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Reliability of underground concrete barriers against normal missile impact

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Abstract. In the present paper, a methodology has been presented for the reliability assessment of concrete barriers that lie at a certain depth in the soil, and a missile (a rigid projectile) impacts the top of the soil cover normally, and subsequently after penetrating the soil cover completely it hits the barrier with certain striking velocity. For this purpose, using expressions available in the literature, striking velocity of missile at any depth of soil has been derived and then expressions for the depths of penetration in crater and tunnel region of concrete barrier have been deduced. These depths of penetration have been employed for the derivation of limit state functions. Using the derived limit state functions reliability assessment of underground concrete barrier has then been carried out through First Order Reliability Method (FORM). To study the influence of various random variables on barrier reliability, sensitivity analysis has also been carried out. In addition, a number of parametric studies is conducted to obtain the results of practical interest.

Key words: missile penetration; projectiles; concrete barriers; structural reliability; FORM.

1. Introduction

The ongoing arms race has involved almost every country to excel in this competition. The stir compels them to conduct scientific research in development of heavy arms, particularly missiles, and to achieve a sheer degree of perfection in studying the impact of these missiles upon different type of targets, specially with regard to soil and concrete which are used as a cover for many strategic structures like bunkers, Nuclear Power Plant (NPP) etc., as safety of these structures always remain the main issue. The absolute safety of these structures always depends on the degree of perfection achieved during the estimation of damages (e.g., penetration) made in these targets due to missile impact. In the past, Forrstal and Luk (1992), Siddiqui and Abbas (2002), Siddiqui *et al.* (2006) studied mechanics of missile penetration in soil targets and Forrestal *et al.* (1994, 1996, 2003), Frew *et al.* (1998, 2006), Khan *et al.* (2003) penetration in concrete targets. They determined expressions for depths of penetration and verified the analytical results with experimental findings.

Reliability of any target is nothing but its chances to survive under a possible missile impact. If a

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missile is considered as a rigid projectile with no warhead and target as an underground concrete barrier then the damage of the target may be measured by its depth of penetration caused by the impacting missile into the target. In deterministic sense, if the estimated depth of penetration is small compared to its thickness then the target may be considered as safe or reliable. However, this safety is not an absolute safety but a "probable safety". It is "probable safety" because all material and geometric properties have some inherent variability, which makes determination of absolute safety almost impossible. The effort can only be made to design a target with a desired reliability under a given range of missile impact. In the recent past, Choudhary *et al.* (2002), Siddqui *et al.* (2002, 2003) and Siddiqui (2003) carried out reliability assessment of different types of target under missiles, projectiles or jet aircraft impacts.

A detailed review of literature shows that although considerable work is available on mechanics of missile penetration into soil and concrete targets, but the studies on reliability assessment of underground concrete targets is very scanty. Further, the available work e.g. work of Chaoudhury *et al.* (2002), Siddiqui *et al.* (2002) is on such concrete targets, which are buried under the rock. No work, however, could be seen on reliability assessment of such concrete barriers that are buried under the soil and hit by a missile after penetrating the soil cover completely. Keeping this point in view, in the present study, a methodology has been presented for the reliability assessment of concrete barriers that lie at a certain depth in the soil, and a missile (a rigid projectile) impacts the top of the soil cover normally, and, subsequently after penetrating the soil cover completely it hits the concrete barrier with certain striking velocity. For this purpose, using expressions available in the literature, striking velocity of missile at any depth of soil has been derived and then expressions for the depths of penetration in crater and tunnel region of concrete barrier have been deduced. These depths of penetration have been employed for the derivation of limit state functions. Using the derived limit state functions reliability assessment of underground concrete barrier has then been carried out through First Order Reliability Method (Nowak and Collins 2000). To study the influence of various random variables on barrier reliability, sensitivity analysis has also been carried out. In addition, a number of parametric studies is conducted to obtain the results of practical interest.

2. Problem formulation

The reliability assessment of underground concrete barrier is concerned with the calculation and prediction of its probability of survival in the event of missile impact followed by its penetration. In the present study, an underground concrete barrier is assumed as failed if missile completely penetrates the concrete thickness. This is due to the fact that things of importance are kept under these barriers, and missile can cause considerable damage to them only if it penetrates the concrete barrier completely. To derive limit state functions under above criterion of failure first expressions for depths of penetration in concrete barrier due to missile impact are required. In the present study, these depths of penetration have been derived under the following assumptions and idealizations:

i. The missile is rigid i.e., deformation of missile is negligible and only soil and concrete deformations have been considered.
ii. Missile is considered to be of ogival nose shape.
iii. Impact of missile is normal and axi-symmetric.
iv. The missile does not carry any warhead and so no explosion has been considered.
v. The rear face scabbing of concrete target, due to missile penetration, is negligible.

In the present study we are concerned with the reliability analysis of buried concrete target which is considered failed if missile penetrates it completely. Hence, conditions that lead to a higher depth of barrier penetration will be conservative estimate for reliability calculations. Assumption (i) and (iii) provide higher depths of penetration than if missile deforms or impacts the target at a certain angle other than normal (i.e., oblique impact).

For most of the targets ogival nose shape missile penetrates more than conical nose shape missile, hence, assumption (ii) is also on a conservative side (Siddiqui and Abbas 2002).

