Review on Empirical Studies of Local Impact Effects of Hard Missile on Concrete Structures

Ismail Abdul Rahman[*1], Ahmad Mujahid Ahmad Zaidi[2], Qadir Bux alias Imran Latif[1]

[1]Faculty of Civil and Environmental Engineering,
[2]Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia
86400 Parit Raja, Johor, Malaysia

*Corresponding email: ismailar@uthm.edu.my

Abstract

Concrete is basic construction material used for any kind of structure. However, in most vital and local structures such as nuclear plants, Power plants, Weapon Industries, weapons storage places, water retaining structures like dams, and also local industries, & etc., concrete structures have to be designed as defensive structures to provide protection against any accidents or knowingly generated incidents such as dynamic loading, dynamic local impact damage and global damage generated by kinetic missiles (steel rods, steel pipes, turbine blades, etc.). The impacting missile (projectile) can be classified as 'Hard' and 'Soft' in nature, depending upon the implication of its deformation with respect to the deformation of target. 'Hard' missile impact can generate both local impact damage and also overall dynamic global damage of concrete structure. This paper only provides the review of previous empirical studies related to our study and can be used for making design recommendation and design procedures for determining the dynamic response of the target to prevent local and impact damage.

Keywords: *Empirical Study, Local Impact Effects, Hard missile, Concrete*

1.0 INTRODUCTION

Over the years, concrete is very commonly used construction material for the military and civil applications to protect structures from local and explosive impact loads. For the designing of high-quality protective structures it is crucial to have a good knowledge about behavior of concrete against impact or explosive loading conditions. Projectile may be exists in a long diversity with fluctuation in sizes, shapes, velocity, weight, density, such as bullets, fragments, tornado, terrorist bombing, etc. The projectile may be classified as 'Hard' and 'Soft' depending upon deformability of projectile with respect to target's deformation. Deformation of hard missile is considerable smaller or negligible compared with target's deformation. Almost in all cases hard missiles are considered as non – deformable or rigid. However, 'Soft' missile deforms itself considerably well as compared to target's deformation. Interest is focused on local damage and global response of target deformation caused by 'Hard' missiles considering failure criteria, contact mechanics, material model, and parametric analysis (velocity of missile, distance b/w missile and target, weight of missile, size and shape of missile, angle at which missile attacks on target, density of missile and target, thickness of structure, strength of concrete and reinforcement of concrete). Local impact effect consists mainly four process: (i) Spalling of concrete (ejection of material from front face or impacted face), (ii) scabbing of concrete (peeling off of material from back face or opposite side of impacted face of target), (iii) Missile Penetration into target (displacement of missile into the target), and (iv) Perforation of the target (full penetration beyond target). The local impact effect of hard missile on concrete structures can be studied by three ways, (i). Empirical Studies (predict empirical formula based on experimental data), (ii). Analytical Studies (create formula based on physical laws and compared with experimental data), and (iii), Numerical Simulation (based on computer based material model generate results and compared with experimental data). This study is based on numerical simulation with the help of finite elements. This paper only provides the review of previous empirical studies related to our study.

2.0 LOCAL IMPACT EFFECTS

There're two breed of impacts occurs at target, when it is subjected to projectile. First one is local impact and other one is explosive impact. The damage caused by projectile with its physical parameters, not because of explosion is known as local impact damage. Local impact effect is further briefly sub-divided in below explained processes:

Radial Cracking: When projectile colloids with concrete target with certain velocity, it results radial cracks originated from the point of impact within the target in every direction. [58]

Spalling: The ejection of material of target from front face (impacted face) due to impact of hard projectile is called spalling. Spalling produces spall crater in the surrounding area of impact. Spall crater is the total damaged portion of peeling off material from target on impacted face. [1, 58]

Penetration: Penetration is defined as the digging of missile into the target body afar from the thickness of spall crater. The lengthwise measurement of dig is called penetration depth. [1, 58]

Cone cracking & Plugging: During penetration missile colloids with rear border of target and generates curved shear cracks in the shape of bell plug is called cone cracking. And than missile continues penetrating through target, it forces plug and shears-off the surrounding material of target is called plugging. This process generates rapid change into the behavior of target. [58]

Scabbing: Ejection of target material from back face of target is called scabbing. [1, 58]

Perforation: Perforation means complete passage or complete crossing of projectile through the target. It causes missile to extend penetration hole through scabbing crater and exit from the rear face of target. [1, 58]

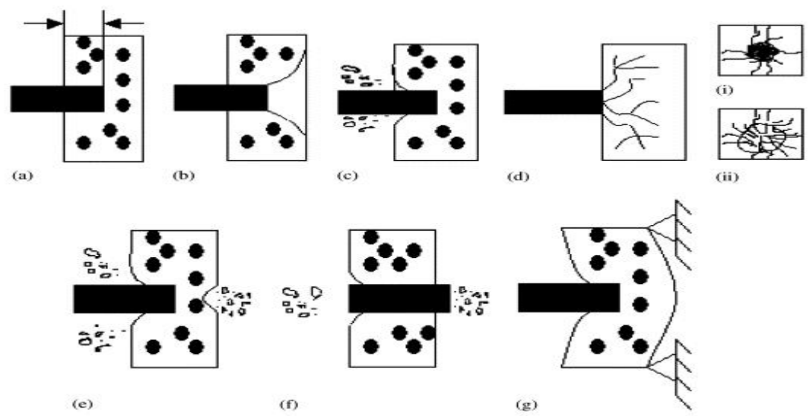

Figure.1. Explains the local impact phenomena caused by hard projectile. (a) Penetration, (b) Cone cracking and Plugging, (c) Spalling, (d) Radial cracking (i) front face and (ii) back face, (e) Scabbing, (f) Perforation, and (g) Global phenomena.

3.0 EMPIRICAL STUDY REVIEW

Empirical formulae for designing of protective concrete structure against local impact effects of hard missile are below discussed in detail in both measuring systems (S.I Units and F.P.S Units). These formulae are verified with original formulae. The notations and symbol used in this paper for the calculation of local impact effects are shown in table:

Table 1. Notation of terms used in paper.

Symbol	Description
x	Penetration depth
e	Perforation limit
h_s	Scabbing limit
E	Modulus of elasticity of projectile
E_s	Modulus of elasticity of Steel
M	Mass of projectile
d	Diameter of projectile
h	Height of projectile nose
R / R_s	Radius of projectile nose
H	Thickness of cone plug
H_o	Thickness of the target
f_t	Tensile strength of target

f_c	Unconfined compressive strength of target
r	Percentage of reinforcement (both ways of reinforcement)
A	Aggregate diameter
v_o	Projectile impacting velocity
N	Nose shape factor
Ψ	Caliber-radius-head
D	Caliber density of projectile
f'_c	Ultimate compressive strength of target
K / k_p	Target penetrability factor

3.1 Modified Petry Formula [1,58]

The most commonly formula used to predict various components of local impact effects of hard missile on concrete structure in USA was modified Petry formula. It is the oldest of available empirical formulae, and developed originally in 1910. According to Petry the penetration depth x (inches) can be predicted as:

$$x = 12K_p A_p \log_{10}\left(1 + \frac{V_o^2}{215{,}000}\right) \quad (1)$$

This equation was derived from the equation of motion which states that the component of drag-resisting force depends upon square of the impacted velocity, and the instantaneous resisting force is constant. In above equation, A_p represents the missile section pressure (psi). K_p is concrete penetrability co-efficient, it depends upon the strength of concrete and on the degree of reinforcement. It equals to 0.00426 for normal reinforced cement concrete, 0.00284 for special reinforced cement concrete (front and rear face reinforcement are laced together with special ties), and 0.00799 for massive plain cement concrete. The modified Petry formula – I suggested by Q.M. Li in S.I unit is:

$$\frac{x}{d} = k\frac{M}{d^3}\log_{10}\left(1 + \frac{V_o^2}{19{,}974}\right) \quad (2)$$

The above listed both formulae are famously known as Modified Petry formula - I. it is suggested that k value for normal reinforced cement concrete 0.000339, 0.000226 for special reinforced cement concrete, and 0.000636 for massive plain cement concrete. The relationship b/w k and K_p is equals to $k = 0.0795K_p$.

