WHY BOUNCE IS BAD

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NOMENCLATURE

ASTM	American Society for Testing and Materials
CS5	Standards Australia Consumer Safety Committee CS005
DoCS	NSW Department of Community Services
ε	Coefficient of kinetic energy restitution
F08	ASTM International Technical Standards Committee F08
g	Acceleration due to gravity at sea level (9.81 m/s^2)
g_{max}	A positive multiple of g that represents the maximum deceleration experienced during an impact
HIC[4]	Head Injury Criteria
Jerk	A vector quantity that specifies the time-derivative (rate of change) of acceleration, or deceleration (g/s or m/s^3)
KE	Kinetic Energy ($\frac{1}{2}mv^2$)
PE	Potential Energy (mgh)
PIC	Playground Injury Criteria
UTS:ITL	Impact Testing Laboratory, Faculty of Engineering, University of Technology, Sydney, Australia

ABSTRACT

All existing playground safety standards throughout the world limit the maximum impact caused by a fall to a deceleration of 200g and/or a Head Injury Criteria (HIC) of 1000. These limits are based on extensive research and aim to reduce deaths and permanent injuries due to head related impacts. These limits were never intended to prevent injuries such as long bone injuries.

This paper discusses in lay person's terms the impact forces involved when a child falls from play equipment onto the undersurfacing material. It also discusses the existing playground undersurfacing test methods for the measurement of impact attenuation and asks the question

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[4] The HIC is an extension of the Wayne Tolerance Curve (WTC) and the Gadd Severity Index (SI) derived from motor vehicle accident research conducted on adult cadavers and animals. The HIC is the most widely accepted human head injury measurement. The HIC does not account for differing brain mass, brain structural capacity and skull size [1]. There was no investigation into the response of a child's trauma in the development of the WTC and thus the HIC. Thus, when the HIC is applied to children falling from play equipment it really is an arbitrary number that allows baseline referencing across the industry. However, injury data do support the use of the 1000 HIC threshold for reducing the statistical prevention of brain injury [2].

as to whether these test methods adequately measure the forces associated with bounce. The author proposes an additional criterion be included in all impact attenuation tests to measure and limit the forces associated with bounce.

INTRODUCTION

The author holds an honorary position as the Engineers Australia representative on the Australian Standards Committee CS005 Children's Playgrounds (CS005 Committee). The CS005 Committee is responsible for the preparation of Australian Standards AS 1924, AS 2155, AS 2555, AS/NZS 4422 [3], AS/NZS 4486 and AS 4685 (draft only) [4]. The author is also on the ASTM International Technical Committee F08 Sports Equipment and Facilities (F08 Committee). This Committee is responsible for several ASTM International Standards Committee including F 355 [5] and F 1292 [6].

In 1996 an Australia and New Zealand Standard was published that specifically addresses the issue of playground undersurfacing impact attenuation and injury prevention associated with falls. This standard was the Australian and New Zealand Standard AS/NZS 4422:1996 Playground Surfacing – Specifications, Requirements and Test Method [3] (AS/NZS 4422:1996). There are similar standards in other countries, for instance ASTM F355 [5] and ASTM F1292 [6] are the impact attenuation Standards used in the United States, and EN 1177 [7] is the equivalent impact attenuation Standard used throughout Europe. The common thread within all of these Standards is the requirement for the fall zone[5] (see Figure 1) to comply with a maximum deceleration of no greater than 200g and a HIC of no greater than 1000. Simply, the pass/fail requirements of AS/NZS 4422:1996 are that the impact resulting from a fall must not exceed 200g and 1000 HIC from any given piece of playground equipment.

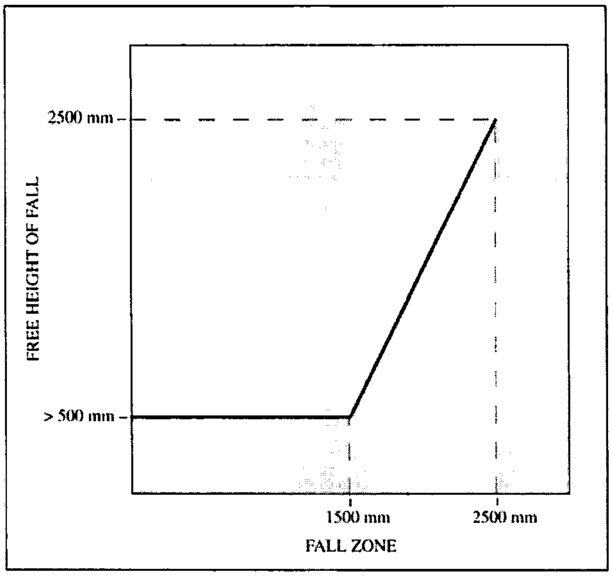

Figure 1: Minimum extent of fall zones [4]

The testing of playground undersurfacing material has been available in Australia and New Zealand for approximately 7 years. It would be reasonable to expect the majority of our

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[5] The fall zone is the surface beneath playground equipment that may be hit by a child falling from that equipment. The line in Figure 1 represents the minimum extent of the undersurfacing for the corresponding adjacent equipment height.

playgrounds to comply with the requirements of this safety Standard. Why is there no evidence of a reduction in the incident rate of accidents from playground equipment falls?