Missile carrying warhead destroy the things behind the concrete barrier in two stages: first it fully penetrates the concrete barrier and then it explodes its warhead to destroy everything behind the barrier. If the missile fails to penetrate the barrier, the destruction behind the concrete barrier may not be significant. It is due to this reason, in the assumption (iv) explosion of the warhead is neglected and penetration of concrete barrier has been considered as the failure of concrete barrier.

As subject of the present study is related to the concrete barrier's penetration, rear face scabbing is ignored in the assumption (v).

Under above assumptions and idealizations, when a missile impacts a uniform soil target at normal incidence (Fig. 1a) with an initial velocity V_o, and proceeds through the soil cover with a velocity V_z at any depth z, its nose experiences an axial force F_Z. Forrestal and Luk (1992) have developed following expression for this axial force F_z as

$$F_z = \alpha_s + \beta_s V_z^2 \tag{1}$$

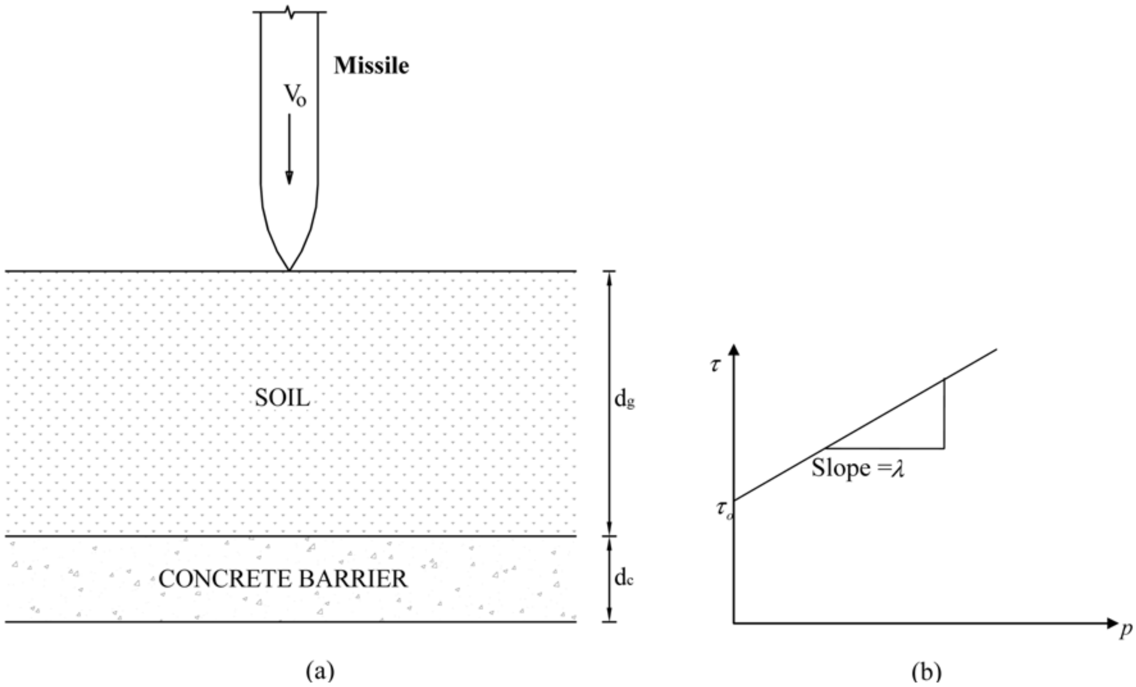

Fig. 1 Problem formulation

where,

$$\alpha_s = \pi a^2 \tau_o A\left[1+4\mu\psi\left(\frac{\pi}{2}-\theta_0\right)-\mu(2\psi-1)(4\psi-1)^{1/2}\right] \tag{2}$$

$$\beta_s = \pi a^2 \rho_o B\left[\frac{(8\psi-1)}{24\psi}+\mu\psi^2\left(\frac{\pi}{2}-\theta_o\right)-\frac{\mu(2\psi-1)(6\psi^2+4\psi-1)(4\psi-1)^{1/2}}{24\psi^2}\right] \tag{3}$$

$$\theta_0 = Sin^{-1}\left(\frac{2\psi-1}{2\psi}\right) \tag{4}$$

$$A = \frac{1}{\alpha}\left(\frac{1+\tau_o/2E}{\gamma}\right)^{2\alpha}-\frac{1}{\lambda} \tag{5}$$

$$B = \frac{3}{(1-\eta^*)(1-2\alpha)(2-\alpha)}+\frac{1}{\gamma^2}+\left(\frac{1+\tau_o/2E}{\gamma}\right)^{2\alpha}\times$$

$$\left\{\frac{3\tau_o}{E}+\eta^*(1-3\tau_o/2E)^2-\frac{\gamma^3[2(1-\eta^*)(2-\alpha)+3\gamma^3]}{(1-\eta^*)(1-2\alpha)(2-\alpha)\left(1+\frac{\tau_o}{2E}\right)^4}\right\} \tag{6}$$

a = missile shank radius;
λ, τ_o = define the yield condition (Fig. 1b)

$$\alpha = \frac{3\lambda}{(2+2\lambda)} \tag{7}$$

$$\gamma = \left[\left(1+\frac{\tau_o}{2E}\right)^3+(1-\eta^*)\right]^{1/3} \tag{8}$$

E = Young's modulus of elasticity of soil;
η^* = volumetric strain;
ρ_o = initial density of soil;
μ = coefficient of friction; and
ψ = Caliber Radius Head (CRH). CRH is defined as ratio of radius of missile nose to the diameter of missile aft body.