Later on, Amirikian [8] suggest revised value for K_p for the account of variation in concrete strength. He suggests that K_p is a function of concrete strength, as shown in figure.2.2. With the revised K_p value this formula known as modified Petry formula – II. Amirikian also suggests that the perforation limit (e) can be calculated by formula based on penetration depth (x).

$$\frac{e}{d} = 2\frac{x}{d} \quad (3)$$

and scabbing limit (h_s)

$$\frac{h_s}{d} = 2.2\frac{x}{d} \tag{4}$$

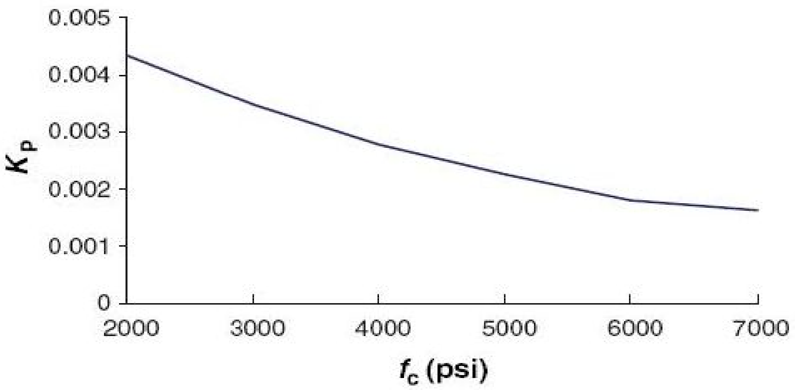

Figure. 2. Variation of concrete penetrability K_p with the unconfined compressive strength of concrete (f_c).

3.2 Ballistic Research Laboratory (BRL) Formula [1, 9-11, and 58]

For the calculation of penetration depth (x) of concrete impacted by hard missile, Ballistic Research laboratory (BRL) was suggested a formula in 1941 [12, 13], and its modified expression was given by [1, 9; 10]:

$$\frac{x}{d} = \frac{427}{\sqrt{f_c}}\left(\frac{M}{d^3}\right)d^{0.2}\left(\frac{V_o}{1000}\right)^{1.33} \qquad \text{(F.P.S)} \tag{5}$$

$$\frac{x}{d} = \frac{1.33\times10^{-3}}{\sqrt{f_c}}\left(\frac{M}{d^3}\right)d^{0.2}V_o^{1.33} \qquad \text{(S.I)} \tag{6}$$

Chelapati et al. [13] suggested perforation limit (e) can be calculated based on above calculated penetration depth (x) by:

$$\frac{e}{d} = 1.3\frac{x}{d} \tag{7}$$

And for scabbing limit (h_s), modified BRL formula is [1, 14]:

$$\frac{h_s}{d} = 2\frac{x}{d} \tag{8}$$

3.3 Army Corp of Engineers (ACE) Formula [1, 13, 15 and 58]

Before 1943, The Ordnance Department of the US Army and Ballistic Research Laboratory (BRL) done many experimental works on local impact effects of hard missile on concrete structure, based on those results Army Corp of Engineers developed the ACE formula:

$$\frac{x}{d} = \frac{282.6}{\sqrt{f_c}}\left(\frac{M}{d^3}\right)d^{0.215}\left(\frac{V_o}{1000}\right)^{1.5} + 0.5 \qquad \text{(F.P.S)} \tag{9}$$

$$\frac{x}{d} = \frac{3.5 \times 10^{-4}}{\sqrt{f_c}} \left(\frac{M}{d^3} \right) d^{0.2} V_o^{1.5} + 0.5 \qquad \text{(S.I)} \qquad (10)$$

Above given formula is for calculation of penetration depth (x) in F.P.S and S.I. Systems. The formula for perforation limit (e) and scabbing limit (h_s) based on regression analysis of data obtained from 37mm, 75mm, 76.2mm, and 155mm steel cylindrical missile ballistic tests, are:

$$\frac{e}{d} = 1.32 + 1.24 \frac{x}{d} \qquad \text{for } 1.35 < \frac{x}{d} < 13.5 \text{ or } 3 < \frac{e}{d} < 18 \qquad (11)$$

$$\frac{h_s}{d} = 2.12 + 1.36 \frac{x}{d} \qquad \text{for } 0.65 < \frac{x}{d} < 11.75 \text{ or } 3 < \frac{h_s}{d} < 18 \qquad (12)$$

In 1944, above formulae were revised because of additional data obtained from 0.5 caliber bullet tests. For the same range of validity of parameters, the revised formula is:

$$\frac{e}{d} = 1.23 + 1.07 \frac{x}{d} \qquad (13)$$

$$\frac{h_s}{d} = 2.28 + 1.13 \frac{x}{d} \qquad (14)$$

3.4 Modified NDRC Formula [1, 16, 17, 58 and 59]:

In 1946, a theory of penetration of rigid missiles into massive concrete targets was suggested by National Defense Research Committee (NDRC). It was developed based on ACE formulae. In this it was assumed that the contact force b/w target and projectile increases linearly until it reached maximum value which is constant. It was subjected for lower penetration depths. The NDRC formula was best among other available formulae, because it offered very close approximation of the experimental results compared to all other formulae. Although this theory was suggested for the calculation of penetration depth (x), beside of that it was also used for calculation of impact force time history and penetration depth time history. Based on that, NDRC suggested that penetration depth (x) can be calculated from G – function equations:

$$G = \frac{KN^* M}{d} \left(\frac{V_o}{1000d} \right)^{1.8} \qquad \text{(F.P.S)} \qquad (15)$$

to a function of $\frac{x}{d}$, i.e.

$$G = \left(\frac{x}{2d} \right)^2 \qquad \text{for } \frac{x}{d} \leq 2 \qquad (16)$$

$$G = \frac{x}{d} - 1 \qquad \text{for } \frac{x}{d} > 2 \qquad (17)$$

or

$$\frac{x}{d} = 2G^{0.5} \qquad \text{for } G \geq 1 \qquad (18)$$

$$\frac{x}{d} = G + 1 \qquad \text{for G<1} \qquad (19)$$

where N* is nose shape factor for projectiles, which is equals to 0.72 for flat nose, 0.84 for hemispherical nose shape, 1.0 and 1.14 for blunt and very sharp noses. K is concrete penetrability factor, which depends on strength of concrete (same as K_p in Petry Modified formulae).