There are many reasons why both the frequency and severity of playground injuries are not reducing. Firstly, in many cases a very large number of playgrounds do not comply with the existing undersurfacing safety Standard. Random field audits of playgrounds by the author within the Sydney Basin Region have produced some quite alarming data. These audits show a very high rate of non-compliance with AS/NZS 4422:1996. Other independent studies also provide evidence of non-compliance. A major study was conducted in 1997 by Kidsafe NSW and NSW Health of 240 Council playgrounds [8]. These playgrounds were assessed to determine the extent to which they complied with safety guidelines. Of the 723 pieces of equipment that required undersurfacing only 45.4% had the recommended type of undersurfacing while only 42 of the 723 pieces had undersurfacing to the required depth. When the fall height of the equipment was considered in addition to the undersurfacing only 1.8% of the 723 pieces of equipment simultaneously satisfied all the safety requirements. The author's experience suggests that, if this comprehensive study were repeated there would be many Local Government Authorities around Australia with similar statistics. Fortunately, there is a growing number of Local Government Authorities around Australia, such as Willoughby Municipal Council and Brisbane City Council, who are proactive with respect to playground safety compliance. A study of 25 Councils that was conducted by the Impact Testing Laboratory, Faculty of Engineering, University of Technology Sydney (UTS:ITL) in 2000 [9] into playgrounds and playground fall heights concluded that the main issue with playground safety was how to maintain compliant surfacing beneath the equipment.

A major problem in manufacturing compliant surfacing is that undersurfacing material does not always perform as well as manufacturers and installers claim. Sometimes the impact attenuation rating of playground undersurfacing falls well short of what was expected or specified. There is a big difference between a material passing an impact test under ideal conditions in a laboratory and passing a test in-situ. The installer may have got the mix wrong. They may have installed the material to an inadequate thickness because of a genuine mistake or intentionally to shave more profit from the project. The weather may have been inclement, too hot, or the humidity levels high. The installer may have installed the product over poorly or inadequately prepared sub-base, or poured it around an old tree stump and in so doing reduced the cover thickness of impact attenuation material. The material that was certified in the laboratory may bear little or no resemblance to the material that was installed. This is a particular problem with natural material such as sand, bark and mulch.

A second reason for the lack of reduction in hospital accident and emergency admissions is that the existing standard was never written to prevent the majority of injuries. Yet, most people associated with playgrounds mistakenly believe that if a playground complies with AS/NZS 4422:1996 there will not be any injuries from impacts or falls. This is not so. Figure 2 is a graph of the expanded Prasad / Mertz Curves and it shows that at a HIC score of 1000 there is a 99.5% chance that a person will suffer a minor head injury, an 89% risk of a moderate injury, and a 3% chance of a critical injury [10]. It can be seen that if we want to lower the rate or severity of injuries we would need to lower the existing 200g/1000HIC threshold to 100g/500HIC.

Furthermore, the playground Standards are voluntary, except in the few cases where they are mandated by a particular stakeholder, as NSW Department of Community Services (DoCS) does with Early Childcare Centres throughout NSW. There is growing ground swell of opinion in the community to make playground safety Standards mandatory as is the case with particular Standards that apply to children's toys.

Inadequate maintenance or total lack of maintenance also contributes to the problem. Regular checking of depth of natural surfacing and making sure that it extends well beyond each piece of equipment is essential. Making sure that the undersurfacing is kept free of litter or objects that could harm children at play is also essential.

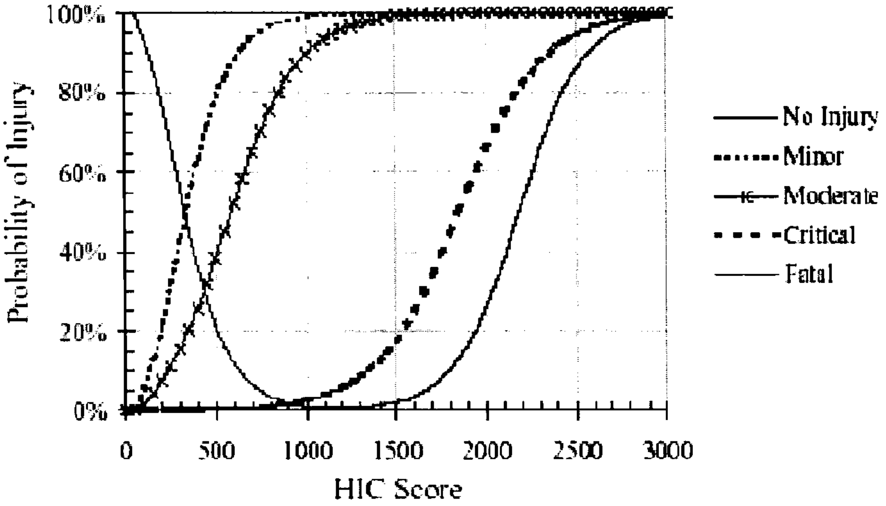

Figure 2: Probability of specific head injury level for a given HIC score [10]

Finally, the 200g/1000HIC criterion does not take into account all of the forces that are occurring during impact. The existing criteria limit the measurement of the impact forces to those associated with deceleration and ignore the forces associated with change in momentum. This simplification is fine when we have impacts that result in a near zero or *dead cat* type bounce where all the energy is absorbed by the undersurfacing material. However, when we have impacts that produce bounce a component of the energy in the undersurfacing is converted back into kinetic energy. As the bounce height increases, so do the forces associated with change in momentum until they reach a magnitude that equals or exceeds the impulse forces associated with deceleration.

