ICI Explosives

ICI Explosives Canada

EGGS, BEER BOTTLES, AND LIGHT TUBES

A Perspective on the Damage Potential of Seismic Detonations

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ABSTRACT

Typical explosive charges used in seismic exploration were detonated at various distances from an array of buried fragile objects such as eggs, beer bottles, fluorescent light tubes and glass ornaments. It was found that nothing could be damaged by the ground vibrations from a one kilogram explosive charge beyond a radius of three metres. Two kilograms damaged nothing beyond five metres, and even 10 kilograms proved safe at 18 metres.

The tests provide a practical yet simple means of demonstrating the validity of the scaling factor developed in Canada by Edwards and Northwood in 1960 to preclude damage to nearby structures:-

$$\frac{E^{2/3}}{D} = 0.19$$

where E is the weight of explosives in kilograms and D is the distance between the explosive charge and the target.

ICI Canada Inc. has applied the conservative 0.19 format for safe blasting for many years. In spite of this, the seismic industry is only too familiar with claims that seismic shots have damaged massive structures hundreds of metres distant. The reasons why people make such claims are addressed.

Damage disputes often prove difficult to resolve because the significance of terms such as resultant peak particle velocity is seldom appreciated by people unfamiliar with the technical background. The simple tests with fragile items such as light tubes offer a more effective means of illuminating the situation and of putting the damage potential of seismic detonations in perspective.

1. INTRODUCTION

1.1 Background

The effect of blasting on nearby structures has been the subject of extensive studies dating back to 1930. Through the years, various criteria were developed to correlate damage with ground vibrations in terms of particle acceleration, amplitude, velocity and frequency. For explosive induced vibrations, particle velocity has evolved as the single most useful gauge of damage potential.

The United States Bureau of Mines (USBM) has been particularly active in this field, (1-7). The US workers developed ratios based on distance and explosive charge weight to control particle velocity. Known as scaled distances, these ratios can be set to control vibration levels at nearby buildings. For most applications, a particle velocity below 50 millimetres/second (mm/sec) is safe, and a scaled distance:

$$\frac{D}{\sqrt{E}} = 22.5$$

D = metres to target
E = kilograms of explosive

is conservative, and can be applied even in absence of instrumentation. Since 1984 this has been the scaled distance used in Canada for seismic exploration near high pressure pipelines. A 2 kilogram (kg) charge may be fired 32 metres (m) from the pipeline.

In Canada, Edwards and Northwood independently established the importance of particle velocity (8). The Canadian workers found that the onset of minor damage such as hairline cracks in plasterboard corresponded with peak particle velocity in the range 100 mm/sec to 125 mm/sec. This is very similar to the USBM observations and to the findings of Langefors in Sweden (9), Kirillov in the USSR (10), and Crandall in the USA (11). In fact, the data obtained by researchers in different countries using varied techniques and instrumentation are remarkably convergent. It is now universally accepted that particle velocity is the key descriptor and a value of 50 mm/sec or less can be equated with a very low probability of damage for any structure. Particle velocities of this order are commonplace in most households on a daily basis due to normal human activity.

1.2 Seismic Exploration

In more conventional explosives applications such as surface mining or quarrying, huge quantities of explosives are detonated at large absolute distances from structures. This can create long-duration, low frequency wave trains which may necessitate a reduction in the particle velocity threshold at lower frequencies as proposed by Siskind et al in 1980 (7). We need not be concerned with this effect when detonating small charges close to buildings. In Canada, we typically shoot only 1 or 2 kg at offsets of 32 to 180 m from the nearest structure to obtain seismic data. The Canadian study employed instantaneous detonation of single charges which aptly describes the seismic application.

1.3 The Canadian Study

The studies carried out in Canada by A.T. Edwards (Hydro Electric Power Commission of Ontario), and T.D. Northwood (National Research Council, Ottawa), are considered classics in the field. During construction in the St. Lawrence Seaway project in 1960, the Commission acquired numerous masonry and frame buildings which were to be demolished. This provided the opportunity to test all types of structural components to failure by shooting increasing explosive charge weights at progressively shorter distances. Charges ranging from 23 kg to 340 kg were detonated at distances of 60 m down to only 9 m from houses at a variety of sites. The following scaling factor was derived to describe the condition for onset of minor damage:-

$$\frac{E^{2/3}}{D} = 0.58$$

E = Explosive Weight (kilograms)
D = Distance (metres)

This correspondèd to particle velocities in excess of 100 mm/sec. The authors then recommended that a safety limit of 50 mm/sec be established, and that the relationship

$$\frac{E^{2/3}}{D} = 0.19$$

be adopted for normal blasting operations.

Since the 60's, ICI Canada Inc. has applied the Edwards Northwood criteria to avoid damaging nearby structures. ICI experience includes construction of the Montreal and Toronto underground transit systems where tunnels had to pass close to water mains, sewers, and buildings requiring special attention. This included hospitals and buildings containing delicate equipment. A classic example was the construction of Cadillac station in Montreal. The station had to be excavated within 15 m of a Bell telephone exchange which could not be disturbed or suffer any possible damage. Application of these criteria to avoid damaging nearby buildings has the solid backing of vibration consultants such as VME, Toronto, who have more than 35 years experience in this field.

