Risk of damage to marine life caused by air gun as a marine seismic source

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The present study is confined to investigate the effect of energy radiated by the shock wave introduced by non-explosive source "air gun" in terms of the risk of damage of marine life. The impulse involves a compression of the water particles, creating a shock wave spreading out spherically into the water in the area around the explosion, which give rise to subsequent pressure pulses designated as bubble oscillations.The total energy radiated by shock wave can be calculated by using Trapezoid Rule. The author develops a computer program and subroutine for carrying out the Runge-Kutta procedure and the trapezoid rule to calculate the pressure pulse and the portion of the energy radiated by the shock wave. The comparison between the air gun and dynamite shows that the seismic efficiency of the air gun is better than that of the dynamite. The air gun with small volume fired at the surface will cause less damage than small charge shot at the depth. Therefore, we conclude that the risk of damage to the marine life increases with increasing depth at which the air gun is fired.

تناول البحث دراسة مخاطر تدمير الطاقة المنبعثة من الموجات التصادمية المتولدة عن مصدر مدفع هوائي علي الحياة البحرية. وقد تبين أن النبض الأول يعمل علي ضغط جزيئات الماء وينشأ موجة تصادمية تنتشر كرويا في الماء في المنطقة المحيطة بالتفجير حول المصدر (المدفع الهوائي) وينتج عن ذلك نبضات ضغط متتالية تنشأ من فقاعة الهواء التذبذبية وقد تبين أن الطاقة الكلية المنبعثة من الموجات التصادمية يمكن حسابها باستخدام طريقة شبه المنحرف . وقد تم تطوير برنامج الكمبيوتر والبرامج التابعة لأجراء خطوات رانج كوتا وطريقة شبه المنحرف لحساب الضغط النبضي الأول ونسبة الطاقة المنبعثة من الموجات التصادمية . وقد بينت المقارنة بين المدفع الهوائي والديناميت أن كفاءة الموجات السيزمية للمدفع الهوائي أفضل من كفاءة الموجات السيزمية للديناميت . حيث تبين أن المدفع الهوائي ذات الحجم الصغير المتفجر عند السطح يسبب ضرر أقل علي الحياة البحرية من الشحنة الصغيرة المتفجرة عند العمق . ولهذا نستنتج أن مخاطر تدمير الحياة البحرية يزداد بزيادة العمق الذي يتم عنده تفجير مدفع الهواء .

Keywords: Shock waves, Non-explosive source, Air gun, Bubble oscillation, Trapezoid rule

1. Introduction

The function of any underwater seismic energy sources whether or not explosive or non-explosive is to introduce a sudden positive (or sometimes negative) pressure impulse into the water. This impulse involves a compression of the water particles, creating a shock wave that spreads out spherically into the water and then into the soil. A delayed effect of the shock wave is an oscillatory flow of water in the area around the explosion, which gives rise to subsequent pressure pulses designated as bubble oscillations [1].

The most widely used of all non-explosive sources is the air gun, which discharges air under very high pressure into the water. The PAR air gun was the first to be used in commercial operations and dominated that field from the late 1960s until the 1980s. It has a number of models with a volume chamber ranging from 1 to 2000 in^3 (0.016 to 32.77 L) or more and pressure up to 10,000 psi (68.9MPa) are used although 2000 psi (13.8 MPa) is most common. The dominant frequency of the pulse depends on the energy. That is, on the product of the pressure and volume of air discharged. Therefore, mixtures of gun sizes from 10 to 2000 in^3 (0.16 to 32.77 L) are sometimes used to give a broader frequency spectrum [2].

Air guns have been used in various applications for years. They were first used in coal-mining operations and were operated at up to 16000 psi (110.3 MPa) charge pressures. Later, single air gun, operated at 2000 psi

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(13.8 MPa), found application as an oceanographic survey tool. Air gun arrays were first used in offshore seismic exploration in the mid-1960s [3]. These early arrays were several hundred cubic inches in total volume and were operated at 2000 psi (13.8 MPa). They were either tuned arrays or several large guns of the same size with wave-shape kits. In the mid 1970s a series of 5000 psi (34.5 MPa) air gun came into use [3]. These guns were the descendants of air guns that had been used as substitutes for explosives in coal-mining operations in 1940s and 1950s [3].