It is at this level we need to introduce a new and third criterion to AS/NZS 4422:1996 for pass/fail assessment of undersurfacing material.

This paper will focus on the forces and energy associated with bounce, the change in momentum and the change in deceleration.

BACKGROUND

The impact attenuating surfacing beneath playground equipment is known by a number of terms, including: playing surface system, surface system, soft fall, impact absorbing playground surfacing, soft surfacing, soft pour, playground surfacing, and undersurfacing. It has been the focus of much attention within the playground industry particularly in recent years. Gone are the days when concrete or asphalt (bituminous material) beneath playground equipment was considered acceptable.

When AS/NZS 4422:1996 was drafted natural materials such as grass, pine-bark nuggets (the broken bark of conifers, grain size 20 mm to 80 mm), wood chips (mechanically broken wood without bark and leaf components, grain size 5 mm to 30 mm), sand (washed without silt or clay particles, grain size 0.2 mm to 2 mm) and gravel (round and washed, grain size 2 mm to 8 mm) were typically used as a undersurfacing material.

A major problem with natural materials is the high ongoing maintenance cost. This cost has two components, namely: the cost of regular topping up to maintain impact absorbing properties; the cost of grooming or raking to ensure that minimum depths are maintained; and the removal of broken glass and used syringes. There are other problems including the supply and use of appropriate high quality materials that exhibit energy absorbing properties. For example, sand that is used as a road-base is not suitable for use as an undersurfacing material. There are also problems associated with needle-stick injuries, splinters, ingestion, choking, and accessibility for people with mobility problems. Ideally all materials should be on-site tested and certified for compliance stating the playground undersurfacing depth and associated maximum free height of fall. Nominally a minimum depth of 300 mm is recommended.

In recent years artificial or synthetic materials have progressively replaced natural materials as the preferred undersurfacing material within playgrounds. These synthetic materials include recycled granulated or shredded soft-rubber, and composites such as sand filled artificial grass over LDPE foam. This change in usage can be attributed to the lower ongoing maintenance costs and the perceived reduction in risk as the market considers the synthetic material to be safer more reliable product that once installed will continue to provide a safe play space for many years.

It is worth noting that until relatively recent times all playground undersurfacing energy absorption testing was confined to the laboratory. However, recent technological advances have allowed the development of relatively low cost portable impact test rigs that can test in-situ in accordance with the relevant test methods and procedures. Previously all in-situ testing was limited to a visual inspection and measurement of depth (for natural materials).

THE KINEMATICS OF FALLS AND IMPACTS

The reader may believe that a fall of a child onto a playground undersurfacing material is a simple matter when considering the forces involved. Nothing could be farther from reality. This simple fall would produce a large number of quite complex forces. If the fall was at an angle there would be horizontal components of the force to consider. When the child impacts upon the surfacing there is an equal and opposite force that impacts upon the child's body. An energy wave enters the child's body and travels through the body at a variety of velocities and frequencies and be absorbed and attenuated by the bones, organs and soft tissue to varying degrees. This energy wave is also reflected, refracted, dispersed, and dissipated by the bones, organs and soft tissue to varying degrees. It may excite and resonate components of the body that have natural modes of vibration at the same or harmonic frequencies to those of the energy wave. This is an example of only some of the forces acting immediately after the impact and does not take into account the complex interface forces flowing between the child and the semi-elastic undersurfacing material. The kinematics of falls and impacts is a very complex science.

As in most areas of science it helps to make a few assumptions and simplifications so that the more complex actual event can be modelled. The following discussion is a simplification that will be used to explain in lay terms the kinematics of the fall of a child onto a semi-elastic undersurfacing material.

Let us assume that the complex geometry and mass distribution of our child is replaced by a homogeneous metal sphere of known mass m and that this sphere has been raised to a known height h. Let us also assume that the sphere is initially at rest, that is, it does not have any initial velocity.

We will now use the conservation of energy principle to determine the velocity of the sphere immediately prior to impact. The application of the conservation of energy principle provides a powerful tool for solving this problem. The basic reason that we can use the energy approach is that just the beginning and ending energies need be considered; intermediate processes do not need to be examined in detail since conservation of energy guarantees that the final energy of the system is the same as the initial energy.

Let us consider Figure 3 which is a schematic diagram of a sphere known mass *m* and known height *h*. At rest all the energy is stored as gravitational potential energy (PE) within the sphere where the potential energy is equal to the mass *m* of the sphere multiplied by the acceleration due to gravity *g* at this particular location multiplied by the height *h* that the sphere has been raised above the playground undersurface, or simply *mgh*. As the sphere falls from rest, its gravitational potential energy is converted to kinetic energy (KE).