1.4 Seismic Charge Range

The charge size used for seismic exploration ranges from 0.5 kg to 10 kg. For most applications, the popular charge size is 1 or 2 kg. The charge is normally increased to 10 kg only in remote areas. The following table shows how ICI Explosives would apply the Edwards Northwood format opposite three sets of structural conditions. In each case, the table provides the offset distances corresponding to the explosive weight indicated.

TABLE I DISTANCE (metres)

FORMAT	APPLICATION	EXPLOSIVE CHARGE WEIGHT		
		1 KG	2 KG	10 KG
$\frac{E^{2/3}}{D} = 0.19$	Historical monuments; delicate structures; plaster etc.	5.2	8.3	24.3
$\frac{E^{2/3}}{D} = 0.39$	Massive concrete structures; steel installations	2.5	4.1	11.9
$\frac{E^{2/3}}{D} = 0.58$	Company owned structures, (no third party)	1.7	2.7	8.0

Thus, a typical seismic charge of 1 kg would damage nothing outside a radius of 5 m. Even 10 kg could be detonated safely only 24 m from fragile structures.

1.5 Damage Disputes

The distances in Table I are much shorter than any regulatory seismic offsets. Yet the seismic industry has to cope with numerous damage claims every year. This can be a serious problem for industry, for government agencies, and for the public who feel their property is at risk. Attempts to settle disputes in terms of scaling factors and complex particle motions frequently prove futile because the technical aspects of the problem are not clearly understood by some or all of the principals.

The Edwards Northwood guidelines have been widely used in Canada for many years. Clearly, it is safe to detonate buried explosive charges much closer to all types of buildings than most people realise. The problem has always been how to demonstrate this in a way that everyone could understand. To do this, a series of tests was initiated using common household items easily recognisable as being fragile in nature.

The purpose of this work was twofold:-

(1) to provide a practical yet simple means of demonstrating the validity of the Edwards Northwood format for seismic shooting, and (2) to simplify damage disputes by fostering a better understanding of the effects of seismic detonations.

2. TESTS WITH FRAGILE OBJECTS

2.1 Standard Seismic Programs

The initial experiments at Vauxhall, AB in February, 1989, involved eggs and beer bottles buried very close to standard seismic shot holes containing 1 kg of GEOGEL high explosive. The typical arrangement is shown in figure 1. The eggs and glass bottles were coupled tightly to the ground by packing firmly with wet earth and mud. The actual distance through the ground between the explosive charges and the fragile targets ranged from 17.6 m to 26.5 m. The tests were repeated at six shot holes. In every case, the eggs and bottles were retrieved unharmed.

In the next series at Vulcan, AB in March, 1989, regular light bulbs and F-40 fluorescent light tubes (length 1.2 m, dia. 37 mm) were buried beside the eggs close to 18 m shot holes containing 2 kg of GEOGEL. The configuration is shown in figure 2. The eggs, bulbs, and tubes were unharmed by five separate 2 kg explosions at only 17.0 m separation.

From testing on regular seismic programs at various locations in southern Alberta in 1989, it became clear that fragile objects could not be damaged when completely buried no more than 17 m from typical seismic explosive charges of 1 or 2 kg. In June, 1989, a new dimension was introduced on a program near High River, AB. The F-40 fluorescent light tubes were embedded in the ground vertically with half of the tube protruding above the ground. A special auger of dia. 38 mm was used to create holes only marginally larger than the tubes, and water was added as the tubes were inserted to ensure good coupling with the ground. A typical arrangement is shown in figure 3. The half-buried tube represents a worst case scenario since only the lower half is subjected to ground vibration. This places a flex strain lengthwise on the tube. Totally buried objects are not subjected to this type of flexing and are consequently less susceptible to possible damage than surface structures. The program at High River employed 1 kg in 12 m holes so the closest tubes and eggs were now only 12.2 m from the detonations. As before, there was no damage.

2.2 Low Pressure Pipelines

In April, 1989, the Alberta Federation of Gas Co-ops expressed concern about the damage potential of seismic explosives detonated close to plastic pipes carrying gas at pressures up to 690 kPa (100 psi). An independent consultant, SCION Engineering Limited, was commissioned to hold special tests on an abandoned pipeline at Trochu, AB. In the tests, 1 kg explosive charges were detonated directly beneath the pipeline at 18 m and 9 m depths. Eggs and beer bottles were buried at 1 m, 3 m, and 5 m offsets from the shot holes. Although the shortest distance between explosives and targets was 8 m, no fragile items were broken (12). SCION also established that the explosive shots had no effect on the old pipeline (13).

