THEORETICAL DESIGN OF AN OPTIMUM SURFACE SEISMIC SOURCE

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Abstract

A mathematical relation has been abstracted for the design of an optimum surface explosive powered impactive source. The active variables used in the design and analysis are the mass of the support system, the mass of the impactor, the charge size in energy units (J), the stiffness constant of the coupling spring and the distance of contraction of the spring. Other variables which are dummies are the velocities of the support system and the impactor, respectively. It was found that the kinetic energy of the impactor at the instant of explosion is increases with the charge size and the mass of the gun system, but decreases with the mass of the impactor.

Keywords: Theoretical design, seismic source

Introduction

Over the past two decades, explosive powered impactive sources (guns) have gained wide recognition, because of the interest in sources that are capable of generating high frequency components for use in high resolution shallow seismic surveys. Some of these sources impact on the ground surface, while others impact inside augered holes usually within 1m of the subsurface. Comparison and evaluation tests have been variously conducted (Pullan and MacAulay, 1987; Parker et al., 1993; and Miller et al., 1994) to help guide engineering geophysicists in the choice of seismic sources for given geologic and hydrologic settings. Most of these sources are so portable that they do not generate enough energy for refraction work when the target depth is greater than 30m in a site with high seismic wave attenuation rate. Obianwu (2002), have adapted a cannongun as a seismic energy source which generated enough energy to delineate depths beyond the reach of most portable impactive sources. The word "optimum" is therefore used in this paper to qualify a source that can be used for both refraction and reflection surveys under most of the practical engineering conditions.

Dobrin and Savit (1988), had posited that the physical theory behind the generation of seismic energy has not been worked out as satisfactorily as that for other aspects of seismic exploration process (such as attenuation, reflection, diffraction and refraction) because materials in the immediate vicinity of most energy sources are subjected to non-linear deformation and the physics of such deformation is much more complex than it is for elastic-wave propagation. In this regard, the aim of the theoretical analysis presented in this paper (which is confined to explosive powered impactive sources) is not to raise physical issues concerning Dobrin and Savit's position on the generation of seismic energy, but to highlight the physics behind:

(1) the amount of energy an explosive powered impactor can deliver to the ground (assuming near source deformation characteristic remain constant for all shots);

(2) the maximum energy the impactor can deliver without causing significant secondary vibrations; and

(3) the practical mechanism for preventing noise pollution occasioned by the associated explosion.

Method

The theoretical analysis here would be based on a simple model (Fig. 1). The model consists of the effective mass of the gun system, M_g, the mass of the pellet M_p, and the mass of the charge M_c. The weight of the gun system is coupled to the ground by an internal shock absorber. The gun system is also used to acoustically seal the explosive chamber from the larger environment. This acts as a silencer mechanism against the sound of the explosion and prevents fallouts from the explosion from reaching the crew or nearby structures.

Energy Transfer Mechanism

It has been mentioned earlier that the mechanism for seismic wave generation on land by explosives, is not well established because of the inelastic deformation of materials at the immediate vicinity of the explosion. However, one can take advantage of momentum considerations to estimate the amount of energy transferred to the ground as usable kinetic energy and those lost to the gun system as internal energy. In this model (Fig.1), explosive energy which is purely due to the bubble pulse is neglected. This can be justified, when it is considered that the explosion actually takes place inside the confines of the chamber and not the shell of the cavity. Whatever happens to the shell of the cavity (i.e., the bottom shell) later is an after effect and mostly impactive.