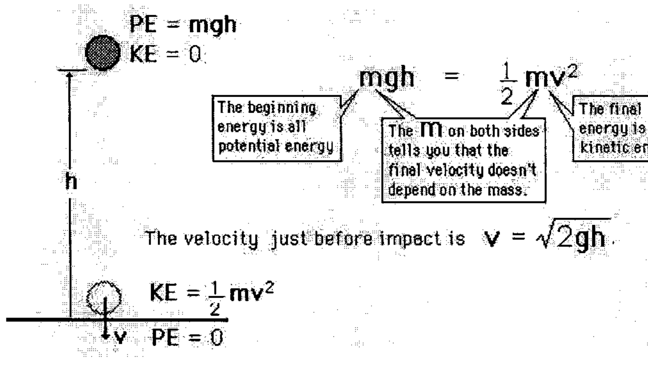

Figure 3: Sphere falling from rest toward a playground undersurface

The conservation of energy principle states that immediately prior to impact all the potential energy has been converted to kinetic energy where the kinetic energy is equal to a half multiplied by the mass *m* of the sphere multiplied by the velocity *v* immediately prior to impact squared, or simply $\frac{1}{2}mv^2$.

The conservation of energy principle permits the calculation of the velocity immediately prior to the sphere impacting the playground undersurfacing material. The potential energy prior to release of the sphere equals the kinetic energy immediately prior to impact, thus PE = KE, or $mgh = \frac{1}{2}mv^2$. If we divide both sides of this equation by the mass and rearrange we obtain an expression of the velocity just prior to impact as $v = \sqrt{(2gh)}$.

It is interesting to note from the formula $v = \sqrt{(2gh)}$ that the velocity immediately prior to impact is not dependent on the mass of the child, just the height from which the child can fall, termed the *free height of fall*.

We will now use the conservation of energy principle to model the impact. We will apply the work-energy method. The work-energy method is a particularly useful tool in cases where an object is brought to rest as in a fall in a playground. For a constant force the work *W* performed equals the force *F* multiplied by the distance *d* over which the force is acting. For the real scenario of a child impacting on the playground undersurfacing material the force is not constantly applied and generally not perpendicular to the surface onto which the child has fallen. For a variable force the work *W* performed equals the integral, or sum, of all the changing forces *F* multiplied by each of the very small distances *dx* over which each of these forces is acting, $W = \int F\,dx$. For impacts that are not perpendicular the work W performed equals $W = \int F \cos\theta\,dx$, where θ is the angle the force makes to the undersurface.

Case 1: The left-hand sketch of Figure 4 depicts a scenario where the undersurfacing is ideal and all the energy of the fall is progressively absorbed by the undersurfacing material over a long distance of penetration and the undersurfacing material is infinitely thick with respect to this penetration distance. There is no reflected shock wave from the sub-base material. Since this is the ideal model scenario there will be no bounce. All the kinetic energy is converted to work. In this example both the g_{max} and the HIC will be low.

The conservation of energy principle permits the calculation of the theoretical depth that the sphere will travel into the ideal undersurfacing material when it is limited to a 200g impact. The kinetic energy KE immediately prior to impact equals the work W that will be done by the sphere penetrating the undersurfacing material. The work is equal to the average force F multiplied by the penetration depth d, thus KE = W, or $\frac{1}{2}mv^2 = F.d$. For the 5kg headform that is specified in AS/NZS 4422:1996 with a free height of fall[6] of 2.5m the impact velocity is approximately 7m/s (25km/hr), the impact energy is approximately 130J, and theoretical penetration depth is approximately 13mm. It must be emphasized that this example is for the ideal case where the impact force is constantly applied to the undersurfacing material and the 130 Joules of energy is dissipated within the undersurfacing material in a progressive manner.

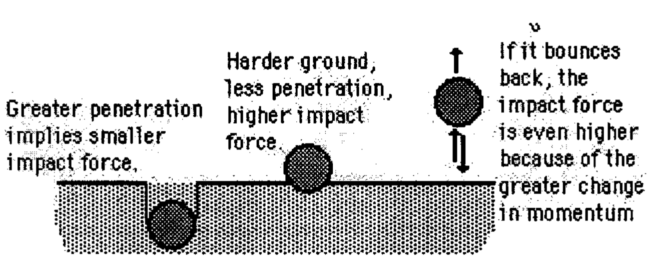

Figure 4: Three different types of impact

Case 2: The middle sketch of Figure 4 depicts a scenario where the undersurfacing is relatively hard. There is very little penetration of the sphere into the undersurfacing at impact and the time over which this small penetration is distributed is quite short. There is very little bounce, but unlike Case 1 the change in momentum is quite large. It is this large rate of change in momentum that results in a very large impulse force.

Case 3: The right-hand sketch of Figure 4 depicts a scenario where the undersurfacing is relatively elastic. In this case there is almost no penetration of the sphere into the undersurfacing at impact and the time over which this penetration occurs is very short. There is a large amount of bounce and because of this bounce the impact force is even higher than in Case 2 because of the greater change in momentum.

200g/1000HIC

Before we consider the Case 3 or *bounce* example in detail it is worth recalling the existing measurement criteria for the measurement of impacts on playground undersurfacing. There are two impact measurement criteria contained within AS/NZS 4422:1996. They are that the g_{max} must not exceed 200g and that the HIC must not exceed 1000 at free height of fall.

We will review each of these criteria in detail separately.

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[6] The free height of fall 2.5m was increased by the depth of the penetration of 13mm to account for the stopping distance as this increased the gravitational potential energy.