In 1982 the use of explosives as a marine seismic source had effectively ceased. The important reason for abandoning explosives detonated just below the surface was the low efficiency. A larger part of the energy of the detonation went into geyser that each shot created instead of into seismic events. In addition the charge of dynamite has harmful effects to marine life [1].

Lavergne [4] studied the acoustic efficiency in a broad frequency band and in the seismic frequency band. The partition of energy between the shock wave and bubble pulses, the seismic effects of cavitation were due to ghost reflection at the air-water interface, and the damage caused to marine life [4]. Also, he concluded that the seismic efficient of charges of the order of 100 gm can be increased by dividing the charges and by shooting as the depth. In addition, the maximum dangerous radius is 120 m with 5 kg, and 12 m with 50 gm.

The present study is confined to investigate the effect of energy radiated by shock wave introduced by non-explosive air gun on the risk of damage to marine life.

2. Theory of free bubble oscillation

The free bubble is defined as a pressurized spherical air bubble released instantaneously into the surrounding infinite water medium confined under given hydrostatic pressure [3]. Air expands from initial "chamber" volume and pressure (V_c, P_c) through the state equilibrium (V_o, P_o) and to the state of minimum pressure "P_m", where the volume of the bubble is maximum. This cycle of oscillation repeats itself until all the original energy is radiated or dissipated [3]. At some distance "r" from the bubble, the acoustic pressure as a function of time "$P(r,t)$" can be recorded. [5] developed an equation to predict "$P(r,t)$" as a function of the significant variable as given by eq. (1).

$$\frac{P(r,t)-P_o}{\rho} = -\frac{f'}{r} - \frac{f^2}{2r^4} - \frac{1}{2c}\left(\frac{f'2}{cr^2} + \frac{2ff'}{r^3}\right). \qquad (1)$$

Where "f" and "f′" are abbreviations for:

$$f = -a^2\dot{a} + \frac{a^2}{c}\left(\frac{\dot{a}^2}{2} + \Delta\right), \qquad (2)$$

$$f' = -a\left(\frac{\dot{a}^2}{2} + \Delta\right). \qquad (3)$$

As has been indicated that eq. (1), had obtained through the solution of eq. (4), which describes the motion of the air bubble in the water.

$$(\dot{a} - c)\left(a\ddot{a} + \frac{3}{2}\dot{a}^2 - \Delta\right) - \dot{a}^3 + \frac{(a^2\Delta)}{a} = 0. \qquad (4)$$

Where "a" is the bubble radius, "$\dot{a}$" is the velocity of the bubble wall, "c" is the velocity of sound and $\Delta(a) = [P(a) - P_o]/\rho$ is the reduced pressure difference.

With Keller and Kolodner's equation, defined by eq. (4) as a non-linear second order ordinary differential equation describing the motion of the air bubble in the water, the following units are specified.

$$a = Aa_o$$
$$t = \tau\bar{T} = \tau a_o(\rho/p_o)^{1/2}$$
$$\bar{c} = c(\rho/p_o)^{1/2} \qquad (5)$$

Where "a_o" is the new unit length indicating the equilibrium radius of the bubble with the corresponding variable "A" and $\bar{T}$ is the new unit of time with the corresponding variable "τ", "$\bar{c}$" is the new dimensionless sound velocity with the corresponding variable "c". With the above mentioned units, a new second order ordinary differential equation is obtained as [5]:

$$(\dot{A}-\bar{c})(A\ddot{A}+\frac{3}{2}\dot{A}^2-A^{-3\gamma}+1)-\dot{A}^3$$
$$-(3\gamma-2)A^{-3\gamma}\dot{A}-2\dot{A}=0. \qquad (6)$$

The present author has introduced new variables $x_1(\tau)=A(\tau)$, $x_2(\tau)=\dot{A}(\tau)$ to convert the non-linear second order ordinary differential eq. (6) into a simultaneous system of two first order equations with two unknown functions $x_1(\tau)$, $x_2(\tau)$ as shown by eq. (7).