In another pipeline demonstration at Crossfield, AB in May, 1990, 1 kg explosive charges were detonated directly beneath a live pipeline carrying gas at 400 kPa (60 psi). The operating pipeline, buried eggs and beer bottles, and vertically embedded light tubes were only 8 m from the explosive detonations. The absence of damage to the pipeline or to any of the fragile targets was witnessed by more than 100 members and guests of the federation of Co-ops (14). Concern about damage from standard seismic procedures was greatly alleviated by this demonstration.

2.3 Testing to Failure

The above programs were held under varied ground conditions in various locations in Alberta. In winter, fragile objects often froze solidly into the ground, yet no damage was observed to any object buried as close as 8 m from 1 kg seismic explosions. This posed the obvious question. Just how close to fragile items could explosives be detonated without causing damage?

A special series of tests was implemented by ICI Canada Inc. near Blackie, AB through 1990. Explosives were detonated in holes drilled to a depth of only 1.5 to 2 m. Various fragile items were buried very close to the explosive charges. Figure 4 depicts the typical set up. Explosives could now be detonated close enough to fragile items to test the failure range. In addition, the degree of fragility was extended by including Christmas tree ornaments of the type which usually have to be replaced every year because they break very easily just by handling. The ornaments are in fact nothing more than a friable shell of thin glass. In many instances, it proved difficult to avoid breaking the ornaments during burial before the explosives tests.

Four separate test series were held with 1 kg charges, and two further series used 2 kg. The fragile-object array was buried at separation distances ranging from 1 m to 11 m. The results are collated in Table II (figure 5).

2.4 Results

The detonation of 1 kg of seismic explosive did not damage any fragile object buried 3 m or more from the charge. Eggs were smashed at 1 m but only cracked at 2 m. Vertically protruding lights tubes generally fractured at 2 m but always remained completely intact at 3 m from 1 kg. Absolutely nothing was damaged at distances greater than 3 m. Thus the failure range for fragile objects from 1 kg detonations is between 2 m and 3 m.

In the 2 kg tests, no items suffered damage when the targets were buried at least 5 m from the explosive. However, light tubes were cracked at 3 m, and the Christmas balls generally fractured at 4 metres. Thus the safe distance for 2 kg detonations is 4 m to 5 m.

The photographs of figures 6, 7, and 8 help to illustrate the above tests. Procedures involving buried explosives and buried targets do not lend themselves to photography, but the protruding light tube technique can be illustrated.

2.5 Tests in Water

The tests at Blackie through 1990 were carried out in ground conditions which ranged from parched soil through frozen earth to waterlogged overburden. To add another element, tests were conducted in a shallow pond as indicated in figure 9. As before, no damage befell fragile items 3 m from a 1 kg charge or 5 m from 2 kg.

2.6 Larger Charges

The typical seismic load is 1 kg to 2 kg but occasional use is made of larger charges up to 10 kg. The opportunity arose to drill and load larger charges on a road allowance near Glenmore, AB. Four kg was loaded in a 12 m hole, 6 kg to a depth of 15 m and finally 10 kg was loaded in a standard 18 m hole. The usual fragile array was buried at the surface at offsets ranging from 8 m to 30 m. The shortest distance through the ground from the top of the charge to the base of the nearest light tube was as follows:-

4 kg charge - 13 m
6 kg charge - 15 m
10 kg charge - 18 m

Nothing was damaged on detonation of the charges at or beyond these distances.

2.7 Edwards Northwood Scaling Factors

Comparing distances with explosive charge size where no damage was observed in any of the fragile targets, Edwards Northwood scaling factors can be derived as follows:-

Charge Weight, E (kg)	Safe Distance, D (m)	Scaling Factor $\frac{E^{2/3}}{D}$
1	3	0.33
2	5	0.31
4	13	0.19
6	15	0.22
10	18	0.26

The factors for 4, 6, and 10 kg are more conservative than those for 1 and 2 kg. This reflects the fact that the larger charges were not tested to failure.

The results offer practical confirmation that the Edwards Northwood format:-

$$\frac{E^{2/3}}{D} = 0.19 \qquad \begin{matrix}(E \text{ in kg}) \\ (D \text{ in m})\end{matrix}$$

is valid as a conservative blasting guideline for the typical instantaneous seismic detonation in a variety of ground conditions.

3. COMPLAINTS

3.1 The Paradox

Experiments with fragile targets confirm that detonation of a typical 1 kg seismic explosive charge will not damage anything beyond a radius of 3 m. Provincial regulations stipulate that 1 kg cannot be shot closer than 180 m from certain structures. This incorporates a 60-fold safety factor at an astronomical scaled distance of 180 $m/kg^{1/2}$. In spite of this, it is not uncommon for landowners to register complaints that massive concrete structures have been damaged by 1 kg from a distance of more than 180 m. There is a huge divergence between what is possible and what people believe is possible. This can be reconciled in terms of the extreme sensitivity of the human body to all vibrations, and of misconceptions about the destructive power of industrial explosives.