It was unfortunate for the NDRC that, after 1946 this study was timely prevented due to reduction in interest on local impact effect studies because of losses at World War – II, without finalizing k factor. Before finalization NDRC suggested k should be lie b/w 2 and 5 depending upon concrete strength. However, later on in 1966 based on both theoretical and experimental data Kennedy [17] suggested that the concrete penetrability factor (k) is proportional to the reciprocal of the ultimate compressive strength or unconfined compressive strength of concrete, which equals to k = 180(f_c or f'_c)$^{1/2}$. The modified NDRC formula defined by new G – function is:

$$G = \frac{180N^{*}M}{d\sqrt{f_c}}\left(\frac{V_o}{1000d}\right)^{1.8} \qquad \text{(F.P.S)} \qquad (20)$$

$$G = 3.8\times10^{-5}\,\frac{N^{*}M}{d\sqrt{f_c}}\left(\frac{V_o}{d}\right)^{1.8} \qquad \text{(S.I)} \qquad (21)$$

Together with same above listed functions of x/d. For the calculation of perforation limit (e) and for scabbing limit (h_s) are:

$$\frac{e}{d} = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^{2} \qquad \text{for } \frac{x}{d} \le 1.35 \text{ or } \frac{e}{d} \le 3 \qquad (22)$$

$$\frac{e}{d} = 1.32 + 1.24\left(\frac{x}{d}\right) \qquad \text{for } 1.35\frac{x}{d} \le 1.35 \text{ or } 3 < \frac{e}{d} < 18 \qquad (23)$$

and

$$\frac{h_s}{d} = 7.91\left(\frac{x}{d}\right) - 5.06\left(\frac{x}{d}\right)^{2} \qquad \text{for } \frac{x}{d} \le 0.65 \text{ or } \frac{h_s}{d} \le 3 \qquad (24)$$

$$\frac{h_s}{d} = 2.12 + 1.36\left(\frac{x}{d}\right) \qquad \text{for } 0.65 < \frac{x}{d} \le 11.75 \text{ or } 3 < \frac{h_s}{d} \le 18 \qquad (25)$$

Q.M. Li, S.R. Reid and A.M Ahmad Zaidi (2006) [59] further modified the NDRC formulae in terms of critical energies required to scabb and perforate the concrete targets for flat nose hard missile impact. According to them critical impact energy for scabbing in S.I units:

$$\frac{E_{cs}}{f_c d^3} = \left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[52.84 - \sqrt{2789.4 - 903.9\left(\frac{H}{d}\right)}\right]^{2} \qquad \text{for } \frac{H}{d} \le 3.0, \qquad (26)$$

$$\frac{E_{cs}}{f_c d^3} = \left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[51.35\left(\frac{H}{d}\right) - 105.34\right]^{2} \qquad \text{for } 3.0 < \frac{H}{d} \le 4.84, \qquad (27)$$

$$\frac{E_{cs}}{f_c d^3}=\left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[1.389\times10^4\left(\frac{H}{d}\right)-4.677\times10^4\right] \text{ for } 4.84<\frac{H}{d}\leq 18.0, \quad (28)$$

and the critical impact energy for perforation

$$\frac{E_{cp}}{f_c d^3}=\left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[150-\sqrt{22.53\times10^3-6.36\times10^3\left(\frac{H}{d}\right)}\right]^2 \text{ for } \frac{H}{d}\leq 3.0, \quad (29)$$

$$\frac{E_{cp}}{f_c d^3}=\left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[54.46\left(\frac{H}{d}\right)-71.96\right]^2 \qquad \text{ for } 3.0<\frac{H}{d}\leq 3.8, \quad (30)$$

$$\frac{E_{cp}}{f_c d^3}=\left(\frac{V_o}{d}\right)^{0.2} f_c^{-0.5}\left[1.473\times10^4\left(\frac{H}{d}\right)-3.774\times10^4\right] \text{ for } 3.8<\frac{H}{d}\leq 18.0, \quad (31)$$

3.5 Ammann and Whitney Formula [1, 58]

This formula was proposed to predict penetration of concrete target against the impact of explosively generated small fragments at relatively higher velocities. According to Kennedy [1] this formula can predict penetration of explosively generated small fragments traveling at over 1000ft/sec.

$$\frac{x}{d}=\frac{282}{\sqrt{f_c}}N^*\left(\frac{M}{d^3}\right)d^{0.2}\left(\frac{V_o}{1000}\right)^{1.8} \qquad \text{(F.P.S)} \qquad (32)$$

$$\frac{x}{d}=\frac{6\times10^{-4}}{\sqrt{f_c}}N^*\left(\frac{M}{d^3}\right)d^{0.2}V_o^{1.8} \qquad \text{(S.I)} \qquad (33)$$

In this formula N* is the nose shape function same as defined in NDRC formula.

3.6 Whiffen Formula [18, 19, and 58]:

During war time in United Kingdom the study of hard missile penetration in concrete target was reflected whiffen formula. This formula was suggested by British Road Research Laboratory, based on extensive range data obtained from World War – II. The data obtained from wartime had variety of penetration studies of fragments from much kind of bombs penetrated reinforced concrete, and extended investigations involving larger range of projectile diameter, and concrete aggregate size.

$$\frac{x}{d}=\left(\frac{870}{f_c^{0.5}}\right)\left(\frac{M}{d^3}\right)\left(\frac{d}{a}\right)^{0.1}\left(\frac{V_o}{1750}\right)^n \text{ with } n=\frac{10.70}{f_c^{0.25}} \qquad \text{(F.P.S)} \qquad (34)$$

$$\frac{x}{d}=\left(\frac{2.61}{f_c^{0.5}}\right)\left(\frac{M}{d^3}\right)\left(\frac{d}{a}\right)^{0.1}\left(\frac{V_o}{533.4}\right)^n \text{ with } n=\frac{97.51}{f_c^{0.25}} \qquad \text{(S.I)} \qquad (35)$$

This formula can work in the range of $800< f_c<10{,}000$(psi), $0.3<M<22{,}000$(lbs), $0.5<d<38$(in), $0<v_o<1750$(ft/sec), and $0.5<d/a<50$ for ogive nose shape projectiles of caliber radius b/w 0.8 and 3.5. the prediction accuracy is about ±15%.

3.7 Kar Formula [11, 20, and 58]:

Kar [20] modified the NDRC formula by using regression analysis in terms of Young's modulus of elasticity (E) for projectile material.

$$G=\frac{180N^{*}M}{d\sqrt{f_c}}\left(\frac{E}{E_s}\right)^{1.25}\left(\frac{V_o}{1000d}\right)^{1.8} \qquad \text{(F.P.S)} \qquad (36)$$

$$G=3.8\times10^{-5}\frac{N^{*}M}{d\sqrt{f_c}}\left(\frac{E}{E_s}\right)^{1.25}\left(\frac{V_o}{d}\right)^{1.8} \qquad \text{(S.I)} \qquad (37)$$

where

$$\frac{x}{d}=2G^{0.5} \qquad \text{for } G\geq1 \qquad (38)$$

$$\frac{x}{d}=G+1 \qquad \text{for } G<1 \qquad (39)$$

where E is modulus of elasticity of projectile and E_s is the modulus of elasticity of steel. The perforation and scabbing can be calculated by:

$$\frac{e-a}{d}=3.19\left(\frac{x}{d}\right)-0.718\left(\frac{x}{d}\right)^{2} \qquad \text{for } \frac{x}{d}\leq1.35, \qquad (40)$$

$$\frac{e-a}{d}=1.24\left(\frac{x}{d}\right)+1.32 \qquad \text{for } 1.35<\frac{x}{d}\leq13.5, \qquad (41)$$

where ***a*** is half of the aggregate size in concrete. The scabbing limit is given by:

$$\frac{h_s-a}{d}b=7.19\left(\frac{x}{d}\right)-5.06\left(\frac{x}{d}\right)^{2} \qquad \text{for } \frac{x}{d}\leq0.65, \qquad (42)$$

$$\frac{h_s-a}{d}b=1.36\left(\frac{x}{d}\right)+2.12 \qquad \text{for } 0.65<\frac{x}{d}\leq11.75, \qquad (43)$$

where $b = (E_s /E)^{0.2}$. If the projectile is made of steel, than the formula for calculation of penetration depth is identical to modified NDRC formula.