From Newton's second law the equation for rigid body motion of the missile with mass m is given as

$$m\frac{dV_z}{dt} = -(\alpha_s+\beta_s V_z^2) \tag{9}$$

Integration of Eq. (9) with the initial condition $V = V_o$ gives, velocity, acceleration and depth of penetration at any time t as

$$V_z = \left(\frac{\alpha_s}{\beta_s}\right)^{1/2}\tan\left\{\tan^{-1}\left[\left(\frac{\beta_s}{\alpha_s}\right)^{1/2}V_o\right]-\frac{(\alpha_s\beta_s)^{1/2}t}{m}\right\} \tag{10}$$

$$\frac{dVz}{dt} = -\frac{(\alpha_s/m)}{Cos^2\left\{\tan^{-1}\left(\frac{\beta_s}{\alpha_s}\right)^{1/2} V_o - \frac{(\alpha_s\beta_s)^{1/2}}{m}t\right\}} \tag{11}$$

$$z = \frac{m}{\beta_s}\ln\left[\frac{Cos\left\{\tan^{-1}\left[\left(\frac{\beta_s}{\alpha_s}\right)^{1/2}V_o\right] - (\alpha_s\beta_s)^{1/2}t/m\right\}}{Cos\left\{\tan^{-1}\left[\left(\frac{\beta_s}{\alpha_s}\right)^{1/2}V_o\right]\right\}}\right] \tag{12}$$

After rearranging Eq. (12), we get the expression for time t in terms of z as

$$t = \frac{m}{(\alpha_s\beta_s)^{1/2}}\left[A' - Cos^{-1}\left\{CosA' \times \exp^{\left(z\frac{\beta_s}{m}\right)}\right\}\right] \tag{13}$$

where
$$A' = \tan^{-1}\left[\left(\frac{\beta_s}{\alpha_s}\right)^{1/2}V_o\right] \tag{13a}$$

Substituting the value of t from Eq. (13) into Eq. (10) we get another expression of V_z as a function of penetration depth z as,

$$V_s = \left(\frac{\alpha_s}{\beta_s}\right)^{1/2}\tan\left\{Cos^{-1}\left(CosA' \times \exp^{\left(z\frac{\beta_s}{m}\right)}\right)\right\} \tag{14}$$

$$V_z = \left(\frac{\alpha_s}{\beta_s}\right)^{1/2}\tan B' \tag{15}$$

where $B' = Cos^{-1}\left(CosA' \times \exp^{\left(z\frac{\beta_s}{m}\right)}\right)$ (16)

When a missile hits the concrete barrier, lying at a depth of z in soil, with a striking velocity V_z it creates a conical shaped *crater region* with depth about two missile shank diameter i.e., $4a$, followed by a circular cylinder shaped *tunnel region* with diameter nearly equal to the shank diameter i.e., $2a$, (Forrestal *et al.* 1994, 1996). The depths of penetration in crater region z_{sc} and tunnel region z_{ft} from the concrete surface can be expressed as

$$z_{SC} = \left(\frac{V_z}{\omega}\right)\sin\omega t \tag{17}$$

in which,
$$\omega = \sqrt{\frac{c}{m}} \tag{18}$$

and
$$c = \frac{\pi a(Sf_c + N\rho_c v_c^2)}{4} \tag{19}$$

where,

S = a parameter (Frew *et al.* 1998);

f_c = unconfined compressive strength of concrete;
N = dimensionless constant that depends on missile caliber radius head ψ

$$= \frac{8\psi - 1}{24\psi^2} \tag{20}$$

ρ_c = density of concrete target; and
V_c = rigid body missile velocity at $z_{sc} = 4a$, it is given by

$$= \sqrt{\frac{m v_z^2 - 4\pi a^3 S f_c}{m + 4\pi a^3 N \rho_c}} \tag{21}$$

Substituting expression of V_z from Eq. (14) in the above equation we get

$$V_c = \sqrt{\frac{m\left(\frac{\alpha_s}{\beta_s}\right)\tan^2 B' - 4\pi a^3 S f_c}{m + 4\pi a^3 N \rho_c}} \tag{22}$$

Putting this value of V_c of Eq. (22) in Eq. (19), we get c as

$$c = \frac{\pi a}{4}\left[S f_c + N \rho_c \left\{ \frac{m\left(\frac{\alpha_s}{\rho_s}\right)\tan^2 B' - 4\pi a^3 S f_c}{m + 4\pi^3 N f_c} \right\} \right] \tag{23}$$

Putting this value of c from Eq. (23) in Eq. (18) we get

$$\omega = \frac{1}{2}\sqrt{\frac{\pi a}{m}\left[S f_c + N \rho_c \left\{ \frac{m\left(\frac{\alpha_s}{\beta_s}\right)\tan^2 \beta' - 4\pi a^3 S f_c}{m + 4\pi a^3 N \rho_c} \right\} \right]} \tag{24}$$

