LUMPED MASS MODELING OF OVERBURDEN MOTION DURING EXPLOSIVE BLASTING

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ABSTRACT

The in situ extraction of oil from most oil shale beds is highly dependent upon explosive fracturing and rubbling of rock in a controlled and predictable manner. Besides the rubbling requirement, it is also important that the surrounding rock remain competent to minimize fluid leakage during processing. For rubbling concepts in which the overburden is explosively lifted to provide the required void in an oil shale zone, an engineering lumped mass model has been devised to describe the motion of the overburden. The model simulates the overburden as an array of interacting lumped masses which are loaded from below with a time-dependent force to approximate the explosive load. Correlation with experimental data obtained from field blasting operations shows that this model will provide an adequate approximation of overburden behavior. The basic features of the model are described in the report along with the correlations with field data. Results from several parametric studies are also presented which were used to aid in blast design. This lumped mass model can be extended to include other parameters and has potential for the study of other related blasting situations.

INTRODUCTION

One of the "synthetic fuels" presently being studied is oil derived from oil shale, a sedimentary rock which contains an organic solid called kerogen. The conversion of oil shale kerogen into liquid and gaseous products is the focus of considerable research in the U. S. at present.

Kerogen is converted into usable fuels by heating oil shale in an oxygen-controlled environment. The resulting fluids, shale oil in particular, is then subjected to additional refining in a manner similar to that used for conventional crude oil.

Although the retorting process can be done is a variety of containers, in situ methods use the surrounding rock as the retort container. The rock within the retort zone must be permeable to permit flow of gases and/or liquids to heat the rock and recover the product fluids. Further, process requirements necessitate control of the degree and extent of the permeability of both the retort zone and the surrounding rock.

A common technique used to increase in situ permeability involves the use of chemical explosives. The explosive not only fractures the rock, but also moves the broken rock, permitting the translation and rotation of individual pieces, thereby creating a rubbled zone. Good rubblization requires large-scale motion of the fractured rock and in some cases significant motion of the adjacent rock.

At least two in situ oil shale processing concepts currently under investigation employ explosive fracturing to prepare underground retorts. In a modified in situ blasting configuration, an initial void is created by mining; subsequent blasting breaks and heaves the resulting fragments into the void. A second method requires large ground (overburden) motion to create the void necessary for fragment movement. An analysis technique is presented in this report which deals with the latter retort bed preparation concept. The work considered is a direct result of an attempt both to understand and to predict the overburden motion during blasting. This type of model, while being developed to examine overburden motion is not restricted to this particular geometry, but has potential use in other blasting operations.

BLAST DESIGN

The use of explosives to fracture and move rock is very common today. The most common technique is that used for quarry or bench blasting.[1] This method uses vertically-drilled blast holes (Figure 1). The first set or row of blast holes fractures the rock between the blast holes and the free face and moves this broken rock in a direction that is nominally perpendicular to the free face. For good results, a free vertical surface should be present to permit free or uncontained motion of the fractured rock.[2] To begin a bench, i.e., to form an initial free face, it is often necessary to blast in a very confined geometry, normally called a "cut" (Figure 2). In this situation the fractured rock must be moved up to clear a hole which is used as the forward side of the bench. Considerably more explosive is required to

