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THE APPLICATION OF THEORETICAL RESULTS IN THE DESIGN OF SAFE SHELTERS IN ROCK

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A review is given ~~of the~~ an approach introduced by the autor used to describe the propagation of shock waves in rock. Its application in the design of safe shelters is discussed and the results are confronted with those from other sources.

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The Application of Theoretical Results in the Design of Safe Shelters in Rock

by

Leif N. Persen *

Introduction

In the design of safe shelters in rock three main regions distinguish themselves as regions where problems of different nature occur. Because the shelter is supposedly attacked by exploding weapons such as shells or bombs, the first region of interest will be the study of surface bursts. Surface bursts may be of three different types, the elevated burst, the tangential burst and the semi-burried burst. The main questions to be answered in this region are: What are the characteristics of the shock waves created in the rock by these bursts? Can they be interrelated and can they be related to fully confined bursts? Can cratering be predicted and how is the shock wave influenced by it? Several other important questions may of course also be asked, but these are the main ones to be investigated here.

The second region of interest will be the transmission of the shock wave over the distance between the surface burst and the shelter. This part of the investigation is usually taken care of by the application of some theory for the propagation of stress waves.

The third region of interest will then be the interaction between the shock wave and the shelter (tunnel). In this region the major questions will be: How does one best describe the interaction between the shock wave and the tunnel? What is the collapse criterion of the tunnel? How do different types of lining affect the carrying capacity of the tunnel? Again, several other questions may be asked, but the ones listed are the ones to be investigated here.

Region II

In this region the propagation of shock waves in rock is at the center of interest. The theory to be used is based on a visco-elastic model as exhibited in detail in [1] and summarized in [2], the latter being presented as part of the present investigation. The details of this theory will be omitted here, but it is worth while to contemplate the general philosophy behind it. A rock site selected for the purpose of building a shelter in it will have to be tested for its quality as a transmitting medium for the stress waves. This is done by performing experimental tests in smaller scale at several locations and in several directions within the site. These tests are designed such that spherically symmetric compression waves, created by spherical charges detonated completely confined along the straight continuation of the measuring distance, are monitored by means of suitable pick-ups as they travel in both directions over this distance. The size of the monitoring distance should be chosen such that it encompasses a sufficient portion of the rock's dislocations, cracks,etc responsible for the attenuation effect. It should however not encompass major faults in the rock. The reason for this is that,with reference to Fig.1,the stress wave travelling from A

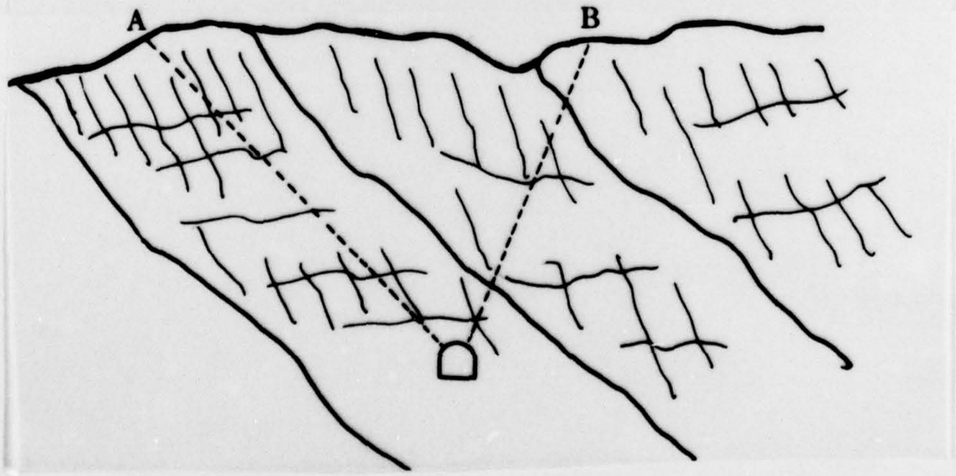

Fig.1. Rock site with major faults whereby stress waves from A become more dangerous than those from B.

will endanger the tunnel far more than the one travelling from the closer location B due to the fact that the latter one has been attenuated additionally by the two major faults it has passed.