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix} x_2 \\ \dfrac{[x_2^3+(3\gamma-2)x_1^{-3\gamma}x_2+2x_2]}{x_1(x_2-\bar{c})} \\ -\dfrac{3}{2}x_2^2x_1^{-1}+x_1^{-3\gamma-1}-x_1^{-1}\end{bmatrix}. \qquad (7)$$

In this case the auxiliary condition for the vector x is defined as:

$$x(0)=[x_1(0)\ \ x_2(0)]^T,\ x_1(0)=A(0),\ x_2(0)=\dot{A}(0). \qquad (8)$$

Then, the numerical Runge-Kutta method of order four [6] was applied to solve the initial value problem for a system of two first-order ordinary differential eq. (7) to get a definition of the radius-time curve. Once the radius-time curve is known, the pressure wave emitted by the bubble can be computed from eq. (1-3).

3. Initial bubble radius

To determine a radius time curve, it is assumed that the initial pulse radiated by the air gun is due to spherical source. That source has an initial volume equals to that of the air gun chamber [7]. If the calculation begins at minimum or maximum radius then the velocity will be equal zero [7].

4. The equilibrium radius

The state of equilibrium of the bubble is attained when the internal pressure in the bubble equals the hydrostatic pressure. The equilibrium radius for the oscillating bubble, which is at first not known, may be computed from the chamber pressure "P_c" and volume "V_c" of the air gun chamber, and the hydrostatic pressure "P_o". With the equation of state:

$$P_o V_o^\gamma = P_c V_c^\gamma = \text{constant}. \qquad (9)$$

Then the equilibrium radius is defined as:

$$a_o=\left(\frac{P_c}{P_o}\right)^{\frac{1}{3\gamma}}\sqrt[3]{\frac{3V_c}{4\pi}}. \qquad (10)$$

Where the hydrostatic pressure "P_o" (μ bar) at a depth of "d" (m) is given by:

$$P_o=10^6(1+\frac{d}{10}). \qquad (11)$$

5. Total energy radiated by the shock wave

The pneumatic energy sources, which we call airpulser, generate the seismic energy entirely mechanically. Air is stored in a chamber under high pressure and when firing, exhaust ports in this chamber are quickly opened [8]. The compressed air is suddenly spill out into the water, creating an air bubble quite similar to that from a dynamite explosion and giving rise to repetitive bubble pulses at a rate determined by the oscillation period. The initial phase of the radiated pressure, which lasts from the moment the ports begin to open until the air bubble formed by expanding air reaches its first maximum volume, is known as the initial pulse. The amplitude of this initial impulse is usually greater than that of any one produced by subsequent collapses of the bubble, because the energy is lost each time the bubble expands and collapses. When the air bubble/ formed by the expanding air/ reaches its maximum volume, the pressure inside the bubble is much less than the hydrostatic pressure just outside the bubble and all energy is stored as potential energy in the acoustic radiation mass. At this moment the bubble starts to collapse and the bubble wall beings to accelerate towards the center of the bubble. During the collapse stage the air inside the bubble is compressed until the bubble reaches a minimum volume and the velocity of the bubble wall is zero. This means that when the bubble is compressed the energy is stored as the potential energy in the air. The process of the bubble expansion and compression, (i.e. the oscillation of the energy between the radiation mass and the air compliance), goes on until all the initial energy is dissipated. Part of this energy is radiated into far field giving rise to what is widely known as the bubble pulse, and the remaining part is dissipated as heat. It is well known that the portion of the energy radiated by the shock wave "P(t)" at distance "r" can be computed by Parseval's formula.

$$E_s = \frac{4\pi r^2}{\rho c} \int_0^{t_D} P^2(t)dt. \qquad (12)$$

Where "ρ" and "c" are the density and the velocity of water; "P(t)" is the pressure recorded or computed at distance "r"; and "t_D" is the shock pulse duration which is the first bubble period (i.e., $t_D = t_B$).