3.2 The Human Response Factor

Many studies have been made of human response to vibration. Some people can detect vibrations with particle velocities as low as 0.25 mm/sec. This is 1/200th of the conservative safety limit of 50 mm/sec. This effect was measured by Goldman (15), and his "isosensor" chart is shown in figure 10. Vibrations can be felt far below possible damage levels. Vibration levels greater than 50 mm/sec are commonplace in most homes on a daily basis due to all sorts of human activity. This includes walking, jumping, nail hammering, door slamming and operation of mechanical equipment such as washers, driers etc. The following maximum levels of particle velocity were recorded in a USBM study (7):-

Door Slamming	-	33 mm/sec
Nail Hammering	-	97 mm/sec
Jumping	-	256 mm/sec

Normal activities outside the home such as operation of vehicles, passage of trains, construction work, etc. also cause high particle velocities inside. A particularly apt example is the hydraulic post pounder used by many farmers in fence building. This device creates ground velocities higher than 50 mm/sec, but few people would think twice about using it close to a building.

3.3 Typical Complaint Scenario

The vibration levels created by normal human activity cause little concern provided the source is instantly recognisable. Children frolicking and jumping in a house can cause vibrations which would rate potentially damaging in terms of some constraints proposed by research workers. If the same vibrations occurred suddenly when the children were not in evidence, the effect on the householder would be very disturbing. Even very small vibrations are cause for great alarm when there is no obvious or familiar source.

The almost universal scenario for damage claims follows a familiar pattern. An explosive shot is fired some distance from a house causing a momentary vibration pulse. For the sake of argument we will assume the velocity is 5 mm/sec. The probability of damage at this level is zero, but the vibration is perceptible and perhaps even unpleasant to some individuals. There is no obvious reason for the sudden pulse and the homeowner wonders if it might have caused damage. In carefully scrutinising the home, he finds hairline cracks in plaster, fine cracks in the foundation or other irregularities. These defects may have existed for a long time, some perhaps even dating back to construction of the house when the structure was subjected to enormous vibrations and strains. The homeowner notices the defects for the first time only after checking the house thoroughly and systematically. A claim is on the way because it is easy to equate the damage to the unfamiliar vibration. In this way seismic operators can become a target for a claim for damage they did not cause.

Buildings sustain damage over the years for many reasons. Climatic effects of wind and temperature can cause movement of the foundation as can normal settling of the house. Houses are in fact designed to withstand movement. Floors and ceilings are designed to move up and down as much as 5 to 10 mm. There are at least 40 possible origins of defects other than human activity (1) and it would be very difficult to find a building anywhere in Canada with no defects.

3.4 Perception of Explosives

A claim can arise even when the charge is so small or the distance so great that the vibration level would not be perceptible by the most sensitive human. The layman's perception of explosives is often based on military images, or on the depictions of destruction shown in popular movies. Military explosives are designed to destroy by direct contact with a target above the ground, and Hollywood greatly exaggerates the destructive power of all explosives, perhaps understandably, for dramatic effect. The layman equates explosives with destruction whereas industry equates explosives with work or, in the case of seismic exploration, with signal. Homeowners sometimes examine their property some time after a seismic crew has passed through their region. When defects are found, the cause is often ascribed to the seismic activity even though no disturbance was noticed at the time. Seismic operators have received claims up to two years after working a program.

Misconceptions about the explosive power of buried seismic charges have also been fostered by settlements made for spurious claims. In some instances, payments have been made partly because seismic operators themselves were unfamiliar with the limitations of small explosive charges, and partly because it was expedient to settle the claim quickly and maintain good public relations. Such payments lend credence to the myth that seismic activity carries a high damage potential irrespective of charge size or distance.

3.5 Special Case: Water Wells

The claim situation is nowhere more obvious than in the case of water wells. Many test programs have been undertaken in an attempt to correlate explosives size and distance factors with damage or change in well characteristics (16, 17, 18, 19). In Alberta, a wide variety of locations was studied, and charges ranged up to 23 kg as close as 5 m from wells. These studies were singularly unsuccessful in damaging wells or reproducing the loss of yield or changes in water quality sometimes claimed after seismic activity with small charges at distances greater than 180 m. Any hole drilled near a water well might penetrate an aquifer, but it remains very unlikely that this will cause damage with the possible exception of obvious flowing holes.

The biggest problem facing seismic operators is that most claims are made for wells for which there is no documented evidence of well performance before the seismic crew passes by. Water wells can be cantankerous devices at the best of times. If a well happens to dry up or change in the time frame during or after a visit by a seismic crew, there is usually little doubt where the blame will be laid. In recent times, some operators have instituted a program of pre-testing specific wells in the vicinity of their seismic programs. For a small initial outlay, this provides an effective means of controlling the claim situation.

4. CONCLUSIONS

For many years ICI Canada Inc. has used the conservative "0.19" version of the Edwards Northwood scaling ratio for safe blasting close to buildings. Tests with recognisably fragile objects such as eggs and fluorescent light tubes have provided a practical demonstration that the 0.19 scaling factor is valid for the charge range commonly used in seismic exploration.