Substituting Eq. (24) for ω and Eq. (13) for t into Eq. (17) we have

$$z_{SC} = \left(\frac{\alpha_s}{\beta_s}\right)^{1/2} \tan B' \times 2 \sqrt{\frac{m}{\pi a [S_{fc} + N \rho_c \times K']}} \times$$

$$Sin\left[\left\{ \frac{1}{2}\sqrt{\frac{\pi a}{m}(S f_c + N \rho_c \times K')} \right\} \times \frac{m}{(\alpha_s \beta_s)^{1/2}} (A' - B') \right] \tag{25}$$

where,
$$K' = \frac{m\left(\frac{\alpha_s}{\beta_s}\right)\tan^2 B - 4\pi a^3 S f_c}{m + 4\pi a^3 N \rho_c} \tag{26}$$

If the depth of concrete target is d_c, then the limit state function (or safety margin) $g(\underline{X})$ can be written as

$$g(\underline{X}) = d_c - z_{SC} \tag{27}$$

Substituting z_{sc} from Eq. (25) we have

$$g(\underline{X}) = dc - \left[2\tan B'\sqrt{\frac{m\alpha_s}{\pi a[Sf_c + N\rho_c \times K]\beta_s}} \times Sin\left\{\frac{1}{2}\sqrt{\frac{\pi a}{m}}(Sf + N\rho_c \times K) \times \frac{m}{(\alpha_s\beta_s)^{1/2}}(A' - B')\right\}\right] \quad (28)$$

where $(\underline{X})$ denotes the vector of random variables given by

$$\underline{X} = (m, a, \eta^*, V_0, \lambda, d_g, \rho_c, S, f_c, d_c, E, \psi, \mu, \rho_0) \quad (29)$$

where, d_g = z = depth of soil above the concrete surface (Fig. 1a).

The final depth of penetration in the crater region is that where the missile velocity becomes zero subject to a maximum depth of 4*a*. It is due to the fact that beyond 4*a* the tunnel region begins and the depth of penetration in this tunnel region can be expressed as (Forrestal *et al.* 1994, Choudhury *et al.* 2002, Siddqui 2003)

$$z_{ft} = \frac{m}{2\pi a^2 \rho_c N}\ln\left(1 + \frac{N\rho_c V_c^2}{Sf_c}\right) + 4a \quad (30)$$

Putting the value of V_c from Eq. (22) in the above equation we get

$$z_{ft} = \frac{m}{2\pi a^2 \rho_c N}\ln\left(1 + \frac{N\rho_c}{Sf_c}\left\{\frac{m\left(\frac{\alpha_s}{\beta_s}\right)\tan^2 B' - 4\pi a^3 Sf_c}{m + 4\pi a^3 N\rho_c}\right\}\right) + 4a \quad (31)$$

The limit state function $g(\underline{X})$ for this region, measured from the concrete surface therefore, can be expressed as

$$g(\underline{X}) = d_c - z_{ft} \quad (32)$$

Substituting the expression of z_{ft} from Eq. (31) in Eq. (32) we get limit state function for tunnel region as

$$g(\underline{X}) = d_c - \left[\frac{m}{2\pi a^2 \rho_c N}\ln\left[1 + \frac{N\rho_c}{Sf_c}\left\{\frac{m\left(\frac{\alpha_s}{\beta_s}\right)\tan^2 B' - 4\pi a^3 Sf_c}{m + 4\pi a^3 N\rho_c}\right\}\right] + 4a\right] \quad (33)$$

Where, $(\underline{X})$ denotes the same vector of random variable as given by Eq. (29).

As we are having two limits state functions, one for crater region and other for tunnel region, to incorporate appropriate limit state function for reliability calculations, first we assume that missile is lying in crater region and with this assumption we compute crater depth z_{sc}. If this crater depth is less than the 4*a*, limit state function given by Eq.(28) is used otherwise Eq.(33) is employed for reliability calculations.

3. Numerical study

For numerical study, a solid missile of Siddiqui *et al.* (2002) has been chosen. This missile has its mass 182 kg; shank radius 0.0825 m and impact velocity 411 m/s. Other statistical data that are needed for reliability assessment have been presented in Table 1. With these statistical data and

Table 1 Statistical data and random variables

Random variables	Distribution	Mean	COV	Reference#
Shear strength of soil, τ_o	Normal	10.0 N/mm^2	0.15	[1]
Coefficient of friction, μ	Normal	0.085	0.10	Assumed
Depth of soil cover, d_g	Normal	10.0 m	0.05	Assumed
Modulus of elasticity of soil, E	Normal	160 MPa	0.15	[1]
Slope of shear strength-pressure curve, λ	Normal	0.375	0.10	[1]
Volumetric strain, η^*	Normal	0.13	0.10	[1]
Density of concrete target, ρ_c	Lognormal	2.0×10^4	0.10	[2]
Unconfined comp strength of concrete, f_c	Lognormal	40 MPa	0.10	[2]
Thickness of concrete target, d_c	Normal	1.2 m	0.05	Assumed
Dimensionless parameter, S	Normal	11.26	0.15	[2]
Shank radius, a	Normal	0.165/2.0 m	0.05	[3]
Caliber radius head, ψ	Normal	9.25	0.05	[3]
Missile impact velocity, V_o	Extreme type I	411.0 m/s	0.10	[3]
Mass of the missile, m	Lognormal	182.0 kg	0.05	[3]

#[1]: Forrestal and Luk (1992); [2]: Choudhury *et al.* (2002); [3]: Siddiqui *et al.* (2002)

using limit state functions (Eqs. 28, 33) reliability of underground concrete barrier has been evaluated. For this purpose, First Order Reliability Method (Nowak and Collins 2000) has been employed.