To calculate total energy radiated by shock wave the integration in eq. (12) has to be evaluated numerically by the aid of the Trapezoid Rule [6]. Therefore, for theoretical model the square acoustic pressure can be integrated through the first period, i.e., through the interval $[0, t_B]$ which is divided into subintervals with uniformly spaced "h", as the following:

$$\int_0^{t_B} P^2(t)dt = h\sum_{i=2}^{n-1} P^2(t_i) + \frac{h}{2}[P^2(t_1) + P^2(t_n)] \; . \qquad (13)$$

Where the uniformly spaced "h" is given by:

$$h = \frac{t_B}{\text{number of steps}}$$

and the period of pulsation of the air bubble "t_B" is given by [8]:

$$t_B = 2\pi \sqrt[3]{\frac{3V_c}{4\pi}} \left[\frac{P_c}{P_o}\right]^{1/3\gamma} \left[\frac{\rho}{3\gamma P_o}\right]^{1/2} . \qquad (14)$$

The present author developed a suitable computer program and subroutine for carrying out the Runge-Kutta procedure and the trapezoid rule to calculate the pressure pulse and the portion of the energy radiated by the shock wave. The results of the program are times (sec), instantaneous bubble radii (cm) and velocities (cm/sec), instantaneous acoustic pressure (μbar) and the portion of the energy radiated by the shock wave (erg)

6. Application in case of the airpulser

For the case of air gun with volume $V_c = 1/6$ L and chamber pressure $P_c = 150$ atm for the specific heat ratio, γ=1.18 when fired at various depths in water of density ρ=1.042 g/cm³ and at a temperature T=20 °C, the initial bubble radius is found to be equal to $a_i = 3.414$ cm. The equilibrium radii a_0's (cm)/ calculated form eq. (10) for different depths/ are shown in table 1. From eq. (5) the initial bubble radii in new unit for different depths (d's in m) were calculated and the results are also shown in the same table 1. Since these radii are minima then the bubble velocities will be equal to zero ($\dot{A}(0) = 0$). For each depth the sound velocity is calculated from Wilson eq. [10], the dimensionless sound speed and the adapted unit of time, calculated from eq. (5), are shown in table 2. The predicated bubble pulse oscillation period at each depth, calculated from eq. (14), and the bubble period in new unit time are shown in table 3. According to eqs. (14, 10) and (5) the bubble period in adapted unit depends only on the specific heat ratio γ. Then it is constant for each depth. Then for each depth one integrate the acoustic pressure through the first period i.e., through the interval $[0, \tau_B]$ by first dividing this interval into subintervals with uniformly space equal "h". If one chose the number of steps to be taken in going from "0" to "τ_B" equals to 334 then "h" will be equal 0.01 for all cases. Thus, the instantaneous acoustic pressure can be calculated from eq.

(1) at distance r=0.5 m and therefore the total energy radiated by shock wave "P(t)" for each case as shown in table 4.

7. Energy transmission

To get a first impression of the computation results, the energy intensity against the bubble radius are shown in figs. (1-4). It is well known that the energy allowed will be spread out in one direction only so that the energy has to decrease on the average in inverse proportion to distance i.e., cylindrical spreading. This is contrasted with the variation of intensity along the bubble radius. Then through the shock pulse duration the intensity of the energy radiated near the source will decrease in inverse proportion to the bubble radius square, i.e., spherical spreading. This may be due to the potential energy stored in the air loss with expansion of the bubble. When the air bubble expands the velocity of the bubble wall increase rapidly until reaching the critical velocity. Then the velocity decreases until it becomes zero. At this moment the bubble starts to collapse and the bubble wall begins to accelerate towards the center of the bubble. When the velocity of the bubble wall is less than the critical value the energy intensity will approach the condition of decreasing in inverse proportionally to the bubble radius.

Table 1
Computed values of the equilibrium radius and the initial bubble radius in new unit of length corresponding to each depth

d (m)	P_o (bar)	a_o(cm)	A(0)
10	2	11.59184	0.294510613
30	4	9.5305	0.358209972
50	6	8.49909	0.4016807
70	8	7.835721	0.435686791

Table 2
Computed values of the sound velocity, the dimensionless sound speed and the adapted unit of time corresponding to each depth

d (m)	c (m/sec)	$\bar{C}$	$\bar{T}$ (sec)
10	1546.968	111.6607	0.008367029
30	1547.308	78.97338	0.004864291
50	1547.648	64.49566	0.003541854
70	1547.988	55.86715	0.002827925

Table 3
The predicted bubble pulse period for air bubble pulsation produced by 1/6 L air gun fired at different depths