The vast majority of seismic work in Canada employs charges of only 1 or 2 kg. These charges cause no damage beyond a radius of 5 metres. Even the upper limit of 10 kg is safe at 24 metres. Of course charges could not be detonated this close to personal property without causing concern due to human sensitivity to vibration and perception of explosives power.

People will continue to express concern if they feel a vibration pulse due to seismic shooting even though the particle velocity is far below that which correlates with possibility of damage. The key here is education in the fact that any vibration caused by seismic work is not being directed at an otherwise vibration-free building. All houses are being vibrated all the time. The short pulse from a distant seismic shot is an insignificant addition to the total vibration content of a building due to climatic effects and human activity.

Hopefully the results of this study will foster a better understanding of the limitations of seismic explosive energy. In exploration, the seismic charge is fired solely for the purpose of providing a signal which is detected after returning to the surface only by highly sensitive seismograph equipment. The probability of damaging even the frailest of structures by direct transmissions is extremely low. If a structure is so frail that it can sustain damage from a seismic shot, then restrictions should be placed on all human activity in the vicinity of that property.

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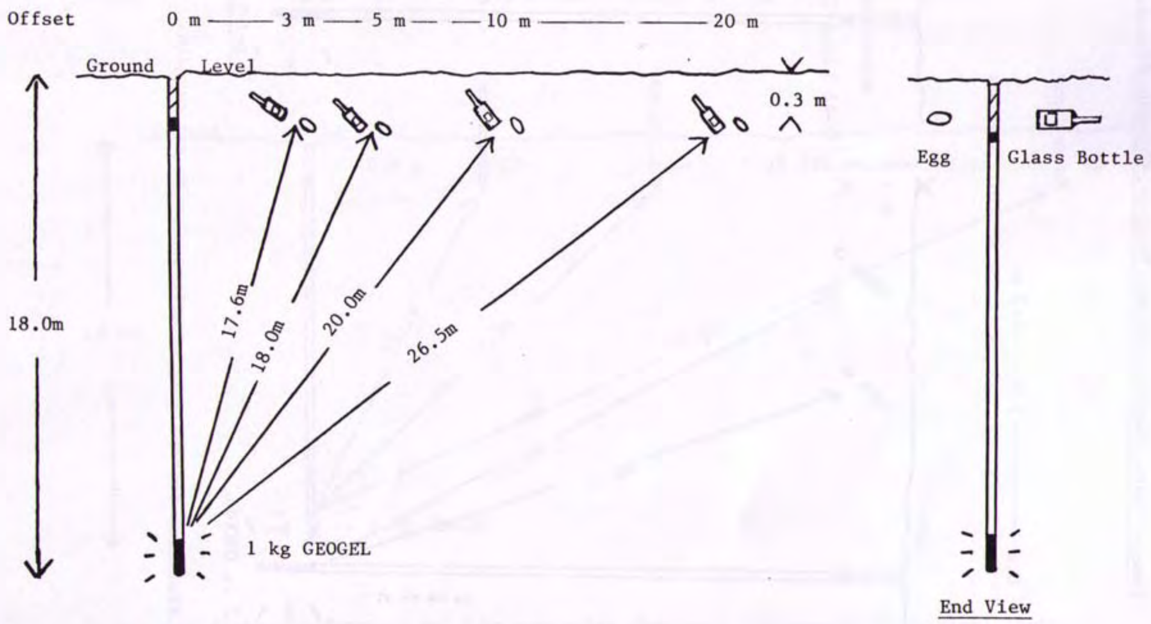
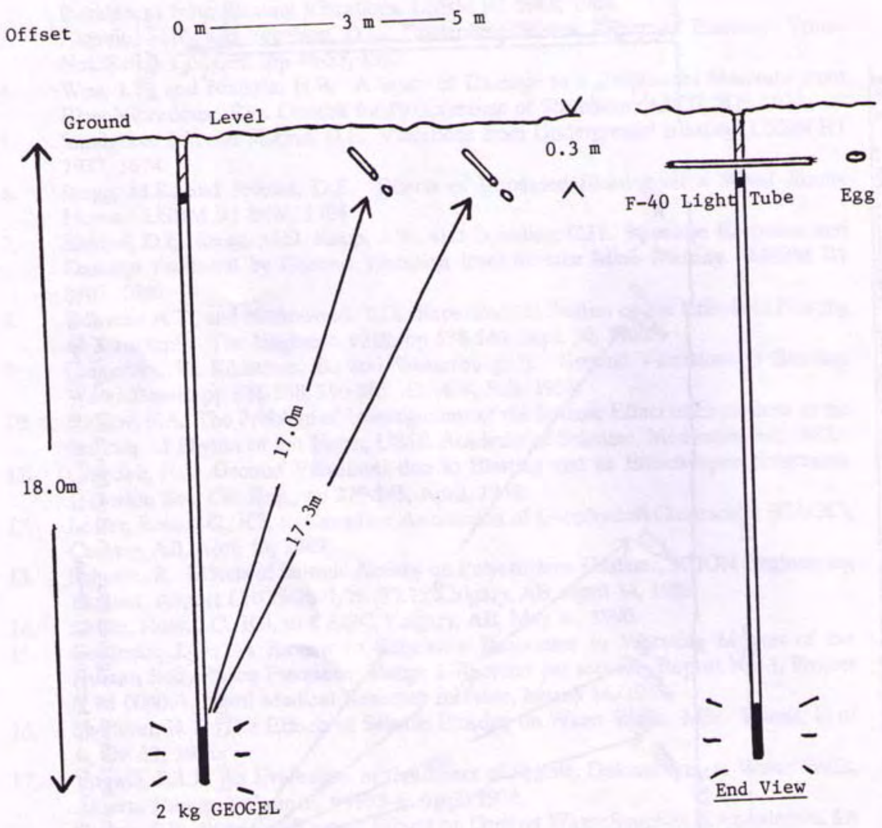
Figure 1 Damage Tests, Regular Seismic Program, Vauxhall, AB., 1 kg