4. Discussion of results

Table 2 presents the result of reliability analysis. The analysis gives reliability index (β) of underground concrete barrier as 1.57 and its corresponding probability of failure (P_f) as 5.85×10^{-2}. These values show that the underground concrete barrier is not as reliable as generally desired for structures of importance. This is due to the fact that in probabilistic design of important strategic structures, reliability index (β) is never chosen less than 3 (Siddiqui *et al.* 2003). There are number of ways to improve above β from 1.57 to a desirable range e.g., by increasing concrete thickness; concrete compressive strength; increasing shear strength of soil (by specifying compaction); constructing concrete barrier deeper in soil etc.

It is to be noted that the desirable range shown in Table 2 is chosen to cover a range which is generally desired to insure safety of most of the civil engineering structures of importance (Siddiqui 2003, Siddiqui *et al.* 2003, Khan *et al.* 2006). However, in practice these values for any structure are to be decided on the basis of extensive calibration studies; the consideration of cost issues and the consequences of failure etc.

Table 2 Results of the analysis

Estimated Parameter	Present Concrete barrier	Desirable range
Probability of failure, P_f	5.85×10^{-2}	10^{-3}-10^{-5}
Reliability index, β	1.57	3-4

4.1. Sensitivity analysis

Sensitivity analysis has been carried out to study the influence of various random variables on concrete reliability. This influence is measured in terms of sensitivity factor (α_j), which for the jth random variable is defined as (Nowak and Collins 2000)

$$\alpha_j = \left.\frac{\partial\beta}{\partial y_j}\right|_{\underline{y}^*} = \frac{y_j^*}{\beta} \tag{34}$$

in which $\underline{y}^*$ is a point, known as most probable point (MPP) or design point and y_j^* is the value of the jth random variable at this point. Design point is obtained after minimizing the following constrained optimization problem

$$\beta(\underline{y}) = (\underline{y}^T\underline{y})^{1/2} \text{ subject to } G(\underline{y}) = 0 \tag{35}$$

where, $\underline{y}$ is the vector of basic random variables in standard normal space; and $G(\underline{y})$ is the limit state function in reduced coordinate system.

In the present study, using above expressions, sensitivity factor for all random variables has been determined and shown graphically in Fig. 2. The magnitude of this factor for a random variable is measure of its influence on concrete reliability and the sign determines its nature i.e., if sensitivity factor is positive its increase will decrease the reliability and if it is negative its increase will increase the reliability. However, this factor is not a direct measure of percentage contribution to reliability because instead of being

$\sum_{j=1}^{n} \alpha_j = 1$ it is $\sum_{j=1}^{n} \alpha_j^2 = 1$.

Fig. 2 shows that sensitivity factor for missile mass, caliber radius head (CRH) and impact velocity are positive which indicates that increase in the magnitude of these variables will decrease the concrete barrier reliability. Other random variables are negative which show that increase in their magnitude will increase the reliability of underground concrete barrier. Further, Fig. 2 points out that the

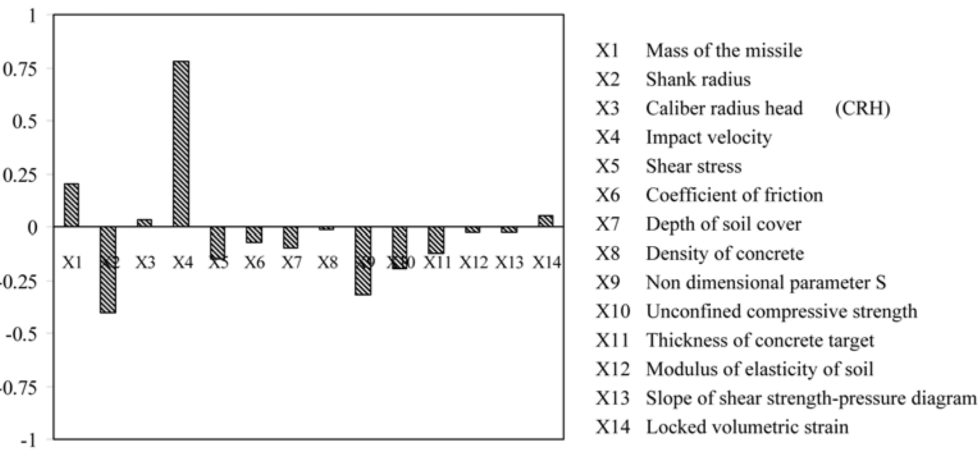

Fig. 2 Sensitivity diagram

missile impact velocity is the most influencing positive variable and shank radius is the most influencing negative variable. This is due to the fact that as the velocity of missile increases its penetrating energy increases rapidly whereas with the shank radius of missile resistance offered by soil (or concrete) to missile penetration increases sharply.