Depth (in m)	Bubble pulse period (in sec)	Bubble pulse period (in adapted units)
10	0.027941488	3.339475313
30	0.016244181	3.339475313
50	0.011827934	3.339475313
70	0.009443785	3.339475313

Table 4
Computed value of the total energy "E_s" radiated by shock wave, the corresponding charge weight of TNT and the risk of damage to marine life at different depths

Depth "d" (m)	Total energy of shock wave "E_s" (joule)	Charge weight "W" (gm)	Risk of damage "R" (m)
10	2405.5	1.3	1.9
30	4898.8	2.6	2.8
50	7844.2	4.2	3.5
70	11104.3	6.0	4.2

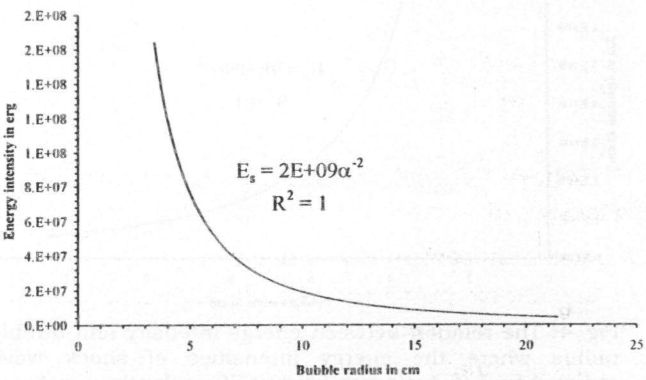

Fig. 1. The relation between energy intensity and bubble radius where the energy intensities of shock wave radiated by 1/6-L air gun fired at 10-m depth in water is computed during the shock pulse duration.

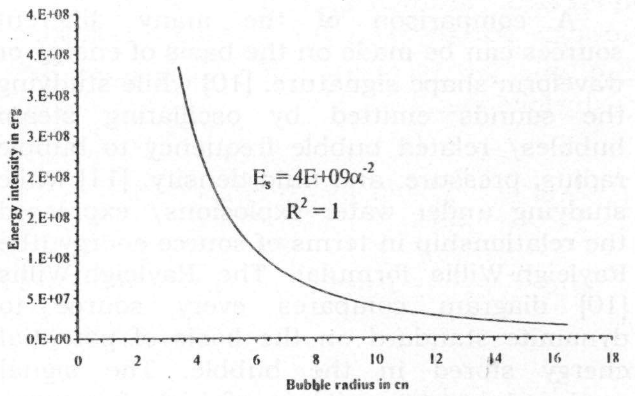

Fig. 2. The relation between energy intensity and bubble radius where the energy intensities of shock wave radiated by 1/6-L air gun fired at 30-m depth in water is computed during the shock pulse duration.

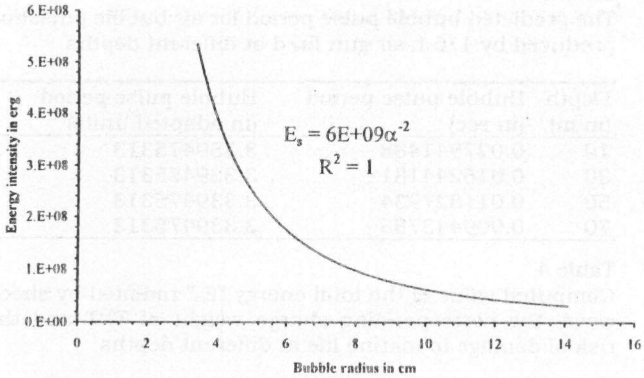

Fig. 3. The relation between energy intensity and bubble radius where the energy intensities of shock wave radiated by 1/6-L air gun fired at 50-m depth in water is computed during the shock pulse duration.

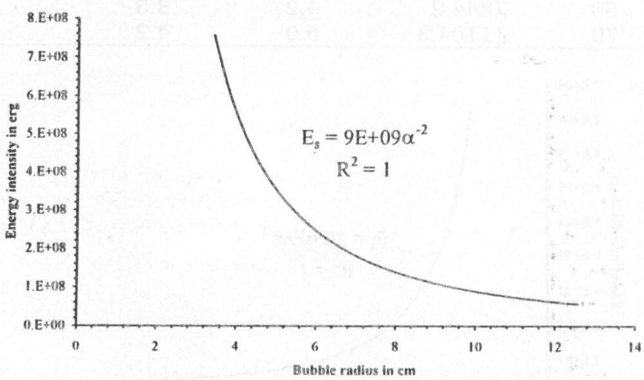

Fig. 4. The relation between energy intensity and bubble radius where the energy intensities of shock wave radiated by 1/6-L air gun fired at 70-m depth in water is computed during the shock pulse duration.