Let us consider the g and g_{max} terms. AS/NZS 4422:1996 defines g as *the acceleration into gravity at the earth's surface at sea level* and g_{max} as *the multiple of 'g' that represents a maximum deceleration experienced during an initial impact.* What does this mean in lay terms? We live in a 1g world; gravity exerts 1g continually on our bodies. When we take off in a jet airplane we briefly experience 1.5g, when we catch a lift in a building we also momentarily experience 1.5g. When this happens our body feels 1.5 times its normal weight. When we ride the roller coaster we experience 2g, and 3g when we ride the rotor and find it difficult to raise our limbs off the wall. At 4g the blood flow to our retina drops and our colour vision turns to black and white and we lose peripheral vision. We will become unconscious after 5 seconds at 5g. So when we decelerate at 200g, we are decelerating with a force 200 times greater than the gravitational force we normally experience.

Research by Stapp [11] that was conducted for the US Air Force Medical Corps confirmed that the rate at which deceleration is applied, that is the *jerk*, can mean the difference between life and death. In one particular experiment a human subject was subjected to a well distributed 45g deceleration at a rate of 500g per second while seated and constrained in a forward facing position. The subject experienced blurred vision and intermittent shadowing of vision for approximately 4 hours after the test, and a black spot in his vision that persisted for 10 weeks. Thereafter it very gradually cleared up. It is worth noting that these experiments did not include any impact per se, they were not designed to measure the actual human body impacting. They were merely using a controlled distributed deceleration to simulate combat pilot tolerance during seat ejection to various types of abrupt deceleration. The subjects, both human and non human, were all placed in a cradle or seat and they were firmly constrained within this seat. If impact had been tested the deceleration would have been non-linear and more impulsive in nature, that is, subjects would have experienced periods of deceleration where the rate of change of deceleration was higher than 500g/s and this would thus have been considerably more dangerous.

On the basis of experimental exposure of human, chimpanzee and hog subjects to abrupt deceleration forces by means of linear decelerations Stapp [11] established that tolerance limits for human subjects approximate a 50g peak at 500g/s provided the subject was adequately restrained.

Let us now consider the HIC term. AS/NZS 4422:1996 defines HIC as *a measure of impact severity that considers the duration over which the most critical section of the deceleration pulse persists as well as the peak level of that deceleration.* What does this mean in lay terms? This term is a little more difficult to quantify as it is something that is calculated and as such does not really have any natural experience that it can be compared to. The HIC evolved from a weighted impulse criterion known as the Gadd Severity Index, or simply the Severity Index SI. The SI was developed to enable a methodical means of comparing head impacts to biomechanical tolerance data, primarily the Wayne Tolerance Curve.

The HIC is calculated using the following expression:

$$\mathrm{HIC} = \left[\left(\frac{\int_{t_1}^{t_2} a \, dt}{t_2 - t_1} \right)^{2.5} (t_2 - t_1) \right] \mathrm{max}$$

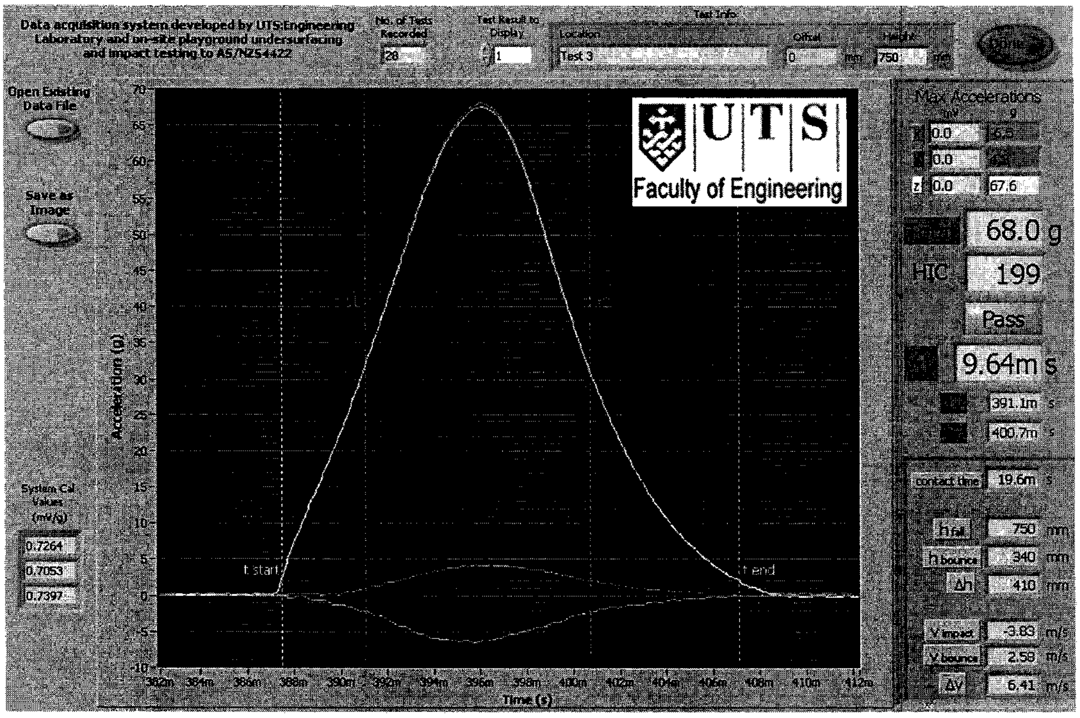
where:

t_{start} is the time, at the start of the impact event, when the deceleration of the headform first equals or exceeds zero;

t_{end} is the time, at the completion of an impact event, when the end deceleration of the headform first equals or falls below zero;

a is the deceleration experienced by the headform and expressed in g; and

t_2, t_1 two intermediate values of t (t is the time in second) between t_{start} such t_{end} between which the function for calculating HIC is maximized. Note this procedure is only valid for impact events with a total duration of more than 3ms [3].


