model has led to its adoption for the specification of ejection seat performance, as well as the measure of ride comfort for exposure to repeated impact in some land and water vehicles [10].

2.1.2.5 Mining Deceleration Specification 1 [14]

The Ministry of Mines for British Columbia set up specifications that cannot be exceeded while bringing mine man conveyances to an emergency halt. These limits are described as follows.

- While the conveyance is travelling upward the deceleration should be no more than 9.8m/s^2 (1Gs).
- While travelling downward the maximum deceleration limit is 24.5m/s^2 (2.5Gs).

These retarding limits are specified to be applied by means of; “a safety device in any shape or form”.

2.1.2.6 Mining Deceleration Specification 2 [15]

The Department of Mineral and Energy Affairs, who controls the operational regulations for all licensed mines in South Africa, issued the mines with a directive for the dynamic testing of winding installations on the 10th of February 1992. It is still binding, but the act is currently being revised. According to the directive, the tests have to be performed annually and witnessed by a senior engineer of the mine. With respect to deceleration, the specifications are shown in the following Table 2.

	Man hoist.	**Rock Hoist.**
Average brake deceleration. (m/s^2)	2.2 - 2.7	2.5 - 3.3
Maximum brake deceleration. (m/s^2)	4.8	5.5

Table 2 South African Deceleration Specifications [14].

2.1.2.7 Summary

When the above sources of information in the form of experimentally found limits, prediction models and data summaries are considered, the limits that are set by the mines are based on a sound safety foundation. They also have a sufficient buffer zone to allow for human survival under slightly larger retardation rates if and when the moment called upon it. Further confirmation of these limits can also be seen with reference to Macaulay [17].

2.2 Shaft protection requirements

2.2.1 Functional analysis of under wind system

The investigation undertaken for SIMRAC, project GAP638 [1], focussed on the safe control of mine cages. From this investigation the following functional requirements were developed.

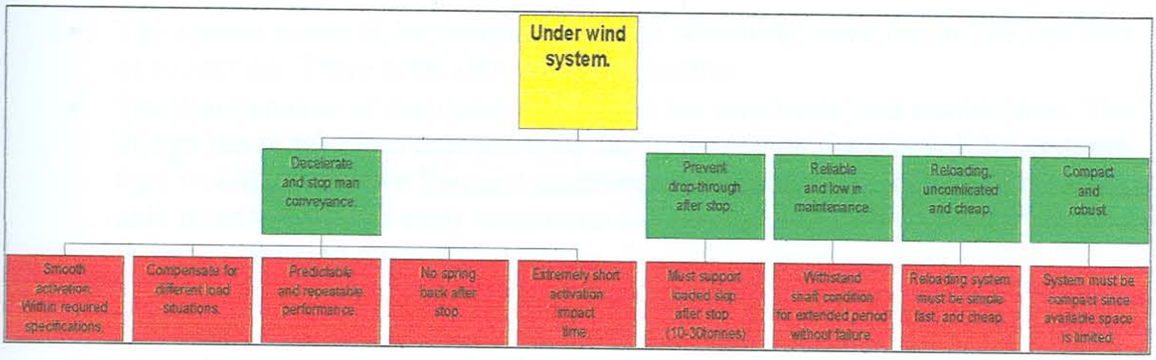

Figure 11 System functional requirement.

2.2.1.1 Decelerating conveyance

- A smooth activation of the decelerating force would be required. This is the primary function of the taper section, introduced to the front of the parallel strip (refer: Figure 2). The retardation force has to be within the specified 2.5Gs average limit, even under dynamic circumstances.
- Compensation has to be made for both a fully and partially loaded. The deceleration force needs to be varied for the change in mass to accommodate the specification of the maximum deceleration limit as explained in chapter 3.
- The performance of the chosen deceleration system needs to be predicted accurately for any given probable situation. The dynamic aspect needs to be accounted for, given the application of the systems. This is discussed in great detail in chapter 4 of this study.
- The ability of the system to absorb the kinetic energy of the moving conveyance without spring back once the cage was brought to rest, is important. A bungee effect would need to be avoided in the shaft as this could then cause secondary rebound damage, which would be unnecessary.
- In the event of two mass systems colliding, as is the case of the conveyance connecting with the deceleration system, forces are introduced upon each other to satisfy the law of conservation of energy. The system has to be developed to maintain this impulse force introduced into the conveyance by the decelerating systems to an acceptable minimum time, to ensure the safety of the occupants (refer: Figure 7).