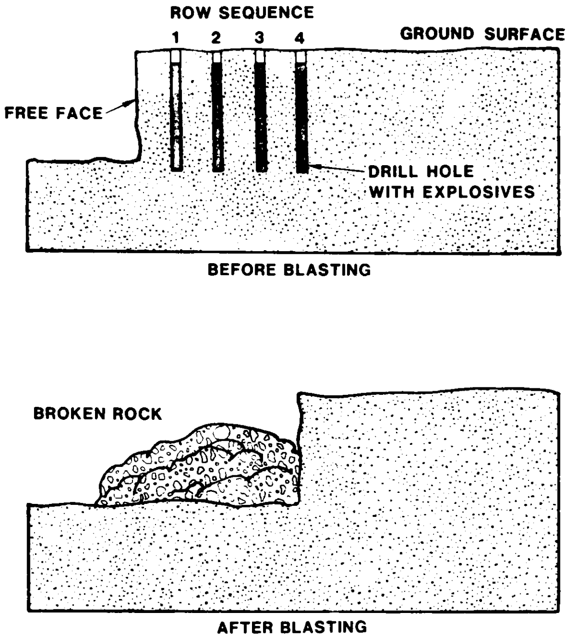


FIGURE 1. CROSS SECTION, BENCH BLASTING

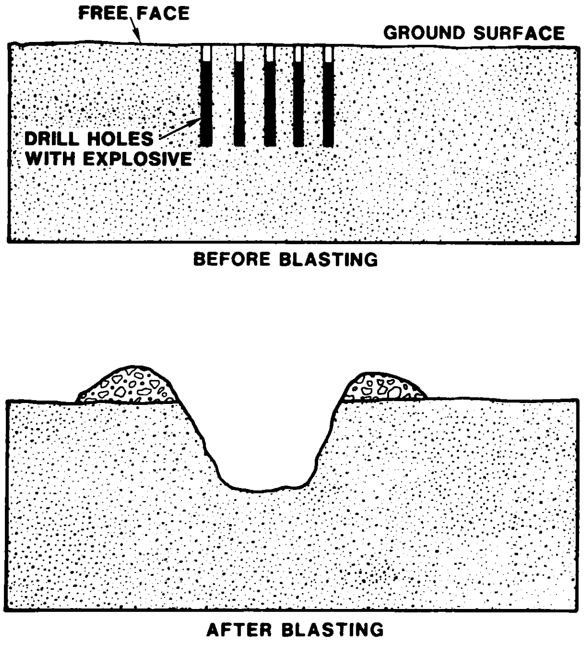


FIGURE 2. CROSS SECTION, SINKING CUT

break the same volume of rock in this case than in a bench blasting geometry.

The blasting requirements for in situ oil shale rubblization are more complex than those for conventional bench blasting.[3] Let us now consider the specific blasting problem associated with in situ rubblization in a region where the proposed retort zone is close to the ground surface, i.e., close enough so that the overburden can be moved upward sufficiently with explosives to introduce adequate porosity into the retort zone. In an operation of this type by Geokinetics, Inc., explosive is placed in the bottom of a series of blast holes drilled from the ground surface (Figure 3). The desired result is to raise the rock material overlying the explosive zone and to fracture and tumble the rock within the explosive zone, creating a rubbled, permeable region which can be retorted directly. In this geometry, the amount and quality of the rubblization depends upon the degree to which fragment motion has been contained by the overburden. In an alternate rubbling concept, the partial-void ("cut") region created by lifting the overburden and some of the rock in the explosive zone is utilized as a free volume region into which rock from an adjoining region can be moved laterally into the "cut" using additional explosive detonations. This alternate concept would thus be carried out in much the same way as conventional bench blasting, with the exception that the overburden is maintained above the rubbled zone to act as part of the container for the subsequent retorting.

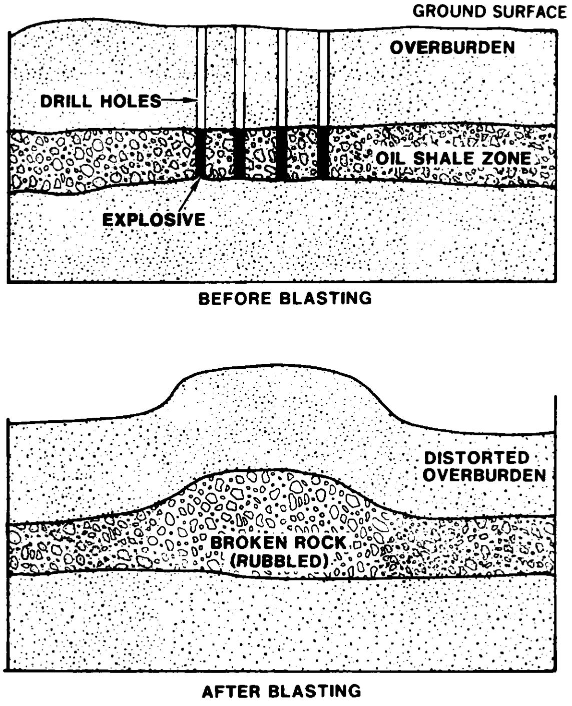


FIGURE 3. CROSS SECTION, OIL SHALE RUBBLIZATION

ANALYSIS METHODS

In the past, the blast design, which includes the quantity of explosive, the timing sequence, and the blast hole size and spacing, have been based primarily on empirical methods.[1,2] These methods have evolved through years of experience, mainly with quarry and tunnel blasting. The use of "powder factors", which relate the amount of explosive to the quantity of rock to be broken, are common to these empirical methods. Although this empirical approach has been adequate for most standard blasting needs, recent applications have led to requirements for more elaborate design and analysis methods.

One of these methods involves comparison of the total explosive energy to the requirements for rock fracture and motion. In this manner, wasted energy can be isolated and designs improved.

The use of shock wave computer solutions, which include detailed physical descriptions of explosive detonations and the resultant shock wave interactions with adjacent rock, are becoming more commonplace.[4-6] These techniques provide a very good solution to the early time explosive-rock interaction problem. One major disadvantage, however, is the difficulty in extending the solutions to longer times when the bulk of the fragment motion occurs.

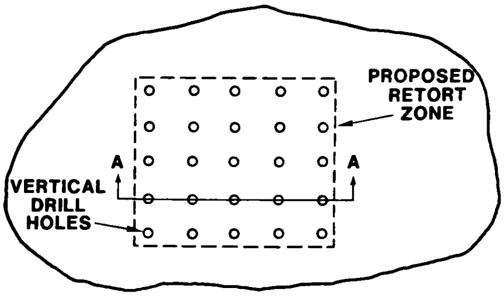
Structural finite element programs are also useful, particularly for examining the gross motion of rock affected by the detonation.[7-9] This method can incorporate complex geometries and can analyze motion for late times. These programs will not, however, handle the details of the explosive detonation.