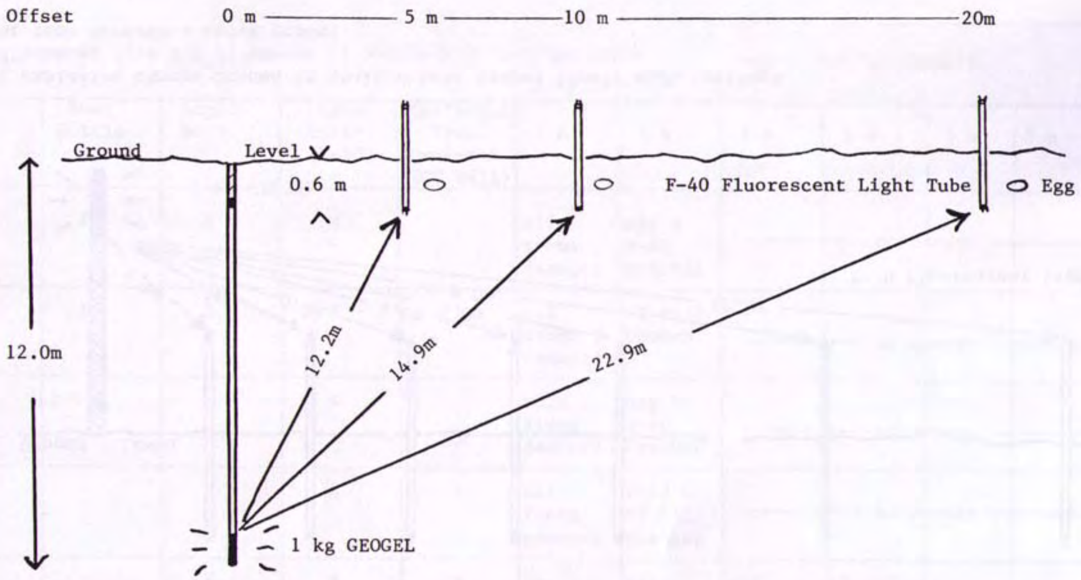
Separation distances between 1 kg seismic explosion and targets.
The eggs and bottles were oriented side-on to the incoming pulse.

Figure 2 Damage Tests, Regular Seismic Program, Vulcan, AB., 2 kg



Separation distances between 2 kg seismic explosion and targets.

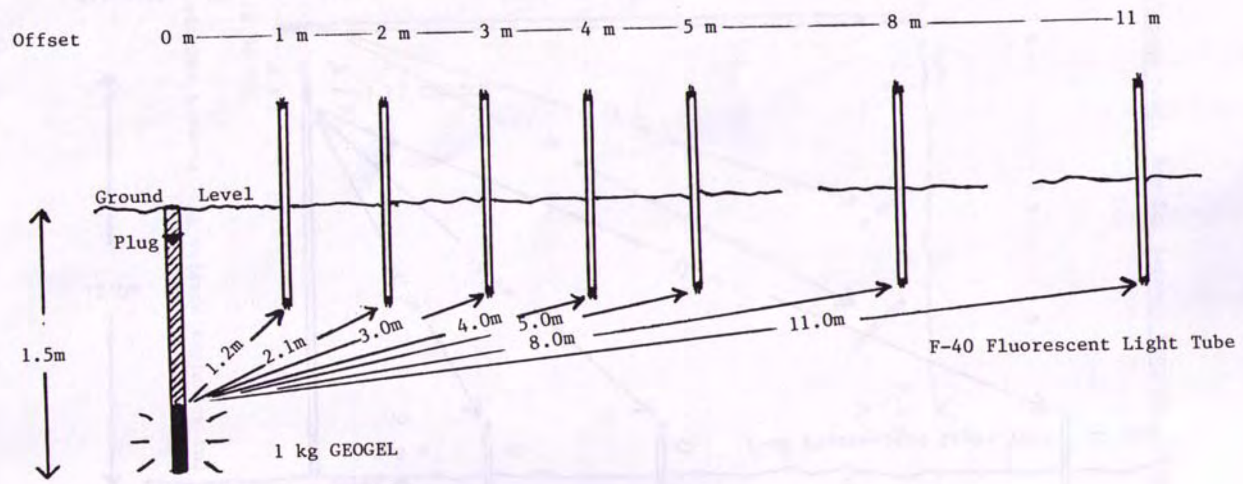
Figure 3 **Damage Tests, High River Program, 1 kg**



Separation distances from top of 1 kg explosive charge to bottom-end of vertical light tubes. Half of light tube protrudes above ground.