2.2.1.2 Prevent drop through

- When an emergency deceleration has taken place, the design of the systems has to be of such a nature as to ensure that the conveyance would not fall through the braking zone under static conditions. Thus the system has to be able to support the full static mass of the conveyance.

2.2.1.3 Reliability and Maintenance

- The system needs to be designed for high reliability since this is the last area of protection. There is no allowance for misfires.
- The maintenance of the systems needs to be very basic and trouble free. The design has to take into account that, due to the remote location of the systems, they would not receive frequent maintenance attention. The systems have to be able to withstand the shaft conditions for extended periods of time whilst not failing to function when called upon.

2.2.1.4 Reloading

- The reloading process of the deceleration system needs to be uncomplicated and easy. Intricate settings and adjustments needed to allow the system to operate, as well as extremely expensive disposable sections, are out of the question. In an industry where standing time causes great financial losses economic time consumption is of the essence.

2.2.1.5 Compact System

- The absence of space in the shaft for the building of elaborate deceleration systems is also a considerable problem. The system needs to be compact enough to be retrofitted in confined spaces, yet still have the ability to fulfil all the other requirements.

2.3 Existing and probable solutions

2.3.1 Introduction

The technique of absorbing and converting a large quantity of kinetic energy to another form of energy is subject to many conditions. The amount of energy to be absorbed by the device is equal to the integral of the force over the stroke length. The required performance of the device is defined by the maximum deceleration that can be applied to the moving mass and the space available to arrest it.

When the mass under deceleration contains human beings, which are susceptible to injury or death in the event of rapid deceleration, the rate of energy dissipation is of great importance. There are thus some limits, which regardless of what means are used to decelerate a human cargo, would remain unchanged for all cases. These conditions are nonnegotiable if the survival of the occupants are of importance.

- The first condition is the deceleration rate, which cannot be exceeded (refer: Table 2). The state of the bodily restraint of the person under deceleration plays a major role in the survival limit [11].
- The second fixed condition is the distance that would be required to decelerate the mass, given a velocity at which it would be moving when striking the emergency decelerating system. Certain environments have limitations and cannot accommodate this.
- The third important requirement of all possible deceleration systems is the minimal size of the initial contact force to be transferred, thus the inertial effects of the system.

All three factors require careful consideration before a deceleration system can be successfully implemented.

2.3.2 Existing protection

The existing protection against the under wind accidents is limited to the control of the cable drum, which comprises of a trigger which activates the emergency brakes to retard the conveyance. As a result there are thus no specific protection devices in the shaft itself, at the point of impact, in the current systems.

The statement in the Mining Act, under which the mines in South Africa fall in terms of shaft operational law, states the following:

> "Chapter 16, Winding:
>
> > Retarding device: 16.59 For a winding system in a vertical shaft or winze where the winding rope is not fastened to the drum or sheave of the winding engine –
> >
> > 16.59.2 the over-run space at the bottom of the shaft below the lowest established stopping place shall be provided with rigid guides or *other appliances* arranged so that an under wind conveyance is retarded and arrested before it can come into contact with any fixed obstacle.
> >
> > 16.61 The shaft or winze shall be carried sufficiently deep to allow an overrun space of *at least 7.5m* in which the conveyance can travel below or beyond the lowest landing place for persons before it comes into contact with any fixed obstacle *excluding any retarding appliance provided in terms of regulation 16.59"* [16].

2.3 Possible solutions

For information purposes, some possible concepts that would enable the safe deceleration of the mine cages in the event of an under wind, are discussed. There are, however some operating conditions that make the systems non-viable. A deceleration system developed to comply with all the requirements does not have to be restricted to the mining industry. Various industrial applications would benefit from a system capable of performing a large mass deceleration function.

Under mining conditions, an application problem is the shaft bottom, usually being the deepest part of the mine and thus attracting all free water, flooding the bottom of the shaft. Another important problem to be considered is the dropping of debris down the shaft, especially in the form of conveyed rock spillage. In a report from Vaal Reef, it was stated that 180 metric tonnes of rock was removed from the shaft bottom [1]. The time period over which spillage accumulated is not known.

The following concepts are some of the mechanisms, which were considered as candidates to solve the problem at hand [1].