Consider the impactor system before the explosion to consist of

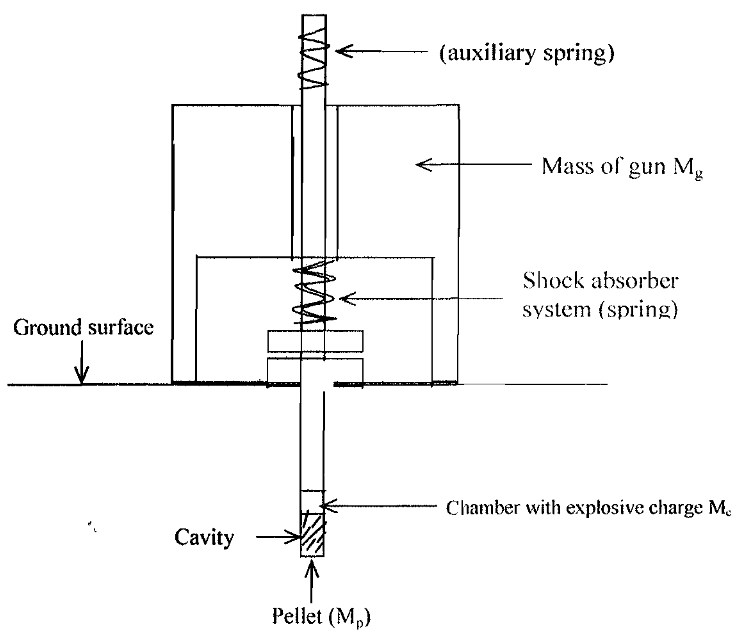

Fig. 1: Schematic Model of an explosive powered impactor

basically three masses. The mass of the gun system M_g, the mass of the pellet M_p (i.e., laterite or clay in this case), and the mass of the charge M_c, are at rest and therefore in equilibrium before the explosion. The exploding charge (black powder) is considered a massless, spring, so $M_c = 0$. At the instant of explosion, and following the law of conservation of momentum, the total momentum of the system before the explosion, equals the total momentum of the pellet and the gun system after explosion.

The explosive energy is considered equivalent to the kinetic energy obtained from an expanding compressed spring at the instant of its release. At the instant a compressed spring is released, its stored elastic potential energy is converted to kinetic energy. If we now look at M_g and M_p interactions as being analogous to two masses separated by a massless compressed spring, it could then be stated that:

$$M_g V_{g1} + M_p V_{c1} = M_g V_{g2} + Mp V_{p2} \quad (1)$$

where V_{g1} and V_{g2}, and V_{p1} and V_{p2}, are the respective velocities of M_g and M_p before and after the explosion. Equation 1, is similar to the equation representing the conservation of momentum of bodies experiencing perfect elastic collision. However, M_g and M_p are initially at rest and as such V_{g1} and V_{p1} are both equal to zero. Furthermore, V_{g2} and V_{p2} are apposite in direction and as such, we can take advantage of cartesian coordinate system and state that:

$$0 = M_g + V_{g2} - M_p V_{p2} \quad (2)$$

So that,

$$M_g V_{g2} = M_p V_{p2} \quad (3)$$

and

$$\frac{V_{p2}}{V_{g2}} = \frac{M_g}{M_p} \quad (4)$$

The loss in explosive energy which is represented by increase in the internal energy of the gun system is equal to the kinetic energy E_{kg} of M_g, while the usable energy for the generation of seismic wave is equal to the kinetic energy E_{kp} of M_p. The ratio of the energy loss to the usable energy is thus given by:

$$\frac{E_{kg}}{E_{kp}} = \frac{M_g V^2_{g2}}{M_p V^2_{p2}} \quad (5)$$

Let the inverse of the ratio of the kinetic energy of M_g to that of M_p be called the energy conversion factor K. The energy conversion factor which is a measure of the ability of the system to convert explosive potential energy to seismic waves is given by:

$$K = \frac{E_{kp}}{E_{kg}} = \frac{M_p}{M_g}\left(\frac{V_{p2}}{V_{g2}}\right)^2 \quad (6)$$

Substituting equation 4 into equation 6, gives

$$K = \frac{M_p}{M_g}\left(\frac{M_g}{M_p}\right)^2 \quad (7)$$

$$\therefore \quad K = \frac{M_g}{M_p} \quad (8)$$

So, neglecting the mass of the exploding black powder, by visualizing it as a compressed spring between two masses, which transfers all its elastic potential energy to the two adjacent masses as kinetic energies, without affecting the momentum or energy relations of the interacting masses (Young et al., 1999), it can be inferred that:

a) The smaller the mass of the pellet (laterite or clay), the more the energy converted to usable energy available for generating seismic waves, and

b) The smaller the mass M_p of the pellet, the smaller the velocity V_{g2} of the cannongun system and the more negligible the effects of rebound energy on the system would be.