Data acquisition system developed by UTS:Engineering Laboratory and on-site playground undersurfacing and impact testing to AS/NZS4422

No. of Tests Recorded: 28

Test Result to Display: 1

Location: Test 3

Offset: 0 mm

Height: 750 mm

System Cal. Values (mV/g): 0.7264, 0.7053, 0.7397

Max Accelerations (mV, g): z 0.0, 67.6

68.0 g

HIC 199

Pass

9.64m s

391.1m s

400.7m s

contact time 19.6m s

h fall 750 mm

h bounce 340 mm

Δh 410 mm

V impact -3.83 m/s

V bounce 2.58 m/s

ΔV 6.41 m/s

Figure 5: Typical output from an impact of a shredded rubber undersurface material; fall height 0.75m, $g_{max} \approx 68g$, HIC 199, $t_2 - t_1$ 9.64ms, $jerk_{av} \approx 8{,}000g/s$, and $jerk_{max} \approx 9{,}000g/s$.

The HIC requires maximization of the above mathematical expression involving the time-average deceleration by varying the limits t_1 and t_2. It can be seen that the acceleration is weighted by the exponent 2.5, and therefore high accelerations for short time durations will contribute more to the integral than low accelerations for extended time durations. The US Department of Transportation National Highway Traffic Safety Administration set a SI threshold of 1000 in the 1960's. The value of 1000 was retained when the HIC was adopted. It is worth mentioning that t_1 and t_2 are not simply the values of the time at the onset and end of the impact, but are the values, within these bounds, which maximize the HIC.

Figure 5 above shows a typical deceleration pulse from the impact test on a shredded rubber undersurface sample. The t_{start}, t_{end}, t_1 and t_2 are depicted as vertical lines within the graph. The large red trace (the hump) is the vector sum of the x, y and z components of acceleration. The g_{max} is 68.0g, being the maximum value measured at the crest of this hump. The HIC is 199, being calculated from the area under the curve between t_1 and t_2. The HIC calculation time ($t_2 - t_1$), labeled Δt is 9.64ms. The impact contact time ($t_{end} - t_{start}$) between the headform and the undersurfacing is 19.6ms. The fall height is 750mm and the impact velocity is 3.83m/s, while the bounce velocity is 2.58m/s and the bounce height is 340mm.

PLAYGROUND INJURY CRITERIA, PIC

Let us now consider the Case 3 example that is depicted in the right-hand sketch of Figure 4 which depicts a scenario where the undersurfacing is relatively elastic.

This type of undersurfacing is typically represented by the artificial rubber-based products. As a general rule these products are HIC limited, that is, they fail the AS/NZS 4422:1996 requirements on HIC and not g_{max}.

Let us consider the sphere in Figure 4 just prior to impact. At this point in time and space all the potential energy associated with the free height of fall has been converted to kinetic energy. As the sphere impacts on the surface several things happen. The most obvious is that the sphere continues to travel in a downward direction deforming the playground undersurfacing material. For the Case 3 right-hand bounce example in Figure 4 the kinetic energy is progressively converted from kinetic energy to spring energy (SE) as the sphere travels into the undersurfacing material.

Spring energy is a particular form of potential energy. If the playground surface was manufactured from a perfectly linear elastic material the sphere would bounce all the way up to the height from which it was originally dropped. The ratio of bounce height to the drop height gives us an indicative measure of the playground surface's co-efficient of kinetic energy restitution ε. For a material where the bounce is equal to the free height of fall the co-efficient of kinetic energy restitution is unity or $\varepsilon = 1$. A perfectly elastic impact is one in which no kinetic energy is lost in the impact. The velocity of the sphere immediately prior to impact is equal to the velocity immediately after impact.

In the playground no impact is perfectly elastic, all impacts are inelastic to some degree and there is always an accompanying irreversible flow of energy. The undersurfacing material exhibits hysteresis. The kinetic energy is converted permanently to other forms of energy. Work is done on the undersurfacing material during the impact and during this impacting process heat and sound are generated, and permanent mechanical deformation can occur to the undersurfacing material. With playground undersurfacing materials this is precisely what we require. For example in sand-based undersurfacing the sand particles will be permanently displaced as the shock-wave or seismic-wave associated with the impact flows through the body of sand. Ideally we want all the kinetic energy to be permanently converted to other forms of energy as depicted in the left-hand sketch of Figure 4. Moreover, we would like this energy transformation to occur over the longest possible time duration as this minimises the forces involved.

What else happens at impact?

Let us assume that we drop a 5.0kg J-type headform onto a playground undersurface from a free height of fall of 2m and it bounces back 0.8m. The g_{max} is measured as 133g and the calculated HIC is 880. Under the current standard this playground surface would pass the test requirements of AS/NZS 4422:1996 for a free height of fall of 2m. The problem with this example is that there is no account of the impulse force associated with this impact.