3.8 CEA – EDF Perforation Formula [21, 58]

In 1974 France, CEA and EDF started to develop reliable prediction formula on behavior of concrete structure against ballistic force under missile impact [21]. They proposed perforation limit formula based on series of drop-weight and air gun tests.

$$\frac{e}{d}=0.82\frac{M^{0.5}V_o^{0.75}}{\ell_c^{0.125}f_c^{0.375}d^{1.5}} \qquad (44)$$

where ρ_c is the unit weight of concrete equals to w/v. The velocity for ballistic limit v_p (m/s) can be calculated by using this eq:

$$V_p = 1.3\ell_c^{\frac{1}{6}} f_c^{0.5} \left(\frac{dH_o^2}{M} \right)^{\frac{2}{3}} \tag{45}$$

where H_o equals to perforation limit (e). Fullard et. Al. [22] modified this equation for non – circular missile cross – section and for reinforced concrete:

$$V_p = 1.3\ell_c^{\frac{1}{6}} f_c^{0.5} \left(\frac{pH_o^2}{\pi M} \right)^{\frac{2}{3}} \tag{46}$$

$$V_p = 1.3\ell_c^{\frac{1}{6}} f_c^{0.5} \left(\frac{pH_o^2}{\pi M} \right)^{\frac{2}{3}} (r + 0.3)^{0.5} \tag{47}$$

where H_o is considered as the total thickness of target, p is the perimeter of cross – section of missile and r is the percentage of reinforcement. This equation can generate good results close to practical within the range of $20<V_o<200$(m/s) [21].

3.9 UKAEA Formula [23, 58]

In United Kingdom Barr [23] suggested a formula for the penetration depth (x), by modification in NDRC formula based on extensive studies of protection of nuclear power plant structures. This formula deals with lower impact velocities:

$$G = \frac{180N^*M}{d\sqrt{f_c}} \left(\frac{V_o}{1000d} \right)^{1.8} \quad \text{(F.P.S)} \tag{48}$$

$$G = 3.8\times10^{-5} \frac{N^*M}{d\sqrt{f_c}} \left(\frac{V_o}{d} \right)^{1.8} \quad \text{(S.I)} \tag{49}$$

The dependence of the non-dimensional penetration depth (x) on the G – function is:

$$\frac{x}{d} = 0.275 - [0.0756 - G]^{0.5} \quad \text{for } G\leq0.0726 \tag{50}$$

$$\frac{x}{d} = [4G - 0.242]^{0.5} \quad \text{for } 0.0726\leq G\leq1.0605 \tag{51}$$

$$\frac{x}{d} = G + 0.9395 \quad \text{for } G\geq1.0605 \tag{52}$$

$$G = 0.55\left(\frac{x}{d}\right) - \left(\frac{x}{d}\right)^2 \quad \text{for } \frac{x}{d}<0.22, \tag{53}$$

$$G = \left(\frac{x}{2d}\right)^2 + 0.0605 \quad \text{for } 0.22\leq\frac{x}{d}\leq2.0, \tag{54}$$

$$G = \frac{x}{d} - 0.9395 \quad \text{for } \frac{x}{d}\geq2.0, \tag{55}$$

The parametric ranges for this formula are $25<V_o<300$(m/s), $22<f_c<44$(MPa) and $5000<M/d^3<200{,}000$(kg/m^3). Within these parametric ranges this formula can access accuracy ±20% for x/d > 0.75, and -50% to +100% for x/d < 0.75. Bar [23, 24] proposed scabbing limit:

$$\frac{h_s}{d} = 5.3G^{0.33} \tag{56}$$

The parametric ranges for this formula are $29<V_o<238$(m/s), $26<f_c<44$(MPa) and $3000<M/d^3<222{,}000$(kg/m^3). Within these parametric ranges this formula can access accuracy ±40% for $2<h_s/d<5.56$. According to CEA – EDF and Fullard [25] the perforation velocity in S.I units:

$$Vp = Va \qquad \text{for } Va \le 70 \text{ (m/s).}$$

and

$$V_p = V_a\left[1+\left(\frac{Va}{500}\right)^2\right] \qquad \text{for } Va > 70 \text{ (m/s).} \tag{57}$$

where

$$V_a = 1.3\ell_c^{\frac{1}{6}}k_c^{\frac{1}{2}}\left(\frac{pH_o^2}{\pi M}\right)^{\frac{2}{3}}(r+0.3)^{\frac{1}{2}}\left[1.2-0.6\left(\frac{c_r}{H_o}\right)\right] \tag{58}$$

where p is perimeter of the missile cross – sectional area, c_r is rebar spacing, and k_c is unconfined compressive strength of target (f_c). For f_c < 37MPa $k_c = f_c$, and for $f_c \geq$ 37MPa k_c = 37MPa. This formula can be used within the parametric range of $11<V_p<300$(m/s), $22<f_c<52$(MPa), $0<r<0.75$(%EWEF), $0.33<H_o/(p/)<5$, $150<M/(p^2H_o)<10^4$(kg/m^3), and $0.12<c_r/H_o<0.49$. For $c_r/H_o>0.49$ the last equation must be used.

Barr [23] suggests above formulae only for flat nose, for the reason that the results obtained from hemispherical nosed projectiles having diameter approximately equal to the thickness of target require 30% higher velocities to perforate reinforced concrete target as compared to the flat face projectile having same mass and diameter. Similar results were also obtained for other type of nose shape projectile such as sharp edge.

3.10 Bechtel Formula [4, 26 – 29, and 58]

This formula was suggested by Bechtel Power Corporation only for hard projectiles like solid steel slug or rod, although it also can be used with caution for hollow pipe projectiles. This formula is based on recent data of missile impact on nuclear plants. The results obtained by using this formula are closely similar results obtained by Stone and Webster formula [29].

$$\frac{h_s}{d} = \left(\frac{15.5M^{0.4}V_o^{0.5}}{f_c^{0.5}d^{1.2}}\right) \qquad \text{(F.P.S)} \tag{59}$$

$$\frac{h_s}{d} = 38.98\left(\frac{M^{0.4}V_o^{0.5}}{f_c^{0.5}d^{1.2}}\right) \qquad \text{(S.I)} \tag{60}$$

According to Sliter [29] and Bangash [4], the Bechtel formula for the scabbing limit for steel pipe missiles is:

$$\frac{h_s}{d} = \left(\frac{5.42 M^{0.4} V_o^{0.65}}{f_c^{0.5} d^{1.2}} \right) \qquad \text{(F.P.S)} \qquad (61)$$

$$\frac{h_s}{d} = 13.63 \left(\frac{M^{0.4} V_o^{0.65}}{f_c^{0.5} d^{1.2}} \right) \qquad \text{(S.I)} \qquad (62)$$

3.11 Stone and Webster Formula [29, 30, and 58]

This is non – dimensional empirical formula. This formula was suggested to calculate the scabbing limit. This formula agrees with all of the experimental results shown in [29].

$$\frac{h_s}{d} = \left(\frac{M V_o^2}{C d^3} \right)^{\frac{1}{3}} \qquad (63)$$

where C is dimensional co-efficient, and it is dependent on the ratio of target thickness to the projectile diameter (H_o/d). For H_o/d 1.5 to 3.0 C in fps system varies between 900 and 950, and in S.I system for same H_o/d ratio range C lies between 0.35 and 0.37. For C value linear relationship may be adopted in fps system $C = 33.3(H_o/d) + 850$, and in S.I systems $C = 0.013(H_o/d) + 0.33$. The parametric range of this formula is $20.7(\text{MPa}) \leq f_c \leq 31(\text{MPa})$, and $1.5 \leq h_s/d \leq 3.0$.