The result of such an experimental examination of the rock site is that five parameters characterizing the rock as a transmitting medium will be determined:

1. c_s = the signal velocity in the rock
2. κ = the non-dimensional parameter characterizing the confined explosion in the rock
3. τ_o = the non-dimensional duration time of the replacement input-pulse or its impulse
4. a = characteristic length in the problem, equal to the radius of the sphere with which the explosion is replaced
5. p_o = the initial pressure (inside the sphere)

of these parameters c_s and κ are very little influenced by the type of explosive used, whereas τ_o is very much influenced by it. The influence of the explosive on the parameters a and p_o is found theoretically.

With these parameters known, the extrapolation to larger charges is easily performed using the theoretical relations. Far more important is however the fact that the analysis offers the opportunity to convert results valid for one type of explosive into predictions for another type of explosive through its influence on the parameter τ_o. Whether this can be extended also to include nuclear explosives can only be determined from an examination of the relevant data from such explosions. A careful study of the data used by SAUER [3] in his exposition in Nuclear Geoplosics indicates that data from confined explosions of nuclear as well as conventional explosives in the same rock are obtainable. Unfortunately these were not available for the present investigation.

Another major advantage over the empirical scaling laws offered by the present approach lies in the fact that the characteristic length a and the peak initial pressure p_o are determined directly in the specific rock site under consideration by means of the small scale experiments. The necessity of carrying over results from other test sites and other types of rock by means of some sort of scaling procedure is avoided. SAUER [3] warns against the limitation in the validity of scaling procedures, and his objections are very relevant. To a certain extent these objections are met and nullified in the presented procedure. The Cowboy-Hobo anomaly described by SAUER [3] may be explained by the proposed procedure as may also the anomaly found between the nuclear and high explosive free-field data.

The only data from fully contained nuclear explosions available to the author were the ones obtained in Operation MINE SHAFT, Mineral Lode event. Particle velocities were recorded as functions of time at 5 locations on a horizontal line running west and 4 locations on a line running south from the center of the explosion. In Fig.2 the arrival time of the signal at each location is plotted against the distance between the cen-

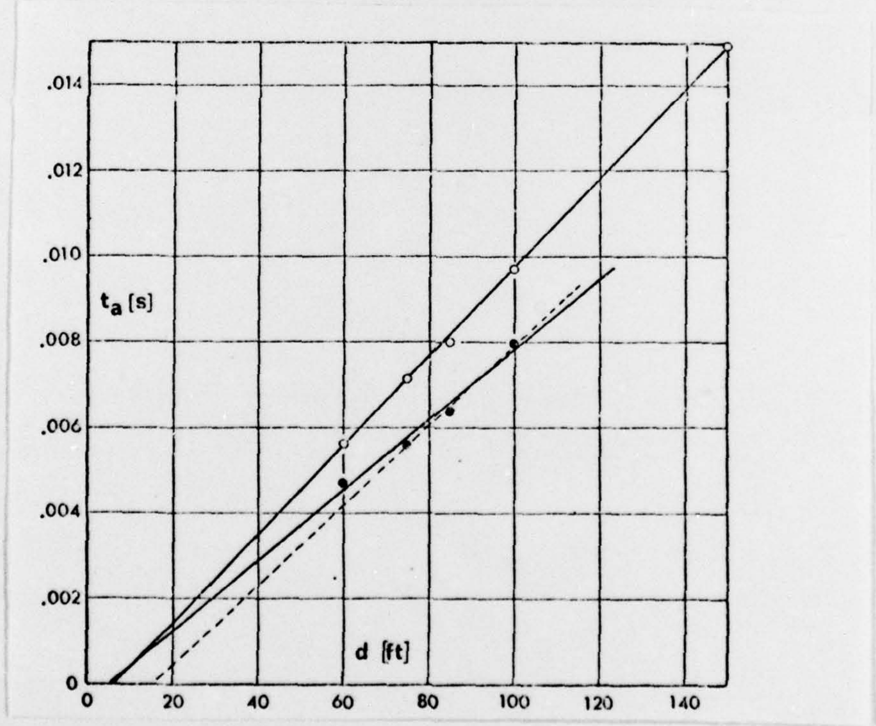

Fig.2. Arrival times t_a plotted against the distance d between the center of explosion and the measuring device (○ on the west line, ● on the south line)