4.2. Parametric study

In the present study, following parametric studies have been conducted to obtain the results of practical interest. The range that has been taken for all the parameters is $\pm 3\sigma$ from their respective means.

4.2.1. Effect of shear strength of soil

Fig. 3 shows that as the shear strength of soil are increasing, reliability index (β) is also increasing. This is due to the fact that, as the shear strength of soil is increasing its resistance to missile penetration also increases. This causes missile to lose its energy more and as a result, the missile hits the concrete barrier with a relatively lesser striking velocity. This decreases the penetration depth and consequently increases the barrier reliability.

4.2.2. Effect of coefficient of friction

Fig. 4 shows that as the magnitude of coefficient of friction are increasing, reliability is also increasing. This is due to the fact that with the increase of coefficient of friction, there is increase in frictional resistance at the missile nose, which causes more dissipation of missile energy during penetration. Thus, missile hits the concrete barrier with lower velocity that consequently increases the concrete barrier reliability.

4.2.3. Effect of depth of soil cover

In the present study, the concrete barrier is being placed at 10 m under the overlying soil. This overlying soil acts as energy dissipater to the missile. If a concrete barrier is placed in deeper soil, missile will lose more of its energy before hitting the concrete barrier and thus the reliability of concrete barrier will improve as shown in Fig. 5.

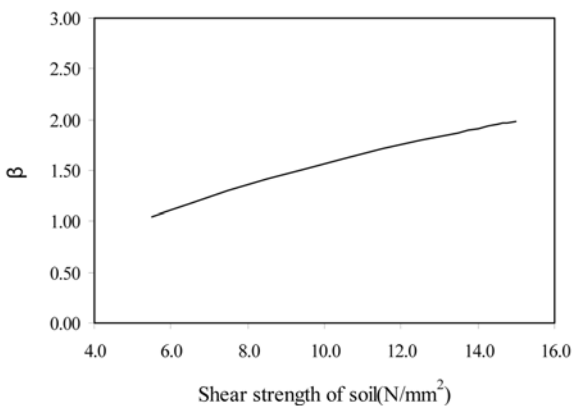

Fig. 3 Variation of reliability index with shear strength

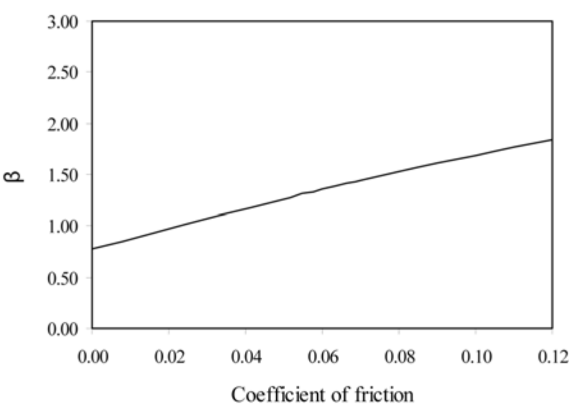

Fig. 4 Variation of reliability index with coefficient of friction

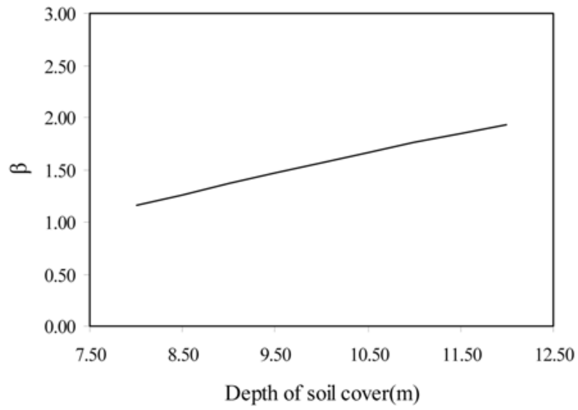

Fig. 5 Variation of reliability index with soil depth

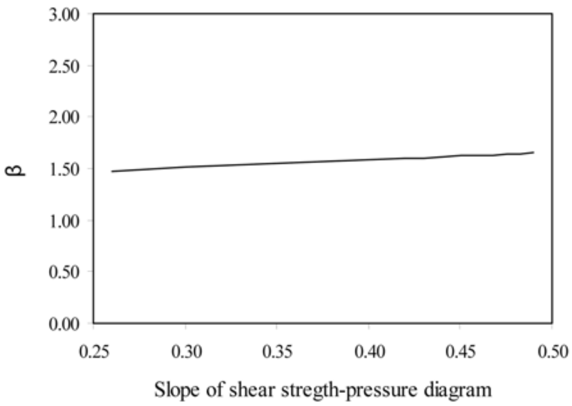

Fig. 6 Variation of reliability index with slope of shear strength-pressure diagram

4.2.4. Effect of slope of shear strength-pressure diagram of the soil

As the slope of shear strength pressure diagram increases, soil strength increases for the same hydrostatic pressure induced in the soil (Fig. 1b). Due to this reason, as the soil strength will increase, striking velocity will decrease or barrier reliability will increase. This trend we observe in Fig. 6 in which with the increase of slope of shear strength pressure diagram there is continuous increase in barrier reliability.