3.12 Degen Perforation Formula [58]

Degen suggested the formula for determination of perforation limit. This formula is based on statistical analysis of the experimental data in [21, 32 – 34]:

$$\frac{e}{d} = 1.29 \left(\frac{x}{d} \right) + 0.69 \quad \text{for } 2.65 \leq \frac{e}{d} \leq 18, \text{ or } 1.52 \leq \frac{x}{d} \leq 13.42 \qquad (64)$$

$$\frac{e}{d} = 2.2 \left(\frac{x}{d} \right) - 0.3 \left(\frac{x}{d} \right)^2 \qquad \text{for } \frac{e}{d} \leq 2.65, \text{ or } \frac{x}{d} \leq 1.52 \qquad (65)$$

where penetration depth can be determined by using modified NDRC formula. The valid ranges of the Degen perforation formula are $28.4 < f_c < 43.1$ (MPa), $25 \leq V_o \leq 311.8$(m/s), $0.15 < H_o < 0.61$(m), and $10 < d < 0.31$(m).

3.13 Chang Formula [35, 58]

Chang was the first researcher who used homogenous dimensional equations in empirical formulae. Chang suggested the formulae for perforation limit (e) and scabbing limit (h_s) for reinforced concrete targeted by flat shape ended steel cylinder:

$$\frac{e}{d} = \left(\frac{u}{V_o} \right)^{0.25} \left(\frac{M V_o^2}{f_c d^3} \right)^{0.5} \qquad (66)$$

and scabbing limit

$$\frac{h_s}{d} = 1.84\left(\frac{u}{V_o}\right)^{0.13}\left(\frac{MV_o^2}{f_c d^3}\right)^{0.4} \quad (67)$$

where u is reference velocity = 200ft/sec (61m/sec). These formulae were proposed based on a test data whose limit ranges $16 \leq V_o \leq 311.8$(m/s), $0.11 \leq M \leq 342.9$(kg), $50.8 \leq d \leq 304.8$(mm), and $22.8 \leq f_c \leq 45.5$(MPa).

3.14 Haldar and Hamieh Formula [36,58]

Haldar – Hamieh [36] suggested the use of an impact factor I_a, defined by:

$$I_a = \frac{MN^* V_o^2}{f_c d^3} \quad (68)$$

where I_a is impact factor and it is a dimensionless term, N* is the nose shape factor defined in the modified NDRC formula. For penetration depth (x):

$$\frac{x}{d} = 0.2251 I_a + 0.0308 \qquad \text{for } 0.3 \leq I_a \leq 4.0 \quad (69)$$

$$\frac{x}{d} = 0.0567 I_a + 0.6740 \qquad \text{for } 4.0 \leq I_a \leq 21 \quad (70)$$

and

$$\frac{x}{d} = 0.0299 I_a + 1.1875 \qquad \text{for } 21 \leq I_a \leq 455 \quad (71)$$

It was suggested that the scabbing limit can be calculated by using NDRC formula if $I_a < 21$, and if $I_a > 21$ than the following formula should be used:

$$\frac{h_s}{d} = 0.0342 I_a + 3.3437 \qquad \text{for } 21 \leq I_a \leq 385 \quad (72)$$

3.15 Adeli and Amin Formula [10, 58]

Adeli and amin [10] modified the impact factor (I_a) introduced by Halder and Hamieh [36] by fitting the collected data of Sliter's on penetration, scabbing and perforation:

$$\frac{x}{d} = 0.0416 + 0.1698 I_a - 0.0045 I_a^2 \qquad \text{for } 0.3 \leq I_a \leq 4 \quad (73)$$

$$\frac{x}{d} = 0.0123 + 0.196 I_a - 0.008 I_a^2 + 0.0001 I_a^3 \qquad \text{for } 4 \leq I_a \leq 21 \quad (74)$$

$$\frac{e}{d} = 1.8685 + 0.4035 I_a - 0.0114 I_a^2 \qquad \text{for } 0.3 \leq I_a \leq 21 \quad (75)$$

and

$$\frac{h_s}{d} = 0.9060 + 0.3214 I_a - 0.0106 I_a^2 \qquad \text{for } 0.3 \leq I_a \leq 21 \quad (76)$$

These formulae can be used within parametric range of $27 \leq V_o \leq 312$(m/s), $0.11 \leq M \leq 343$(kg), $0.7 \leq H_o/d \leq 18$, $d \leq 0.3$(m), and $x/d \leq 2$.

3.16 Hughes Formula [58]

Hughes assumed that by modification in assumption of NDRC formulae, the resistance offered by target material against penetration of hard missile first increases linearly, and at second stage as penetration depth increases the resistance offered by target starts decreasing parabolically:

$$\frac{x}{d} = 0.19\frac{N_h I_h}{S} \tag{77}$$

where N_h is nose shape factor which is equal to 1.0 for flat nose, 1.12 for blunt nose, 1.26 for spherical nose, and 1.39 for very sharp nose shapes, and I_h is a non-dimensional impact factor which can be obtained:

$$I_h = \frac{MV_o^2}{f_t d^3} \tag{78}$$

Hughes [37 suggested tensile strength of concrete instead of compressive strength of concrete as a resistance offered by concrete. Some of researchers account it as inappropriate approach because it seems that penetration resistance is dominated by compressive strength of concrete. However, the ratio of tensile strength of concrete to the compressive strength of concrete is normally constant. Hughes [37] also accounts influence of strain rate on tensile strength of concrete by introducing Dynamic Increase Factor (DIF) denoted by S. By using any one can find the dynamic tensile strength of concrete and dynamic compressive strength of concrete. It should be noted that dynamic strain rate effect on tensile strength concrete is should be different than the dynamic strain rate effect on compressive strength of concrete. This problem was avoided when Hughes [37] eventually obtained S through an empirical formula:

$$S = 1.0 + 12.3l_n\left(1.0 + 0.03I_h\right) \tag{79}$$

Formulae for scabbing limit and for perforation are:

$$\frac{e}{d} = 3.6\frac{x}{d} \qquad \text{for}\ \frac{x}{d} < 0.7 \tag{80}$$

$$\frac{e}{d} = 1.58\frac{x}{d} + 1.4 \qquad \text{for}\ \frac{x}{d} \geq 0.7 \tag{81}$$

$$\frac{h_s}{d} = 5.0\frac{x}{d} \qquad \text{for}\ \frac{x}{d} < 0.7 \tag{82}$$

$$\frac{h_s}{d} = 1.74\frac{x}{d} + 2.3 \qquad \text{for}\ \frac{x}{d} \geq 0.7 \tag{83}$$

The above formulae can be used if $I_h < 3500$. However, these formulae are considered conservative within $I_h < 40$, and $H_o/d < 3.50$.

3.17 Healey and Weissman Formula [58]

Healy and Weissman suggested formula for penetration depth by introducing small modification in NDRC and Kar formulae:

$$G = \frac{206.5N^{*}M}{d\sqrt{f_c}}\left(\frac{E}{E_s}\right)\left(\frac{V_o}{1000d}\right)^{1.8} \qquad \text{(F.P.S)} \qquad (84)$$

$$G = 4.36\times10^{-5}\left(\frac{E}{E_s}\right)\frac{N^{*}M}{d\sqrt{f_c}}\left(\frac{V_o}{d}\right)^{1.8} \qquad \text{(S.I)} \qquad (85)$$

Where

$$\frac{x}{d} = 2G^{0.5} \qquad \text{for } G\geq1 \qquad (86)$$

$$\frac{x}{d} = G+1 \qquad \text{for } G<1 \qquad (87)$$

3.18 IRS Formula [58]

The IRS suggested a complete set of formulae for determining penetration depth and complete design formulae for complete protection of concrete target against local impact effect of hard missiles.