8. Air gun / dynamite picture

A comparison of the many different sources can be made on the basis of energy or waveform shape signature. [10] while studying the sounds emitted by oscillating steam bubbles/ related bubble frequency to bubble radius, pressure, and fluid density. [11] while studying under water explosions/ expressed the relationship in terms of source energy (the Rayleigh-Willis formula). The Rayleigh-Willis [10] diagram compares every source to dynamite standard on the basis of potential energy stored in the bubble. The signal produced by dynamite is of high frequency because of the rapid explosion process. It is radiated in frequency range, which only in part can be utilized seismically. In the case of the air gun the seismic energy is not generated chemically, as in the case of dynamite, but entirely mechanically. Consequently, the mechanism of the transition of the potential energy into pressure wave to be produced is completely different for the two methods. Since the releasing process is much slower than the produced signal then it has significantly lower frequency than of dynamite. Therefore, one concludes that the seismic efficiency of the air gun is better than that of dynamite. Also, the comparison between the air gun and dynamite is related only to the initial energy of both sources.

The comparison between the air gun and dynamite had been investigated by [8]. He suggested that at a chamber pressure of 150-atm energy of $E_o = 13600$ joule is contained in a 1/6-L air gun before releasing. Since the specific energy for TNT is 3100 joule/cm³ the 1/6-L air gun with an initial energy of 13600 joule corresponds to 6.6 gm TNT. Therefore, he concluded that $0.04V_c$ gm TNT corresponds to an air gun of "V_c" cm³ size operated at chamber pressure of 150 atm. One conclude that an energy "E_o" is contained in the air gun corresponding to $\varepsilon * V_c$ gm TNT where $\mathcal{E}$ is a constant dependent on its potential energy.

If we suppose that the energy radiated by the shock wave is the potential energy stored in the air gun before fired. Therefore, we can calibrate the energy radiated by the shock wave for an air gun, (volume $V_c = 1/6$ L and chamber pressure $P_c = 150$ atm), with the charge weight of dynamite as show in table 4.

9. Effect on marine life

According to [12], the damage radius follows,

$$R = KW^{0.5} \quad . \qquad (15)$$

Where "R" is the damage zone radius (m), "W", the charge weights (kg), and "K", is a coefficient dependent on fish species. From observation in the Black Sea, Lovlia and his co-workers concluded that "K" varies between

12 and 54. [4] has described the seismic action of one type of source, e.g., small charges of dynamite. He stated, by theoretical cavitation computation that an interesting feature that the negative peak pressure can be of relative importance only in case of shallow shots. This result is of interest when we consider the preservation of marine life; under the hypothesis that negative peak pressures are one of the major causes of destruction of certain species of fishes by outward explosion of the air bladders [13]. It is clear that strong charges shot at the surface will cause much more damage than equivalent charges shot at the depth. Thus, small charges can be very efficient sources, though harmless to marine life, when the number of charges and the depth at which they are fired are selected properly.

An air gun with volume $V_c = 1/6\,L$ and chamber pressure $P_c = 150\,atm$ fired at "1" meter has an initial energy of 13600 joule corresponding to 6.6gm TNT. Therefore, according to eq. (15) and if value of "K" is 54, the maximum dangerous radius is 4.4-meter i.e.; the risk of damage to non-vertebral is 4.4 meter. Also, if the value of "K" is 12, the minimum dangerous radius is one meter approximately i.e.; the risk of damage to the vertebrate is one meter. Also, if the value of K is the geometric mean between 12 and 54 (K equals 25.5) then the middle dangerous radius is 2.1 meter approximately i.e., the risk of damage to the protochordata is 2.1 meter.