4.2.5. Effect of unconfined compressive strength of concrete

Since unconfined compressive strength of concrete offers resistance to missile penetration, increase in its value will correspondingly increase the resistance to missile penetration. Based on the principle "*less is the penetration more is the reliability*", we can say that the barrier reliability will increase with increase in compressive strength of concrete as shown in Fig. 7. This figure also shows that, by increasing the compressive strength of concrete alone it is not feasible to achieve desirable range of reliability (i.e., above 3). Further, to construct a concrete barrier with above 100 MPa strength is also an expensive task. Therefore, to achieve a desirable range of reliability index (β) it is better to increase the strength of concrete along with other feasible parameters such as thickness of concrete barrier, depth of soil cover, shear strength (by specifying compaction) etc.

4.2.6. Effect of concrete thickness

In the present study an underground concrete barrier is said to be failed if given missile completely penetrates the barrier. In Fig. 8 it is seen that, as the thickness of concrete barrier is increasing, reliability is continuously increasing. This is so because as the concrete thickness will increase, chances of same missile to penetrate it completely will obviously decrease. Thus, this is an expected trend.

4.2.7. Effect of shank radius

As the missile penetrates the soil or concrete barrier its nose is always in contact with surrounding material and it experiences the force of resistance by the surrounding material. With the increase of shank radius, contact area of missile nose increases, that increases resistance to missile penetration

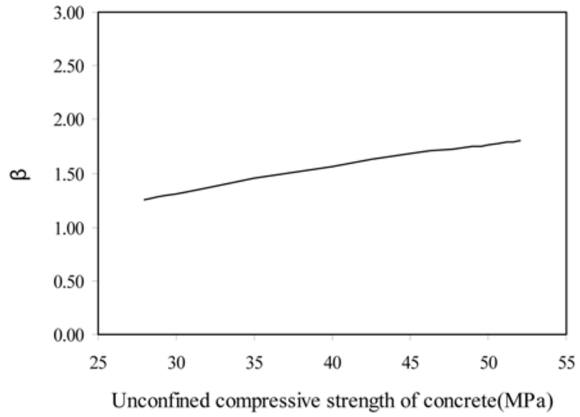

Fig. 7 Variation of reliability index with unconfined compressive strength

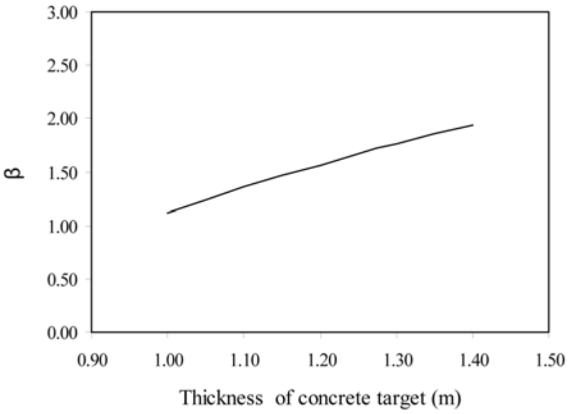

Fig. 8 Variation of reliability index with thickness of concrete target

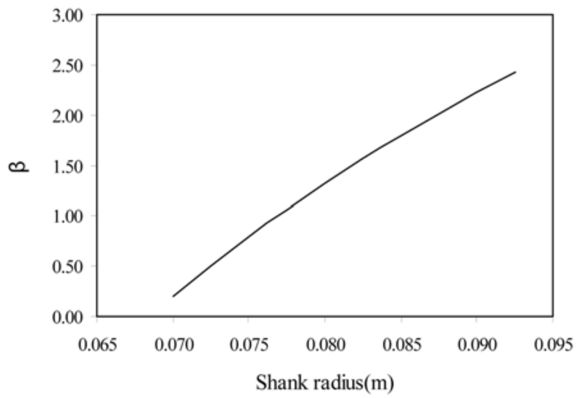

Fig. 9 Variation of reliability index with shank radius

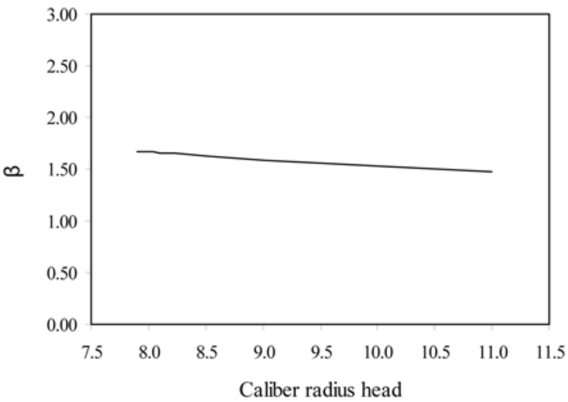

Fig. 10 Variation of reliability index with caliber radius head

and thus increases the reliability of concrete barrier (Fig. 9). This figure also shows that the rate of increase in the barrier reliability is quite high. This is due to the fact that, in the limit state equations (Eqs. 28 and 33) shank radius (a) is the most influencing negative variable (Fig. 2).

4.2.8. Effect of CRH

Fig. 10 shows that as the Caliber Radius Head (CRH) of missile nose is increasing reliability is decreasing, but in a slow rate. Reliability is decreasing because with the increase in CRH missile nose is becoming more pointed which ease the penetration of soil and concrete barrier. Further, rate of decrease in reliability, however, is slow because CRH is a less influencing positive variable (i.e., variable with positive sensitivity factor) compared to other considered positive variables, as it is obvious from sensitivity diagram, shown in Fig. 2.