$$x = 1183f_c^{-0.5} + 1038f_c^{-0.18}\exp\left(-0.82f_c^{0.18}\right) \qquad (88)$$

where x is penetration depth in cm, and f_c is in kg/cm^2. For minimum thickness of concrete wall which can avoid penetration, scabbing and perforation is:

$$SVOLL = 1250f_c^{-0.5} + 1673f_c^{-0.18}\exp(-0.82f_c^{0.18}) \qquad (89)$$

SVOLL is minimum thickness of wall. Above equations in S.I systems are:

$$x = 3703.376f_c^{-0.5} + 82.152f_c^{-0.18}\exp\left(-0.104f_c^{0.18}\right) \qquad (90)$$

$$SVOLL = 3913.119f_c^{-0.5} + 132.409f_c^{-0.18}\exp(-0.104f_c^{0.18}) \qquad (91)$$

3.19 Criepi Formula [38, 58]

Formula for penetration depth in CGS system, and in S.I systems respectively are:

$$\frac{x}{d} = \frac{0.49N^{*}Md^{0.2}\left(V_o\times10^{-6}\right)^2\left[114-1.47\left(f_c\times10^{-6}\right)\right]}{\left(f_c\times10^{-6}\right)^{\frac{2}{3}}}\left[\frac{\left(d+1.25H_r\right)H_r}{\left(d+1.25H_o\right)H_o}\right] \qquad (92)$$

$$\frac{x}{d} = \frac{0.0265N^{*}Md^{0.2}V_o^2\left[114-6.83\times10^{-4}f_c^{\frac{2}{3}}\right]}{f_c^{\frac{2}{3}}}\left[\frac{\left(d+1.25H_r\right)H_r}{\left(d+1.25H_o\right)H_o}\right] \qquad (93)$$

where H_r = 20cm (0.2m) is the reference or assumed thickness of the concrete slab. The perforation and scabbing can be obtained by non-dimensional numbers formulae:

$$\frac{e}{d} = 0.9\left(\frac{u}{V_o}\right)^{0.25}\left(\frac{MV_o^2}{d^3 f_c}\right)^{0.5} \tag{94}$$

$$\frac{h_s}{d} = 1.75\left(\frac{u}{V_o}\right)^{0.13}\left(\frac{MV_o^2}{d^3 f_c}\right)^{0.4} \tag{95}$$

3.20 UMIST Formula [39,40, 58, and 59]

In 1985, United Kingdom Nuclear Electronic (UKNE) initiated a major research program on the behavior of concrete structures against the local impact effect of hard missile by establishing the R3 Concrete Impact Working Party. Impact experiments were conducted at the Structural Test Centre (STC) at Cheddar, Roger stone Power Station, and at the Horizontal Impact Facility at Winfrith Technology Centre (WTC). A collection of empirical formulae were proposed to predict critical kinetic energies of missiles for identified local impact effects on reinforced concrete slabs [39], which were adopted in R3 Impact Assessment Procedure for nuclear facilities [40]. Because complexity of phenomena methodology employed in [39] is based on the formulation of empirical equations correlated with test results. The proposed empirical formulae for penetration depth (x) is modified form of penetration formula in [39] with consideration of nose shape effect is given by [40]:

$$\frac{x}{d} = \left(\frac{2}{\pi}\right)\frac{N^*}{0.72}\frac{MV_o^2}{\sigma_t d^3} \tag{96}$$

where the nose shape factor N is 0.72, 0.84, 1.0, and 1.13 for flat nose, hemispherical nose, blunt nose and sharp nose respectively, and the parametric range are $50 < d < 600$(mm), $35 < M < 2500$(kg), $0 < x/d < 2.5$, and $3 < V_o < 66.2$(m/sec).

$$\sigma_t(Pa) = 4.2 f_c(Pa) + 135\times10^6 + \left[0.014 f_c(Pa) + 0.45\times10^6\right]V_o \text{ (m/sec)} \tag{97}$$

This equation can be used for rate dependent characteristic strength of concrete. The critical kinetic energies of the missile causing cone cracking (E_c), Scabbing (E_s), and perforation (E_p) are given as follows:

$H_o/d < 5$: Cone cracking is most important mode of local impact phenomena; it should be considered when concrete target is subjected to store the pressurized gases or liquids. The critical kinetic energy for cone cracking can be determined by:

$$\frac{E_c}{\eta\sigma_t d^3} = -0.00031\left(\frac{H_o}{d}\right) + 0.00113\left(\frac{H_o}{d}\right)^2 \quad \text{for } 0.0\frac{H_o}{d} \le 2 \tag{98}$$

$$\frac{E_c}{\eta\sigma_t d^3} = -0.00325\left(\frac{H_o}{d}\right) + 0.0013\left(\frac{H_o}{d}\right)^3 \quad \text{for } 2 < \frac{H_o}{d} < 5 \tag{99}$$

Where the influence of nose shape factor can be neglected, the critical kinetic energy for scabbing is:

$$\frac{E_s}{\eta\sigma_t d^3}\frac{N^*}{0.72} = -0.005441\left(\frac{H_o}{d}\right) + 0.01386\left(\frac{H_o}{d}\right)^2 \tag{100}$$

Where the nose shape factor is considered as same as considered in penetration formula, the critical kinetic energy for perforation is:

$$\frac{E_p}{\eta\sigma_t d^3} = -0.00506\left(\frac{H_o}{d}\right) + 0.01506\left(\frac{H_o}{d}\right)^2 \quad \text{for } 0.0\frac{H_o}{d}\leq 1 \tag{101}$$

$$\frac{E_p}{\eta\sigma_t d^3} = -0.01\left(\frac{H_o}{d}\right) + 0.02\left(\frac{H_o}{d}\right)^3 \quad \text{for } 1\leq\frac{H_o}{d}<5 \tag{102}$$

It was noted that the above equations are valid for $H_o/d \geq 0.40$, and $H_o/d \geq 0.34$ respectively. The R 3 Impact Assessment Procedure [40] also warns about test data from which these formulae were derived have minimum H_o/d value of 0.5, and where assessments are required for $H_o/d \leq 0.5$ the derived critical energies must be treated with caution. The nose shape effect on perforation cannot be neglected. The experimental results of hemispherical nose shape missile with approximately equal diameter to the thickness of concrete strengthen this statement in UKAEA formula [23], also the experimental data of conical nosed missiles indicates that higher velocities are required for perforation of reinforced concrete target approximately 15%, and 11% for $H_o/d \approx 1.0$, and for $H_o/d \approx 0.60$ respectively [40].

$H_o/d \geq 5$:

$$\frac{E_c}{\sigma_t d^3} = \frac{\pi}{4}\left[\left(\frac{H_o}{d}\right) - 4.7\right] \tag{103}$$

$$\frac{E_s}{\sigma_t d^3}\frac{N^*}{0.72} = \frac{\pi}{4}\left[\left(\frac{H_o}{d}\right) - 4.3\right] \tag{104}$$

and

$$\frac{E_p}{\sigma_t d^3}\frac{N^*}{0.72} = \frac{\pi}{4}\left[\left(\frac{H_o}{d}\right) - 3.0\right] \tag{105}$$

$$\eta = \frac{3}{8}\left(\frac{d}{C_r}\right)r_t + 0.5 \quad \text{if } \left(\frac{d}{C_r} < \sqrt{\frac{d}{d_r}}\right) \tag{106}$$

$$\eta = \frac{3}{8}\left(\sqrt{\frac{d}{d_r}}\right)r_t + 0.5 \quad \text{if } \left(\frac{d}{C_r} \geq \sqrt{\frac{d}{d_r}}\right) \tag{107}$$

where d is the diameter of the projectile, d_r is the diameter of the reinforcing steel bar, C_r is the rebar spacing and r_t is the total bending reinforcement ($r_t = 4r$ with r being % EWEF, defined as $r = \pi d_r^2 / 4H_o C_r$, where H_o is the thickness of the concrete target). The scabbing and perforation models are applicable for 22<d<600(mm), 1<M<2622(kg), 0<V_o<427(m/s), 19.9<f_c<78.5(MPa), 0<r<4(% EWEF) and 50.8<H_o<640(mm).