It is clear that an air gun with small volume fired near the surface will cause less damage than small charge shot at a pro found depth. Thus the risk of damage to marine life caused by small volume air gun fired at shallow water is practically negligible.
An interesting feature shown by the theoretical computation, is that the shock pressure wave radiated at different depths by an air gun has an effect on the risk of damage. For an air gun with volume $V_c = 1/6\,L$ and chamber pressure $P_c = 150\,atm$ the energy radiated by the shock wave at different depths calibrated with charge weight of dynamite as shown in table 4. According to eq. (15), when value of "K" is 54, the risk of damage "R" to marine life caused by the shock pressure wave can be calculated as shown in table 4. Fig. 5 shows the relation between the energy radiated by the shock wave and the risk of damage. It yields the relation $R = 0.0396 E_s^{0.5}$. Therefore, we conclude that the risk of damage to the marine life increases with increasing depth at which the air gun is fired.

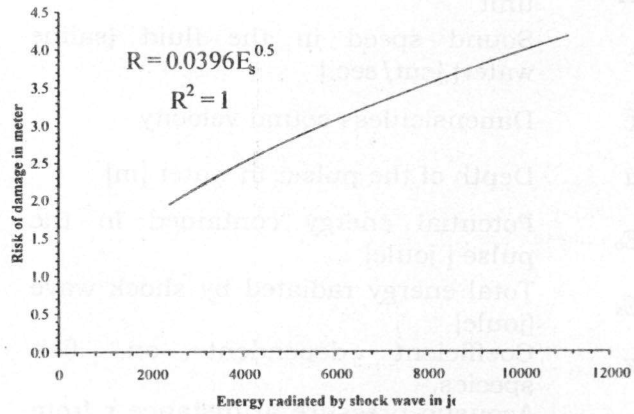

Fig. 5. The relation between the energy radiated by shock wave and the risk of damage to the marine life, for an air gun with volume 1/6 L and chamber pressure 150 atm fired at various depths in water.

10. Conclusions

It is clear that an air gun with small volume fired near the surface will cause less damage than smaller charge shot at depth. Thus the risk of damage to marine life caused by small volume air gun fired at shallow water is practically negligible.

An interesting feature shown by the theoretical computation is that the shock pressure wave radiated at different depths, by an air gun has an effect on the risk of damage. The relation between the energy radiated by the shock wave and the risk of damage is found to be $R = 0.0396 E_s^{0.5}$. Therefore, one conclude that the risk of damage to the marine life increases with increasing depth at which the air gun is fired.

Nomenclature

a	Instantaneous bubble radius; $a=a(t)$ [cm]

$\dot{a}$	Velocity of the bubble wall [cm/sec.]
a_i	Initial bubble radius [cm]
a_o	Equilibrium radius of the bubble [cm]
A	Relative bubble radius; $A=a/a_o$
$\dot{A}$	Velocity of the bubble wall in new unit
c	Sound speed in the fluid (saline water) [cm/sec.]
$\bar{c}$	Dimensionless sound velocity
d	Depth of the pulser in water [m]
E_o	Potential energy contained in the pulse [joule]
E_s	Total energy radiated by shock wave [joule]
K	Coefficient dependent on fish species.
$P(r,t)$	Acoustic pressure at distance r from the bubble in water [bar]
P_c	Chamber pressure of the air gun before releasing [atm]
P_m	Minimum pressure in the bubble when its volume is maximum
P_o	Hydrostatic pressure just outside the air bubble [μbar]
r	Radial distance from the bubble center [cm]
R	The damage zone radius [m]
t	Time [sec.]
t_B	Bubble pulse oscillation period [sec]
$\overline{T}$	Adapted unit of time
V_c	Volume of the air gun chamber [liter]
V_o	Equilibrium volume of the air bubble
W	Charge weights [kg]
x_1	New variable represent relative bubble radius; $x_1(\tau) = A(\tau)$
x_2	New variable represent velocity of the bubble wall in new unit;
$\varepsilon\varepsilon$	Constant dependent on potential energy of the pulser
γ	The variable of state of expansion of the air stored in pulser
γ_o	The variable of state of the air during the bubble oscillation
ρ	Density of the fluid (saline water) [g/cm³]
τ	Time in adapted units; $t = \tau\overline{T}$
τ_B	Bubble period in adapted units; $t_B = \tau_B\overline{T}$

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