In the above example the co-efficient of kinetic energy restitution is 0.8/2.0 = 0.4. The velocity immediately prior to impact is approximately 6.3 m/s and the bounce velocity immediately after impact is approximately 4.0m/s giving a co-efficient of elastic restitution of 0.63. The kinetic energy immediately prior to impact is 98J and the kinetic energy immediately after impact is 39J. The playground undersurfacing has absorbed 59J of energy. The product of average force and the time over which the force is exerted is called the impulse of force. From Newton's second law.

$$F_{average} = ma_{average} = m\frac{\Delta v}{\Delta t}$$

The impulse of the force can be extracted and found to be equal to the change in momentum of an object provided the mass is constant.

$$\text{Impulse} = F_{average}\Delta t = m\Delta v$$

The above formula is useful in the study of the average impact force during impacts. For impacts, the mass and change in velocity are often readily measured, but the force during the impact is not. If the time of impact can be measured, then the average force of impact can be calculated.

How do we minimize the impact force? The process of minimizing an impact force can be approached from the definition of the impulse of force.

$$\text{Impulse} = \underset{\text{Reduce impact}\downarrow}{F_{average}}\Delta \overset{\text{Extend time}\,\uparrow}{t} = m\Delta v$$

If an impact stops the sphere or headform, then the change in momentum is a fixed quantity, and extending the time of the collision will decrease the impact force by the same factor. Alternatively, the same scenario can be examined with the aid of the work-energy principle.

$$\underset{\text{Reduce impact}\downarrow}{F_{avg}}\overset{\uparrow\text{Extend distance}}{d} = -\frac{1}{2}mv^2$$

An impact that stops a moving object must do enough work to take away its kinetic energy, so extending the penetration distance during the impact reduces the impact force.

Let us consider the change in momentum that occurred in the bounce case above. If we consider the momentum we obtain $(m.v)_{bounce} = 31.5 - (-20) = 51.5$kg.m/s. For the ideal case with no bounce example the change in momentum would simple be the change in momentum, this is, $(m.v)_{no\ bounce} = 31.5$kg.m/s.

It should be noted that we have only considering the average force that is being applied and not the instantaneous force that is actually being applied, the maximum rate of change of momentum, or the maximum rate of change of acceleration.

The research by Stapp [11] concluded that the rate of change of acceleration (called the 'jerk') should be limited to 500g/s for a 50g collision. The maximum slope of the curve in Figure 4 is the jerk. In this example the jerk is approximately 9,400g/s for a 68g collision. When a hog was subjected to at forward facing jerk of 10,000g/s the collision resulted in 2 bowel ruptures and a moderate visceral hemorrhage. It should be noted that the data represented in Figure 4 is for an impact that under our present system of measurement and reporting is an excellent material. It has a gmax of 68g and a HIC of only 199.

Let us now compare the results of an impact where the gmax and HIC values are well within the limits of AS/NZS:4422 with an impact test as we approach the 200g/1000HIC limit as is represented in Figure 5.

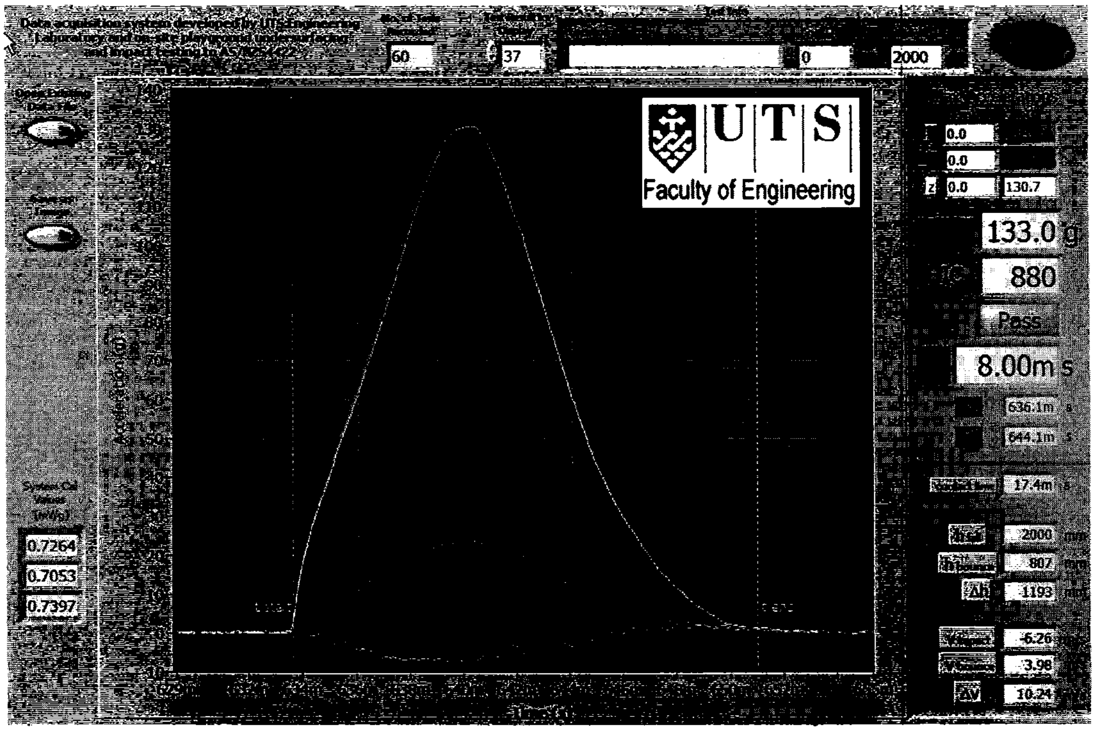


Figure 6: Output from the impact of a 100mm thick shredded rubber undersurface material; fall height 2.0m, $g_{max} \approx 133g$, HIC 880, $t_2 - t_1$ 8.00ms, $jerk_{av} \approx 20{,}000g/s$, and $jerk_{max} \approx 35{,}000g/s$.