ter of the explosion and the gage. The slope of the straight line through these data points will give the signal velocity of the rock. It is observed that this quantity is different along the two lines indicating that the rock's properties as a wave transmitting medium may be different in different directions. It should perhaps be mentioned that the two fully drawn lines indicate signal velocities c_s which are rather low:

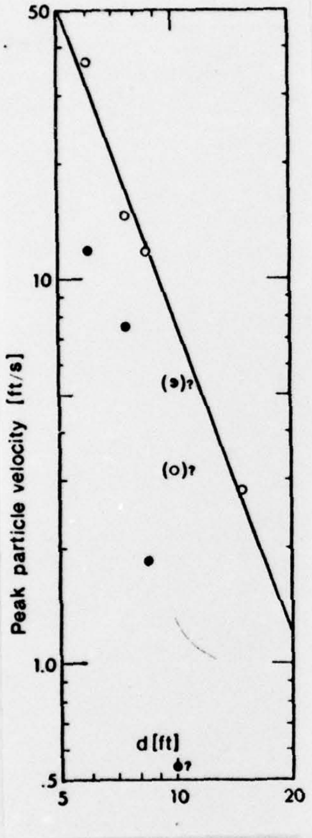

Fig.3 Peak particle velocity plotted against distance

$$(\bullet) \qquad c_s = 12180 \text{ [ft/s]} = 3712 \text{ [m/s]}$$
$$(\circ) \qquad c_s = 9610 \text{ [ft/s]} = 2930 \text{ [m/s]} \qquad (1)$$

If one disregards the data-point which on the south line obviously deviates the most, the dashed line in Fig.2 is obtained with

$$(\bullet) \qquad c_s = 10750 \text{[ft/s]} = 3277 \text{ [m/s]} \qquad (2)$$

None of these values coincides, and they are all less than $c_s = 14400$ [ft/s] specified in [4] by COOPER as the "peak compressional wave speed for granite".

The peak particle velocity data plotted in Fig.3 show the same type of difference between the west and south line observations. The data points shown in a paranthesis () are dubious, and this leaves only 3 points on the south line and 4 points on the west line for the determination of the attenuation curve. It is felt that this represents an insufficient basis from which to draw any general conclusions. However, the straight line through the data points on the west line has a slope $\lambda = -2.695$ (Fig.3) whereas SAUER [3] uses $\lambda = -1.65$ for his "composite curve" and COOPER [4] operates with $\lambda = -2.00$ for his "scatter band". These latter values agree very well with the author's own experience, and one is led to believe that the value obtained here is unrealistic and reflects conditions in the rock site which one can only make a guess about. Further attempts at utilizing the data were thus deemed futile.

The presentation given by COOPER [4] contains a number of statements on the general philosophy behind the work done both theoretically and experimentally in this field. It is therefore relevant to confront the present approach with these statements to discover how many questions one agrees on and also to stress the differences where they occur. In discussing the lesson from the research of the past five years COOPER [4],p.11,sums up:

> "And it is well to keep in mind that field experiments can and should play a vital role in evaluating theoretical procedures. A reliance on theory alone to provide quantitative and even qualitative predictions can and has led to embarrassing departures from reality."

This agrees exactly with the philosphy of the present approach, which relies on in-situ experiments of a scale sufficient to embrace the structure of the rock site responsible for its energy-absorbing effect as a wave-transmitting medium. (This will still be a "small" scale experiment compared to the expected real event.)