Q.M. Li, S.R. Reid and A.M Ahmad Zaidi (2006) [59] further modified the UMIST formulae in terms of critical energies required to scabb and perforate the concrete targets for flat nose hard missile impact. According to them critical impact energy for scabbing is:

$$\frac{E_{cs}}{f_c d^3} = \frac{1}{2}\frac{\sigma_t}{f_c}\left[-0.005441\frac{H}{d} + 0.01386\left(\frac{H}{d}\right)^2\right] \qquad \text{for } \frac{H}{d} \le 5 \qquad (108)$$

$$\frac{E_{cs}}{f_c d^3} = \frac{\pi}{4}\frac{\sigma_t}{f_c}\left[\left(\frac{H}{d}\right) - 4.3\right] \qquad \text{for } \frac{H}{d} > 5 \qquad (109)$$

The critical impact energy for perforation is:

$$\frac{E_{cp}}{f_c d^3} = \frac{1}{2}\frac{\sigma_t}{f_c}\left[-0.00506\frac{H}{d} + 0.01506\left(\frac{H}{d}\right)^2\right] \qquad \text{for } \frac{H}{d} \le 1 \qquad (110)$$

$$\frac{E_{cp}}{f_c d^3} = \frac{1}{2}\frac{\sigma_t}{f_c}\left[-0.01\frac{H}{d} + 0.02\left(\frac{H}{d}\right)^3\right] \qquad \text{for } 1 < \frac{H}{d} \le 1 \qquad (111)$$

$$\frac{E_{cp}}{f_c d^3} = \frac{\pi}{4}\frac{\sigma_t}{f_c}\left[\left(\frac{H}{d}\right) - 3.0\right] \qquad \text{for } \frac{H}{d} > 5 \qquad (112)$$

3.21 Semi Empirical/Analytical Formula [58, 59]

As it is clear that approximately all empirical formulae for determination of scabbing, and perforation both are dependent of penetration depth, so it is necessary to predict penetration depth with greater accuracy. Li and Chen [43] further develop Forrestal et al.'s [44] model and proposed semi – empirical or semi – analytical formulae for the penetration depth (x). The formulae are in dimensional homogenous form, and defines nose shape factor analytically. These formulae are applicable for wide range of penetration depth:

$$\frac{x}{d} = \sqrt{\frac{\left(1 + \left(k\pi/4N\right)\right)}{1 + \left(I/N\right)}\frac{4kI}{\pi}} \qquad \text{for } \frac{x}{d} \le 5 \qquad (113)$$

$$\frac{x}{d} = \frac{2}{\pi}N\ln\left[\frac{1 + \left(I/N\right)}{1 + \left(k\pi/4N\right)}\right] + k \qquad \text{for } \frac{x}{d} > 5 \qquad (114)$$

where

$$I = \frac{I^*}{S} = \frac{1}{S}\left(\frac{MV_o^2}{f_c d^3}\right) \qquad (115)$$

$$N = \frac{\lambda}{N^*} = \frac{1}{N^*}\left(\frac{M}{\ell_c d^3}\right) \qquad (116)$$

where N, I, and N* are the impact function and the geometry function and nose shape factor respectively. S is an empirical function of f_c (MPa) and is given by:

$$S = 72 f_c^{-0.5} \tag{117}$$

The above equations are applicable for x/d ≥ 0.5, and reduced the results obtained by Forrestal et al. [45] for an ogive – nose projectile. Forrestal et al. [44, 45], and Frew et al. [55] suggested that if x/d ≥ 5.0 than k = 2.0, this statement is strengthened by the instrumented experiments in [56], and with penetration experiments with wide range of projectile diameter [57]. And Li and Chen [43] recommended x/d < 5.0, for small – to – medium penetration depths:

$$k = \left(0.707 + \frac{h}{d}\right) \tag{118}$$

where h is the length of nose of the projectile, In the case of shallow penetrations when x/d < 0.5, the penetration depth is given by:

$$\frac{x}{d} = 1.628\left(\frac{\left(1 + \left(k\pi/4N\right)\right)}{1 + \left(I/N\right)}\frac{4kI}{\pi}\right)^{1.395} \tag{119}$$

where k can be determined by above given equation for small and medium penetration depths. If N » 1 for this condition the above given equations at first can be simplified to [43]:

$$\frac{x}{d} = \sqrt{\frac{4kI/\pi}{1 + \left(I/N\right)}} \qquad \text{for } \frac{x}{d} \leq \text{k} \tag{120}$$

$$\frac{x}{d} = \frac{2}{\pi} N \ln\left(1 + \frac{I}{N}\right) + \frac{k}{2} \qquad \text{for } \frac{x}{d} > \text{k} \tag{121}$$

and the resultant form of both equations is:

$$\frac{x}{d} = 1.628\left(\frac{\frac{4kI}{\pi}}{1 + \left(I/N\right)}\right)^{1.395} \tag{122}$$

When I/N « 1, which is not uncommon in penetration problems:

$$\frac{x}{d} = \sqrt{\frac{4kI}{\pi}} \qquad \text{for } \frac{x}{d} \leq \text{k} \tag{123}$$

$$\frac{x}{d} = \frac{k}{2} + \frac{2I}{\pi} \qquad \text{for } \frac{x}{d} > \text{k} \tag{124}$$

Chen and Li [48] recommended a simplified formula of x/d = 0.5(I), to predict the penetration depth for deep penetration. The correspondence form of above both equations:

$$\frac{x}{d} = 1.628\left(\frac{4k}{\pi}I\right)^{1.395} \tag{125}$$

Q.M. Li, S.R. Reid and A.M Ahmad Zaidi (2006) [59] further modified this formula in terms of critical energies required to scabb and perforate the concrete targets for flat nose hard missile impact. According to them impact function in terms of kinetic energy is:

$$I = \frac{2}{S}\left(\frac{E_k}{f_c d^3}\right) \tag{126}$$

The critical impact energy for the occurrence of scabbing is:

$$\frac{E_{cs}}{f_c d^3} = 0.196S\left[0.782 - \sqrt{0.611 - 0.198\left(\frac{H}{d}\right)}\right]^2 \quad \text{for } \frac{H}{d} \le 3.0, \tag{127}$$

$$\frac{E_{cs}}{f_c d^3} = 0.106S\left[\frac{H}{d} - 2.12\right]^2 \quad \text{for } 3.0 < \frac{H}{d} \le 4.84, \tag{128}$$

$$\frac{E_{cs}}{f_c d^3} = 0.577S\left[\frac{H}{d} - 3.48\right] \quad \text{for } 4.84 < \frac{H}{d} < 18.0, \tag{129}$$

and the critical impact energy for perforation

$$\frac{E_{cp}}{f_c d^3} = 0.196S\left[2.222 - \sqrt{4.935 - 1.393\left(\frac{H}{d}\right)}\right]^2 \quad \text{for } \frac{H}{d} \le 3.0, \tag{130}$$

$$\frac{E_{cp}}{f_c d^3} = 0.128S\left[\frac{H}{d} - 1.32\right]^2 \quad \text{for } 3.0 < \frac{H}{d} \le 3.80, \tag{131}$$

$$\frac{E_{cp}}{f_c d^3} = 0.633S\left[\frac{H}{d} - 2.56\right] \quad \text{for } 3.80 < \frac{H}{d} \le 18.0, \tag{132}$$

4.0 COMPARISON OF EMPIRICAL FORMULAE, AND RECOMMENDATIONS

The local impact effects on concrete structures phenomenon depends upon physical parameters such as density of both projectile and target, Impact velocity, hardness of projectile, and compressive and tensile strength of concrete target, shape and size of projectile, reinforcement of target, size and shape of aggregate used in concrete target, etc.