Figure 4

Testing to Failure, Blackie, AB.



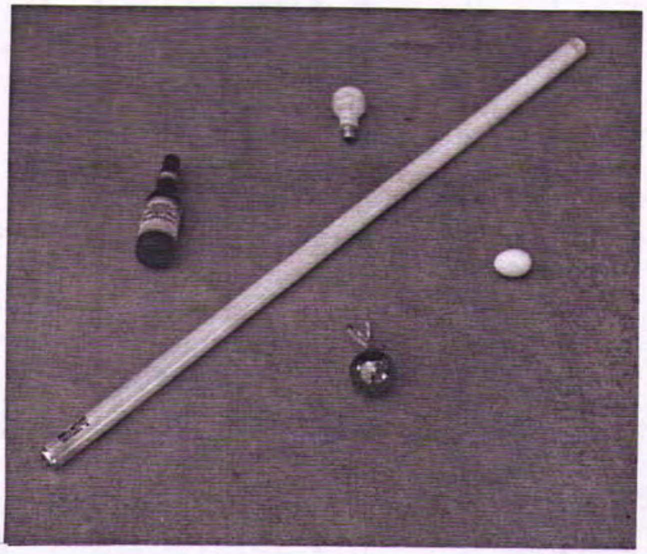
1 kg seismic explosive charge loaded in shallow hole tamped firmly with cuttings.
Separation distances from top of charge to bottom-end of light tubes.
Half of light tube protrudes above ground.

Figure 5 Table II Results of Tests-To-Failure For Fragile Targets Buried Close to Explosive Detonations

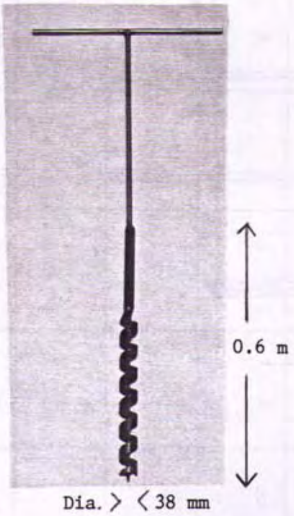
Charge Size	Targets					Separation Distance**						
	Egg	Beer Bottle	Light Bulb	Light Tube* (F-40)	Christmas Tree Ornament (CT Ball)	1 m	2 m	3 m	4 m	5 m	8 m	11 m
1 kg	X	X	X	X		all items damaged	egg & F-40 cracked	no damage				
1 kg	X	X	X	X	X	all items damaged	CT Ball broken	no damage				
1 kg	X			X		both items damaged	egg & F-40 cracked	no damage				
1 kg	X			X	X	all items damaged	F-40 & CT Ball cracked	no damage				
2 kg	X		X	X	X	-	all items damaged	all items damaged	CT Ball broken	no damage		
2 kg	X	X		X	X	-	-	F-40 & CT Ball broken	CT Ball broken	no damage		

* F-40 light tube embedded vertically, 50% above ground.
** actual distance between top of charge and bottom of target.

Figure 6 Equipment



(a) Array of targets recognisably more fragile than construction materials.



(b) Hand-auger used to drill 0.6 m by 38 mm dia. holes for vertical placement of fluorescent light tubes. Actual dia. of F-40 tubes is 37 mm, so the 1.2 m long tube is coupled tightly with 50% protruding above ground

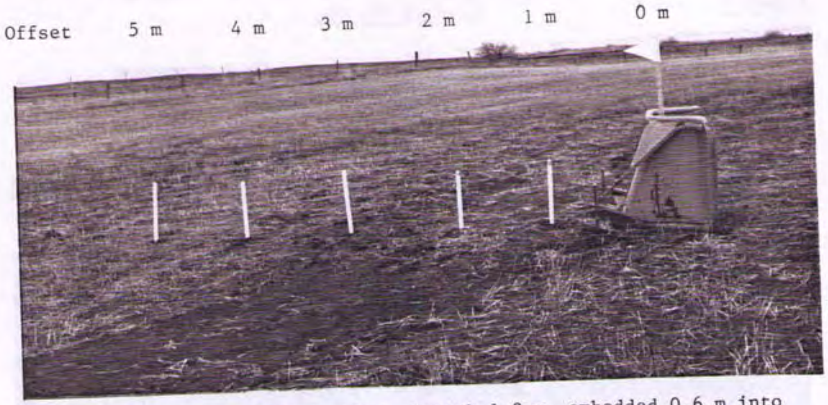
Figure 7 Closing the Gap

(a) Dick Luten of Explosives Limited looks on as a portable unit is used to drill a hole only 3 m deep. An F-40 light tube is embedded 2.1 m from the hole. 1 kg of GEOGEL high explosive was loaded here.