COOPER [4],p.20, goes however on to the following statement:

> "Although one might distinguish between certain material property differences in the various sites involved, (e.g., characteristic impedance), the site-to-site variations produce changes in the peak particle velocity that probably are not distinguishable within a single well-instrumented event's data scatter."

This statement, if it is accepted, would inevitably lead to the conclusion that nothing more precise than COOPER's scatterbands could ever be obtained for the attenuation curves, and that attempts in that direction would be more or less futile. The width of these scatterbands corresponds to a factor of 4, and in later statements COOPER [4],p.25 and p.78, modifies his first:

> "Some of the uncertainty in making predictions for a particular site might be reduced by a direct experiment at that site. However, it is unlikely that knowledge of the site will ever be complete enough to reduce the implied uncertainty to less than a factor of two."

> "Although some of this scatter may be systematic, it is doubtful that additional studies or data at a given site will reduce the scatter to less than a factor of 2 or 3--which may be considered as an inherent uncertainty."

These statements by COOPER have been drawn to attention here both because they seem to reflect an accepted opinion and because they are at variance with the philosophy of the present approach.

It must be accepted as an experimental fact that identical explosions in different sites may give data which differ considerably even though the geology of the sites seem to be the same. The difference appears in the slopes of the attenuation curves as well as in the absolute values at a given range. COOPER's [4] philosophy implies plotting all data obtained at different sites on to one and the same diagram and living with the great scatterband thus obtained. SAUER's [3] philosophy implies an attempt at improving the situation by using properly selected coefficients for each geological specification with which the data from each geology is to be multiplied. In this way the data are brought to converge around what is called "composite attenuation curves". Both approaches operate with constant slopes λ of the attenuation curves for particle velocity irrespective of geology. [COOPER: $\lambda = -2.00$, SAUER: $\lambda = -1.65$] The philosophy of the present approach implies testing each site which is being considered for sheltering purposes. The result of these tests will be the determination of the parameters κ and τ_0, the characteristic length a and the initial pressure p_0. The two latter ones describe the interaction between the explosive and the rock at the origin. In the philosophy of SAUER one may conceive of this as an experimental determination of his "coefficient". The present approach will in addition to this advantage also avoid the difficulty met with in SAUER's approach which manifests itself by the necessity in certain circumstances to operate with different coefficients for particle velocity and particle acceleration. The benefits of the present approach may however go beyond that. The explosion is replaced by an imaginary sphere of radius a inside which a pressure p_0 acts to create the shock wave. Because this can be done both for a nuclear as well as for a conventional charge one may use this to find the conventional equivalence of a nuclear charge without going into the uncertainties of an energetic argument.

Finally it ought not to be suppressed that the present approach has not been seriously tested against experimental evidence from nuclear events. The claims made are based on experience with conventional charges, and the only test against nuclear data are to be found in PERSEN [2]. This gap ought to be bridged in future investigations.

Region I

The main problem in this region may be said to be the question of coupling. The charge may detonate above , on , or below the surface and to describe the coupling adequately it is suggested to distinguish between two cases, namely those which do and those which do not create a crater. This distinction is based on the fact that the coupling process is governed by different physical parameters in the two cases. The distinction seems to be contrary to the philosophy underlying the CENSE I experiments discussed by INGRAM/DRAKE/INGRAM [5], but agrees with COOPER's philosophy [4]. In the case of a cratering explosion COOPER [4],p.38, describes the advantages of using the crater as a reference:

> "We shall assume that the cube-root of the crater volume is a characteristic length that can be used to correlate the close-in, near surface direct-induced ground motions from both high-explosive and nuclear cratering bursts. By close-in we mean ground ranges less than about $7.5V^{1\ 3}$ where V is the apparent crater volume. Such a geometrical scaling avoids arguments over the differences between nuclear and high-explosive sources by hypothesizing that the direct-induced ground motions can be directly correlated with the size of the crater in both cases.In other words, it is hypothesized that whatever physical phenomenon causes a large crater also causes correspondingly larger close-in ground motions independent of details of the explosive source."