4.2.9. Effect of missile velocity

Velocity of a missile is measure of its kinetic energy. If its velocity increases it will have more

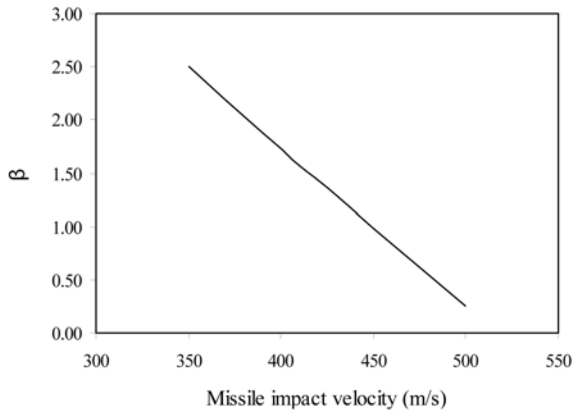

Fig. 11 Variation of reliability index with missile impact velocity

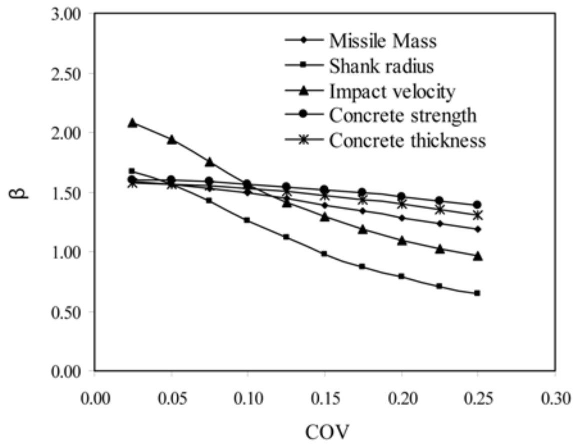

Fig. 12 Effect of uncertainty on reliability of concrete barrier

impact energy and thus more penetration power. It is due to this reason that in Fig. 11, as the impact velocity is increasing reliability of concrete barrier is decreasing. Further, this rate of decrease is very fast. This is because impact velocity is the most influencing positive variable (i.e., variable with positive sensitivity factor) in the governing limit state equations (Eqs. 28 and 33) as shown in sensitivity diagram (Fig. 2).

4.2.10. Effect of uncertainty

Fig. 12 shows that as the uncertainty, measured in terms of coefficient of variation (COV) increases, corresponding reliability decreases for all variables. This trend is same irrespective of nature of the variables i.e., for positive and negatives both type of variables, increase in the uncertainty adversely affects the reliability. This shows that if through some proper care we could reduce the uncertainties involved in variables, reliability of concrete target can be improved. Further, These figures illustrate that with increase in uncertainty in the missile velocity and shank radius there is a sharp decrease in reliability, whereas, this decrease is very small with increase of uncertainty in missile mass, compressive strength of concrete and thickness of concrete. This may be attributed to powers on these variables. Velocity and shank radius are appearing in the expression of penetration depths with second and third power (e.g., Eqs. 30 and 31), however, mass of missile, compressive strength of concrete and thickness of concrete are appearing with single power (e.g., Eq. 33).

5. Conclusions

In the present study, a procedure for the reliability assessment of underground concrete barriers against normal missile impact was presented. The procedure was applied on a numerical example and it was observed that the reliability of underground concrete barrier of present example is well below the desirable range (3-4) and to achieve this range of reliability an optimum combination of various governing parameters (e.g. concrete thickness, compressive strength of concrete, depth of soil cover, shear strength of the soil etc.) would be a better proposition. To demonstrate the relative influence of various random variables on barrier reliability a sensitivity diagram was also shown. A number of parametric studies were conducted that showed results of practical interest. Effect of uncertainty was also studied and it was observed that uncertainty involved in variables adversely affects the barrier reliability and if through some proper quality control and better study, uncertainty involved in various parameters can be minimized reliability of barrier can be improved.

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Notation

η^* volumetric strain
ρ_s density of concrete target
ρ_0 initial density of soil
τ_o shear strength of soil
ω angular velocity
ψ caliber radius head
μ coefficient of friction
β reliability index

α	sensitivity factor
λ	Slope of shear strength-pressure curve
a	missile shank radius
c	a constant
CRH	Caliber radius head
d_c	thickness (or depth) of concrete target
d_g	depth of soil cover
E	Young's modulus of elasticity of soil
f_c	unconfined compressive strength of concrete
F_z	Total axial resisting force acting on the missile nose
$g(.)$	limit state function
$g(\underline{X})$	limit state function (or safety margin)
L	Nose length of the missile
m	missile mass
N	dimensionless constant
P_f	Probability of failure
P	pressure
S	a parameter
t	time
V_c	rigid body velocity in concrete target at $z_{sc}= 4a$
V_o	missile impact velocity
V_z	Velocity of missile at depth z
X	random variable
$\underline{X}$	vector of random variables
Y	random variable in reduced coordinate
z	penetration depth at time t
z_{ft}	depth of penetration in tunnel region
z_{SC}	depth of penetration in crater region