(b) Result. The tube is not damaged after detonation of 1 kg charge. The actual distance from the top of the charge to the base of the tube was 3.0 m.

Figure 8

Testing to Failure

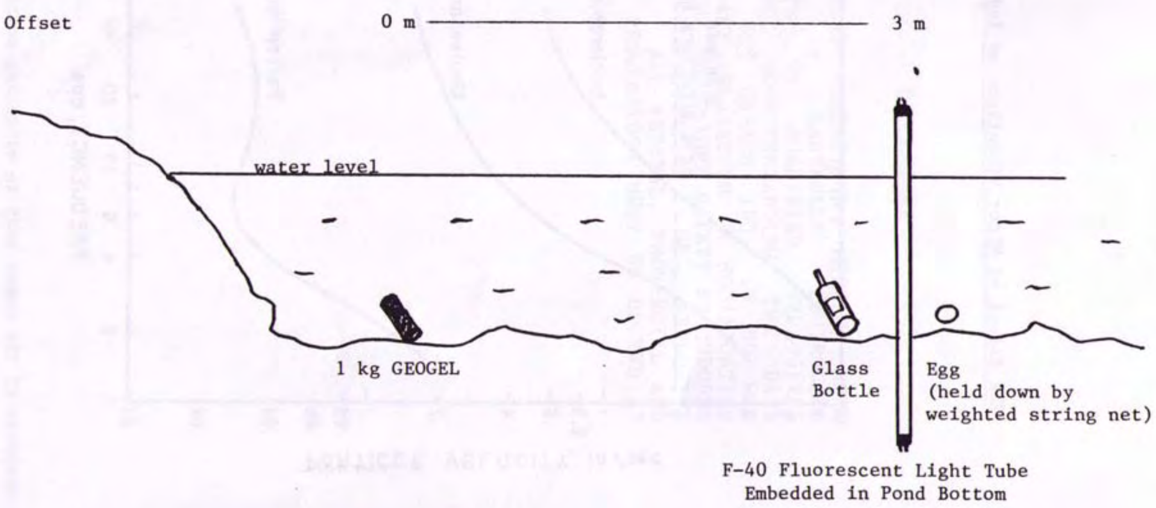


(a) F-40 fluorescent light tubes, length 1.2 m, embedded 0.6 m into the ground at 1 m, 2 m, 3 m, 4 m and 5 m offsets from a 1 kg explosive charge in a 1.5 m hole. A steel shield weighing 300 kg protects the near tubes from surface projectiles in the event of spalling or cratering at the top of the drill hole. Location of hole is indicated by flag.

(b) The explosive charge has been detonated. The ground vibration pulse breaks the tube at 1 m and cracks the tube at 2 m. The tubes at 3 m, 4 m and 5 m are unharmed.

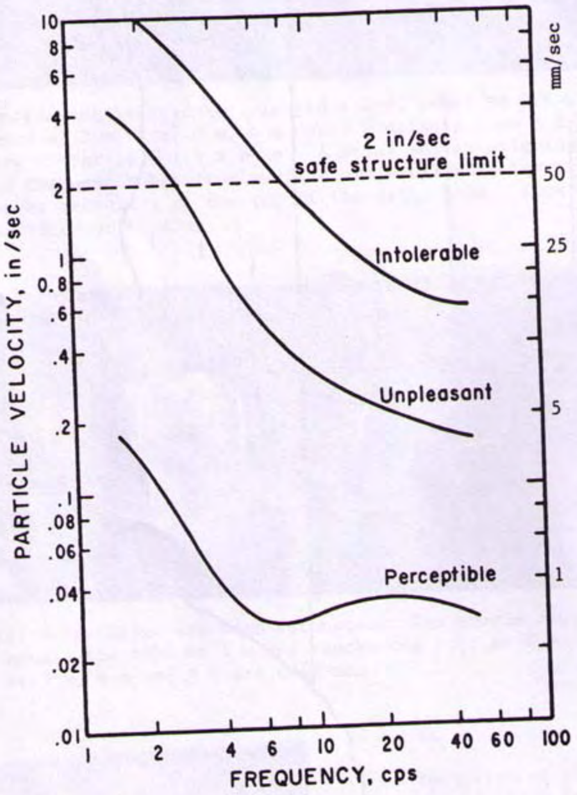
(c) Rear view of the surface shield which is open at the top and at the side opposite the target line.

Figure 9 Testing In Water, Blackie, AB.



1 kg seismic explosive detonated 3 m from targets in a shallow pond.

Figure 10 The Effect of Minor Vibrations on Individuals



Subjective response of the human body to vibrating motion, (after Goldman).

DISCLAIMER

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