This agrees exactly with the philosophy put forward independently by PERSEN [1],Ch.12, where also the question of how to draw conclusions valid for surface bursts from knowledge of the contained explosion in the same rock is discussed.It is nice to be able to express the result of these considerations in the phrasing of COOPER [4],p.16,:

> "Theoretical calculations and limited test data for surface explosions on "uniform" hard rock suggest that the early-time ground shock under ground zero approximates a spherically diverging stress and velocity field within a conical region out to about 45-60 degrees from the vertical axis."

The basic philosophy behind the handling of cratering surface bursts thus seems to be well agreed upon. The difference between the two approaches lies in the way in which the event is described. Because the fully confined explosion in the present approach is described through the characteristic length and the initial pressure, i.e. through the imaginary sphere, the surface burst is treated similarly. The correlation of the two events is obtained through the relation between their characteristic lengths and their initial pressures. The present approach thus allows a much more precise formulation of the relation sought, but its advantage goes beyond that. The physical significance of the two parameters a and p_o is to express the interaction between the explosive and the adjacent rock during the explosion. This means however that they in a way describe the "cratering" that takes place at a confined explosion. Consequently one may expect that relations between the parameters in the two cases may exhibit some degree of generality, whereby the cratering taking place at a surface burst may be predicted from knowledge of the parameters of the confined burst. How this is done is exhibited in PERSEN [1],Ch.12, and although the experimental verification of the procedure is lacking in generality, it is interesting to confront this result with others'. COOPER [4],p.27, gives his result in the following statement for the particle velocities for the surface burst:

> "The particle velocities are consistent with data from tamped bursts scaled to a yield of only 0.16 of that for the cavity test."

A somewhat different result was conveyed to the author in privat communications based on the composite curves of SAUER [3] where the scaling factor was set at 0.25 in the same meaning as above. PERSEN [1] gives however his result in a somewhat different way which makes it necessary to convert one into the other for the purpose of comparison. Let fW be the surface charge which will produce the same stress at a given distance as the charge W will when detonated confined. Let λ be the slope of the attenuation curve, and β be the ratio between the stress created at a given distance by the charge W when it is detonated confined and the same stress when it is detonated as a cratering surface charge. According to the attenuation curve one will have the following relation between these quantities:

$$\beta = f^{-\lambda/3} \tag{3}$$

By means of this relation one may now compare the results as shown in the following table where entries in parantheses are

Case	λ	f	β
COOPER	2.00	6.25	(3.39)
SAUER	1.65	4.00	(2.14)
PERSEN	2.23	(2.54)	2.00

computed by means of (3). It is easily seen that if the correlation between the confined and the surface bursts is expressed through β, then the PERSEN and the SAUER approaches agree rather well. If , however, the correlation is expressed through f, the three cases show different results which may reflect the fact that the coupling has been different in these cases. It seems however that the present approach offers a more refined way of describing the correlation than do the direct scaling through charge magnitude.

The non-cratering surface burst has been investigated in two different series of experiments carried out in Norway and described by PERSEN [6] in a report which is to be considered an integral part of the present report. The report is an attempt at setting up empirical relations relevant for the purpose.

Region III

The interaction between the tunnel and an on-coming shock wave is a very complex problem. Several experimental investigations have been carried out both in Norway and in Germany sponsored by the German Defense Ministry. The results of these experiments are described by PERSEN [7] in a report which is an integral part of the present report. The position taken in these investigations are perhaps best described by referring to COOPER [4],p.14, where he divides the interaction into early-time and late-time phenomena:

> "Early-time phenomena have been the subject of much theoretical and experimental study and most qualitative features are thought to be reasonably well understood.* "
>
> " * This is not to say that structural failure mechanisms produced by early-time phenomena are necessarily well understood."

The report adresses itself to the early-time phenomena, and represents an attempt at improving our understanding at this point. The report is mainly giving empitical information.

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