Nevertheless, it must be emphasized that the laterite or clay used as a pellet must be enough to tightly seal the chamber and give adequate tamping effect, so that almost all the available energy of the black powder is released effectively as explosive kinetic energy. This minimum for adequate tamping sets the lower limit for the mass of the pellet, below which the sharp explosive effect could not be realized. This minimum mass of the pellet depends on the diameter of the chamber.

Maximum Charge Size

For a heavy gun that is not to be held with the hand, it is important to determine theoretically, the maximum charge size that can be exploded without compromising stability and the expected high value of signal-to-noise ratio. Recall that equation 5 states that the ratio of the energy loss to the usable energy is:

$$\frac{E_{kg}}{E_{kp}} = \frac{M_g V^2_{g2}}{M_p V^2_{P2}}$$

So that,

$$\frac{E_{kg}}{E_{kp}} = K^{-1} = \frac{M_p}{M_g} \quad (9)$$

But the energy loss E_{kg} can be written as

$$E_{kg} = \frac{M_p E_{kp}}{M_g} \quad (10)$$

Let the total kinetic energy of the explosive be E_k. Then equation 10 can be rewritten to read:

$$E_{kg} = \frac{M_p}{M_g} (E_k - E_{kg}) \quad (11)$$

$$E_{kg} = \frac{M_p E_k}{M_g} - \frac{M_p}{M_g} E_{kg} \quad (12)$$

$$E_{kg} \left(1 + \frac{M_p}{M_g}\right) = \frac{M_p}{M_g} E_k \quad (13)$$

$$E_{kg} = \frac{M_p}{M_g} E_k \left(1 + \frac{M_p}{M_g}\right)^{-1} \quad (14)$$

$$E_{kg} = \frac{M_p}{M_g} \left(\frac{M_g}{M_g + M_p}\right) E_k \quad (15)$$

$$E_{kg} = \left(\frac{M_p}{M_g + M}\right) E_k \quad (16)$$

For a system modelled after Fig.1, the maximum energy E_k of the charge that can be fired without significant secondary vibrations is given by:

$$E_k = \left(\frac{M_g + M_p}{M_p}\right) E_{kg} \quad (17)$$

The maximum charge size which is operationally safe for the gun to fire can be determined by first finding the maximum energy loss E_{kg}, that can be absorbed by the shock absorber without bouncing the entire system. But it is known that the force exerted on a spring is related to the length of compression X by the relation:

$$F = -SX \quad (18)$$

where S is the force constant or the stiffness

of the spring. Equation 18 can be used to find the length of compression of the shock absorber spring X before bouncing can take place. Of course, before bouncing can take place the compressional force on the spring due to the explosion would be at least equal to the weight of the gun system which is holding down the spring. The work done W in compressing the spring is given by:

$$W = 0.5SX^2 \quad (19)$$

It is considered that to avoid bouncing, W should be more or at least equal to the maximum energy loss E_{kg} of the explosion. Substituting equation 19 into equation 17 as E_{kg} gives:

$$E_k = 0.5\left(\frac{M_g + M_p}{M_p}\right) SX^2 \quad (20)$$

Which is the energy of the maximum charge a gun which is modelled after Fig.1 can fire without secondary vibrations. In practice, it is advised that the charge should not exceed 2/3 of the theoretical limit.

It could also be shown from equation 10 that the usable energy E_{kp} available for conversion to seismic waves is given by:

$$E_{kp} = \left(\frac{M_g}{M_g + M_p}\right) E_k \quad (21)$$

Equation 21 shows that the usable energy increases with the charge size (E_k) and the mass of the gun system, but decreases with the mass of the impactor. Equation 21 could be re-arranged to give:

$$\frac{E_{kp}}{E_k} = \left(1 + \frac{M_p}{M_g}\right)^{-1} \quad (22)$$

where E_{kp}/E_k is the fractional gain in usable energy. A plot of fractional gain in usable energy (E_{kp}/E_k) against the ratio of the mass of the pellet to the mass of the gun system (M_p/M_g) is shown in Fig. 2. The curve shows that about 90% of the explosive energy of the charge could be available for conversion into seismic energy, if the mass of the pellet is equal to or less than 0.15 of the mass of the gun system.