About drawbacks of empirical formulae, the first and far most is as it is stated by all most all researchers that the guarantee of empirical formulae are given only for that test results, from which the empirical formulae derived. If we talk about projectile, the classification of hard projectile is another issue; some researchers mention that it is depend on hardness or density of both the projectile and target, with consideration of velocity. However many researchers classify the hard projectile by only the velocity range. And some empirical formulae such as Whiffen Formula [18, 19] is for small fragments from many type of bombs, as it is clear that the these conditions happens only in ballistic or explosive studies which is rather different than the local impact phenomenon of hard projectile, and also the same projectile classification creates very confusion situation. In Whiffen study the small fragments are considered as hard missile as together with missile, which is very confused as in terms of classification of hard projectile.

About target as this paper reviews about only the local impact phenomenon caused by hard projectile on concrete structures, so we are focusing on concrete targets only either plain concrete or reinforced concrete. Because of dynamicity the behavior of concrete structure against hard missile local impact effect is very difficult to predict very close to the practical one, because concrete behavior changes dynamically as the local impact processes takes place, target changes its behavior rapidly by dramatic increase in strain. As it is depend on the strength of concrete, and the strength of concrete is depends on material shape size and texture of aggregates and mixing of aggregates. Most of the empirical studies didn't consider the behavior of concrete. For example: size, shape and textural behavior of aggregates used in concrete. And in reinforced concrete the reinforcement of concrete, for example type of reinforced bar pattern of reinforcement, and the reinforced concrete should be considered as doubly reinforced concrete, because in normal construction mostly we use reinforced concrete as doubly reinforced.

As the first review of this study given by Kennedy [1], if we compare the results obtained by using different empirical formulae considering typical missile within the range of velocities up to 300m/sec, the NDRC formula gives the close results with practical results among all others formulae, as the each empirical formulae based on experimental data and its validity guaranteed only within its test range.

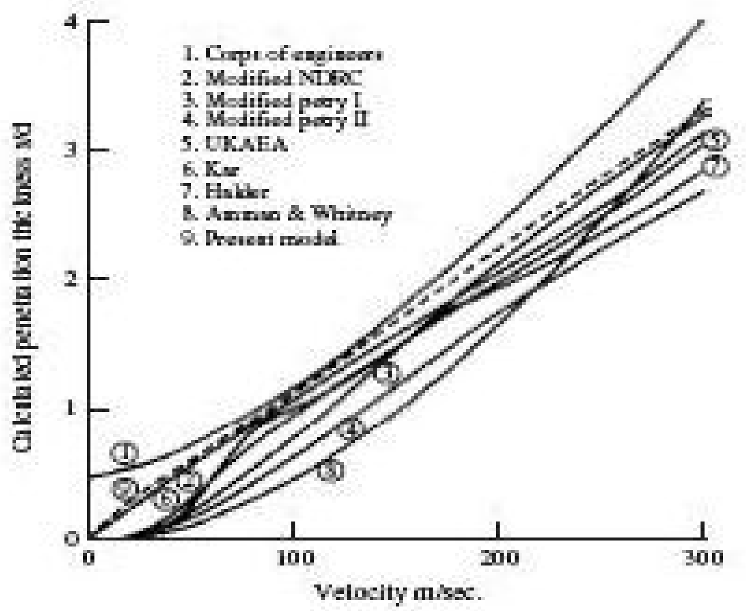

Figure.3 shows the comparison between various empirical penetration formulae [50].

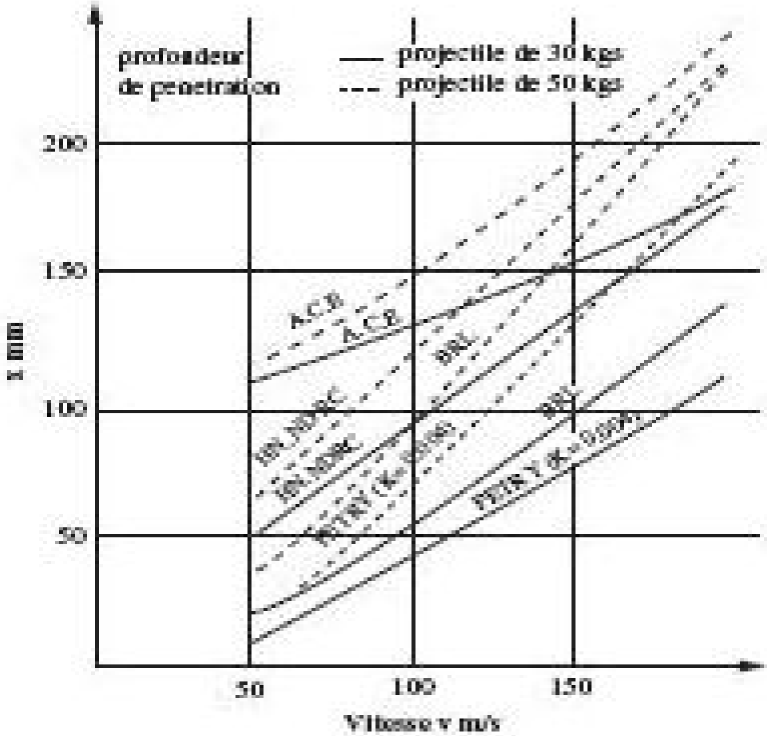

Figure 4. Shows the comparison of various empirical formulae for penetration depth (x), [21].

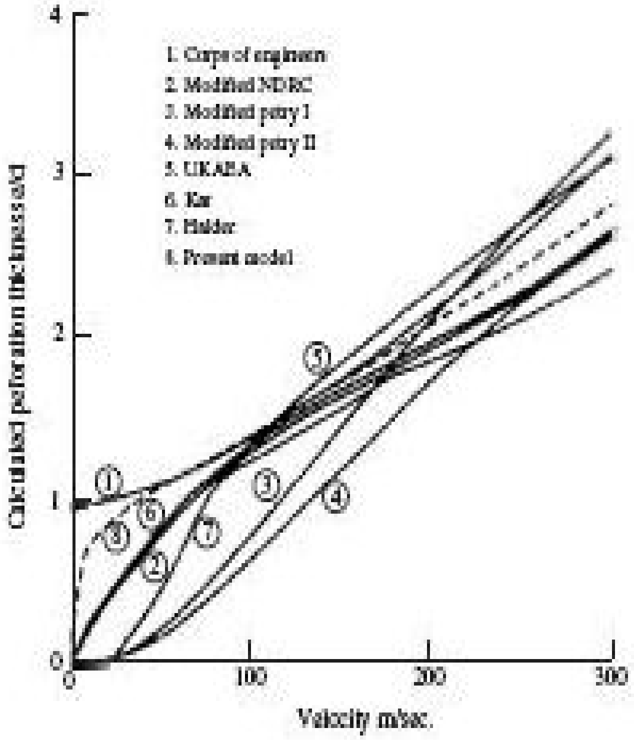

Figure 5. Shows the comparison of various empirical formulae for perforation depth (e), [50].

5.0 CONCLUSION

In this paper the local impact effects of a hard projectile on concrete targets have been discussed. The paper consists of empirical formulae studies on local impact phenomenon. Empirical formulae on penetration depth, perforation and scabbing limits, with their required critical impact kinetic energy as well as their ranges of application, have been given in both Imperial and SI units with modification of nose shape factor. The NDRC formula, one of the most representative empirical formulae for penetration depth, and it has been justified based on a semi-analytical penetration model.

6.0 REFERENCES

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