A comparison of the data contained within Figure 5 with Figure 6 confirms that an approximate g_{max} 68g is associated with a $jerk_{max}$ of approximately 9,000 g/s while a g_{max} 133g is associated with a $jerk_{max}$ of approximately 35,000 g/s. It is proposed that a third criteria be included in the impact test method for playground undersurfacing that takes into consideration the rate of change of acceleration, the rate of change of the impulse force, or the rate of change of momentum.

CONCLUSIONS AND RECOMMENDATIONS

As with industrial safety a balance must be found between risk exposure and safety. Risk management within the playground environment is more complex than industrial safety because the primary aim of a playground is to stimulate a child's imagination, provide excitement and adventure and allow scope for children to develop their own ideas of play. Ideally playgrounds should encourage the development of motor skills and present the child with manageable challenges. A playground should also include elements that encourage the development of a child's creative, cognitive, social and sensual skills too. Risk taking should be accepted as a given with child development. A well designed playground is actually encouraging the child to take risks, but in a semi-controlled environment that protects a child from hazards he or she may be unable to foresee when using playground equipment as intended. A well-designed playground will also help the child to develop a sense of boundaries, a very important and often overlooked life skill. A well-designed playground will also be designed so that risk involved in play is apparent and foreseeable by the child.

The encouragement of risk-taking in children must occur without the child sustaining an injury that causes death, or leaving the child permanently disabled or disfigured. It should also minimise the frequency and severity of all other fall related injuries, particularly long bone injuries associated with permanent nerve damage.

Children will inevitably fall from play equipment unless playground equipment is totally encapsulated to remove all possible fall sites along the line of some McDonalds-type playspaces where the playspace in one contiguous sanitised convoluted tube. It is now generally accepted that adequate undersurfacing material is a necessary component of good playground design for the purpose of reducing the severity of accidents and that this undersurfacing needs to be commensurate with the free height of fall.

The primary objective of this study was to discuss why undersurfacing materials that result in a large bounce or high rates of change of deceleration are undesirable as impact attenuating undersurfacing materials. An additional pass/fail criterion was proposed to take account of the forces associated with bounce and high rates of deceleration. This criterion was nominally called the Playground Injury Criterion or *PIC*. It was proposed that experimental research be undertaken to determine an acceptable magnitude for the PIC term and it was suggested that the magnitude of the PIC be equivalent to the 200g/1000HIC terms for a normalised undersurfacing test sample.

A secondary objective was to explain why we continue to observe severe injuries from playground falls even when the undersurfacing material complies with AS/NZS 4422:1996. In summary there are two main reasons, namely:

- That the existing test method does not include the forces associated with the rate of change in momentum and deceleration; and
- The pass/fail magnitude existing 200g/1000HIC terms are too high and it is recommended that these values need to be lowered.

Inadequate or poorly maintained undersurfacing continues to be cited as the prime cause of playground injuries. Yet, when our children fall from play equipment as they inevitably will, they will impact on undersurfacing, so it is absolutely necessary that undersurfacing provides adequate absorption and attenuation of falls. It is also the author's opinion that both the number and severity of fall injuries would be reduced if Local Government Authorities (and other organisations) were required to legally comply with the testing requirements of AS4422: 1996. This would ensure that the surface children fell onto absorbed a controlled amount of impact energy and limited the maximum impact to less than 200g and a Head Injury Criteria (HIC) to less than 1000.

Death following falls from playground equipment is rare. However, such falls are one of the biggest causes of bone fractures in children attending the accident and emergency departments in our public hospitals. Reduction of fractures from playground equipment will produce better outcomes for children, and reduce the load on our stretched health system. Fractures occur when children fall from play equipment. There is limited measurement data available on the way children fall, the forces involved and the properties of surfaces to which they fall.

It is recommended that research funding be directed toward quantifying the Playground Injury Criteria PIC so that this can be incorporated into the playground safety standards as a pass/fail terms for impacts with excessive levels of bounce.

BIOGRAPHY:
Dr David Eager is a Senior Lecturer in the Faculty of Engineering at the University of Technology Sydney and is a Fellow of Engineers Australia, a Chartered Professional Engineer, and on the National Professional Engineers Register. He also holds an honorary position as a Councilor on the Board of Kidsafe NSW.

David has a PhD in Engineering in the area of Occupational Health and Safety, a 1st Class Honours Degree in Mechanical Engineering, and a Graduate Certificate in Dispute Resolution. He currently holds the honorary position as the Engineers Australia representative on the Australian Standards Committees for Children's Playgrounds CS005, Trampolines CS100, Adventure Rides and Devices ME51, and Global Warming EV15. David also currently holds the honorary position as an Australian representative on the ASTM International Technical Committees; Forensic Sciences E30, Occupational Health and Safety Technical E34, Sports Equipment and Facilities F08, and Amusement Rides and Devices F24.

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