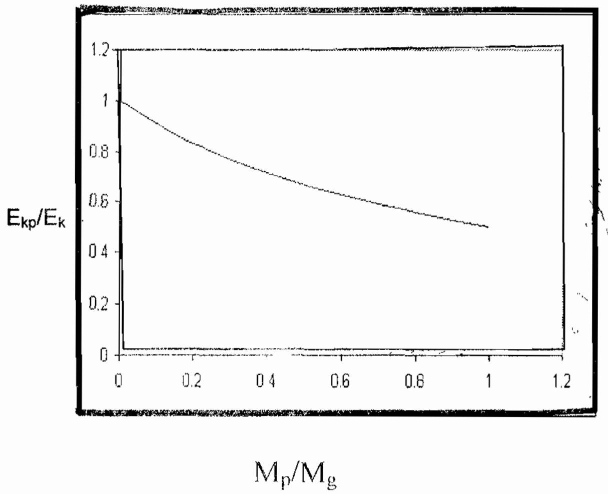

Fig. 2: A plot of the fractional gain in usable energy E_{kp}/E_k against the ratio of the mass of the pellet to the mass of the gun system M_p/M_g.

Verification of Result

In an attempt to verify the result of the theoretical analysis of an optimum surface seismic source, a prototype cannongun was tested at the University of Calabar. Firstly, ten 500 grains shots were fired which convinced us that the prototype cannongun is functional. In other to verify Equation 20, which deals with the maximum charge size that can be fired without bouncing, a 50 grains charge was fired first, then a 300 grains charge, a 550 grains charge, an 800 grains charge and a 1000 grains charge. We found that the cannongun did not bounce for the first four shots. There was a very slight bouncing-like movement when the 1000 grains shots was fired. At this point the charge size was increased by steps of 10 grains. It was found that the 400 kg cannongun clearly bounced when the charge size of 1030 grains was fired. This experimental charge size that clearly bounced the cannongun is equivalent to 206 KJ of energy.

The force constant (stiffness) k, of the shock absorber (spring) is 33000 Nm^{-1}, the distance of compression of the spring is 0.12m, the mass of the cannongun M_g is 400 kg and the mass of the pellet M_p is 0.5 kg. Substituting the above values into Equation 20 gives E_k = 190.3 KJ, which is the theoretical value. The theoretical value of 190.3 KJ is 8.3% less than the experimental value of 206 KJ. We think that the experimental and theoretical values are relatively comparable. Some of the explosive energy of the charge is considered to have been lost to heat and sound.

Discussion

From the foregone analysis, it is obvious that the smaller the mass of the pellet the more is the usable energy produced by the gun system. Indeed, research carried out by Miller et al., (1992), suggests that blank loads transfer as much as three times more recordable seismic energy to the ground than loaded shells.

The parameters used for calculating the maximum charge size could be easily found. The stiffness of the spring S can be deduced by placing a known weight on the spring and measuring the length of compression of the spring. If the mass of the gun system M_g is known, then X can either be estimated from equation 18, or by practically measuring the change in the height of the system due to the weight of the gun on the spring. M_p can be deduced from experiment but experience by the present writers shows that for a gun with about 4cm diameter and chamber depth of 20cm, the maximum possible pellet size is about 1.25kg while the minimum is about 0.05kg. The charge size can be easily converted from mass to energy and vice versa. 500 grains (~32.5g) of black powder is equivalent to 100kJ of explosive energy (Parker et al., 1993). With the above expository, it is expected that better and more powerful explosive powered impactive sources would be developed in the future. It should be noted that the depth of the cavity is not considered in this analysis. This is because the model considered is impactive. However, it is advised that the mouth of the chamber should be at or very close to the base of the cavity.

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