2.3.1 Concept 1

A concept under evaluation, which has recently made great progress, is the use of aluminium honeycombs as energy absorbing structures [18]. These systems are used as bases to alleviate the impact during landing of air dropped cargo. During trial experiments, crushing of the honeycomb platforms were done up to velocities of 300m/s. The dynamic versus the quasi-static performance of the honeycomb deceleration force significantly increased by 74% under dynamic conditions. This is due to the strain rate influence as well as the inertia of the structure itself. This is an effective method of energy absorption with a low probability of misfire. Problems would however arise with the specific application, when these platforms are stacked in layers at the bottom of the shaft. In the case of the flooding, the system's performance would be greatly affected, due to the incompressibility of water. The energy absorption should occur with the crushing of hollow compartments in the honeycomb. If the bottom of the structure were submerged, the cavities would be filled and be rendered solid, with no energy absorbing capabilities. This would have severe implications upon the energy absorbing capacity of the structure. With respect to the rock spillage, the platforms would be covered and crushed, and again be rendered useless.

2.3.2 Concept 2

Tube inversion is also a very effective energy absorbing method. The dynamic properties are good and the reliability is impeccable due to the simplistic method of execution [18]. This method of energy absorption is used in submarines to isolate the nuclear reactors from the ships hull in the event of a shock wave during depth charge demolition detonations. For the application of under wind protection, the length of stroke required, would place the tube length in an Euler buckling situation. This type of retardation method would be used for considerably higher acceleration applications with shorter travel distances. Pipes or shells can be used in various other configurations as well. Tube flattening or lateral compression, is a good absorber but has a low stroke length. Local or transverse collapse, for instance the bumper of a car, also has good energy absorbing characteristics. Useable stroke length remains an application problem. Axial or concertina buckling in a bellows fashion has proved a popular energy absorber and also delivers a constant retarding force profile. The load however, must be applied exactly axially to these devices, to prevent Euler collapse. The length of the pipes must also be restricted to eliminate Euler buckling [20].

2.3.3 Concept 3

Bellamble Mining proposed the use of visco-elastic shock absorbers in the event of an accidental under wind [5]. The energy of the moving cage would be absorbed by the visco-elastic properties of the fluid in the device. The viscosity (10-20m^2/s) and the compressibility (15% at 400 MPa) of the fluid would allow the single device to function as both a shock absorber and a spring to retard the moving mass. The problem with this application would again be the flooding of the shaft, as well as the spilling of conveyed rock. These viscous devices are cumbersome and heavy, do not provide very long stroke lengths and are expensive. They also have an inherent sealing problem when exposed to high velocity rates.

2.3.4 Concept 4

Coulomb damping was also considered as an for the energy dissipation application. Coulomb friction force is generally accepted to adhere the following characteristics.

- It is dependant on the materials in contact and their surface preparation.
- The magnitude of the force is also proportional to the normal force across the interface.
- It is also independent of the sliding speed and apparent area of contact.
- Static friction force is larger than that of kinetic friction force.

The magnitude of the force resisting relative motion between the surfaces in contact is greatly dependant on the coefficient of friction of the surfaces. This, in turn, is dependant on the condition and temperature of the surfaces. Devices of this nature also tend to have low specific energy absorbing capacity per unit mass, and are thus typically applied in rotational applications [20], as is the case with the winder drums.

2.3.5 Concept 5

The concept of energy dissipation by means of converting kinetic energy to strain energy when repeatedly deforming a steel element by dragging it through a set of inline rollers is not new technology [refer: section 1.2]. The principle was introduced and developed by Seltrust Engineering, as the Strain Energy Linear Ductile Arrestor or the so-called SEDA system. This principle was applied in the SIMRAC project GAP638 investigating arrestors for cage under-wind conditions [1].

This concept holds great promise since it is mechanical and, therefore, perfectly reliable. The system is mounted against the walls of the shaft, keeping it from shaft bottom and therefore has no problem with water, until the shaft fills to within the intended path of travel of the conveyance. It also makes use of cables strung across the shaft opening and not platforms, thus the spilled rocks would not impede its function as long as a full distance of travel is allowed for (refer: Figure 3). The problem is the various conditions in terms of speed and mass to be retarded, and the determination of exactly what configuration would be ample to fulfil the deceleration requirements.

The task of defining the specifications and performance of such as system for operational conditions is the focus of this dissertation.

2.4 Conclusion

The deceleration of the cage is possible by means of concept 5, applying the kinetic to strain energy conversion technique. The hindrance involving shaft flooding and rock spillage would still have to be monitored, but would be less prominent than with the other systems. The specification of the required geometry of the system to perform the deceleration within the prescribed limits would be described by means of a design prediction program, as discussed in chapter 5, thus making it the most attractive option. For these reasons concept 5 has been chosen for further development (refer: section 1.2).