The analysis method discussed in this report is the lumped mass method.[10,11] Like the finite element approach, this technique is not useful for analyzing the detailed explosive behavior, but will provide an approximate solution for rock motion induced by the explosive event. Although this method is the topic of the remainder of this report, it should be noted that the assessment of the blasting design can be best made by using a combination of all the tools and techniques which are available.

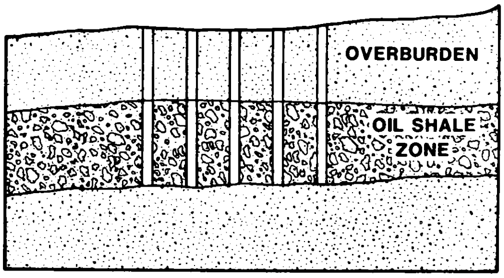
LUMPED MASS ANALYSIS

The lumped mass analysis method is based on the idea of concentrating or "lumping" a continuous solid material at discrete locations.[10,11] The response of these interacting lumped masses to various loading conditions constitutes the analysis.

This method is general, and can be used in three-dimensional analysis. For this study, however, the three-dimensional geometry was approximated by considering a vertical slice through a typical retort (Figure 4). The effects of either lateral or longitudinal variations can be studied by changing the slice orientation.



PLAN VIEW



VERTICAL SECTION A-A

FIGURE 4. RETORT BLASTING

The overburden zone in this example was divided into a series of masses (Figure 5). The general overburden motion can be represented by a single mass through its depth, and a series of masses along the retort length. Since the lateral (y direction) motion in the overburden is small, it was not included in this analysis. Each mass has only one degree of freedom, the vertical motion.

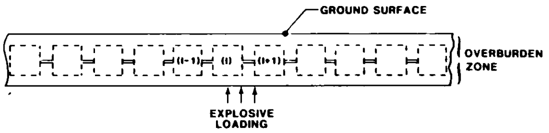


FIGURE 5. LUMPED MASS GEOMETRY

The equations of motion of each mass can be written after all loads on the masses are defined. The free body diagram in Figure 6 shows the loads applied to mass I. Since the problem is highly gravity-dependent, the weight of the lumped mass, $WT_{(I)}$, must be considered.

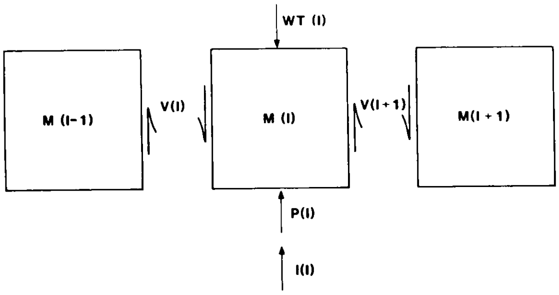


FIGURE 6. FREE BODY DIAGRAM

The interaction between adjacent masses is accomodated with shear forces, $V_{(I)}$. The magnitude of these forces is equal to the shear stress times the shear area. The shear behavior is considered perfectly plastic. Other assumptions can be included if desired. The direction of the shear force is dependent upon the relative velocity difference between adjacent masses.

The loads contributing to the mass motion are due to the explosive below the overburden. The effects of the explosive are integrated over the lower overburden surface to produce concentrated loads $P_{(I)}$ defined in two ways: 1) The load is taken as a time-dependent quantity, whose characteristics are set at the beginning of the analysis based on explosive characteristics. 2) The load on any mass is an interactive function with the vertical motion of that mass. This permits an interaction between the load magnitude and the volume increase of the explosive gases due to overburden motion. This option most nearly approximates the explosive gas behavior and was used primarily in this study.

Load I, is the load due to an initial short-duration pressure pulse. The time duration is so short that only the integrated pressure-time, impulse, is important. This impulse is accounted for by a simple velocity change due to conversion of impulse to momentum. (Velocity change is equal to the impulse divided by the mass.) The magnitude of the impulse is dictated by the explosive behavior.

Based on these loads and the free body diagram given in Figure 6, the equation of motion of mass I can be written:

$$M_{(I)}\ \ddot{X}_{(I)} = -WT_{(I)}+V_{(I+1)}-V_{(I)}+P_{(I)}$$

where

$M_{(I)}$ = mass of lumped point, I
$\ddot{X}_{(I)}$ = acceleration of lumped point, I
$WT_{(I)}$ = weight of lumped point, I
$V_{(I+1)}$ = shear force at right side of lumped point, I
$V_{(I)}$ = shear force at left side of lumped point, I
$P_{(I)}$ = applied load at lumped point, I

The initial velocity boundary condition for mass I is:

$$\dot{X}_{(I)} = \frac{I_{(I)}}{M_{(I)}}$$

where

$\dot{X}_{(I)}$ = initial velocity at lumped point, I or velocity after application of impulse
$I_{(I)}$ = impulse at lumped point, I

An equation of motion for each mass can be written. The resulting set of equations which are coupled by the shearing forces can then be solved.

COMPUTER PROGRAM IJUMP

A Fortran computer program, IJUMP, was written to provide the numerical solution of the lumped mass equations of motion. Due to the non-linear nature of the equations resulting from the shear coupling, a time step method was used for the integration of the equations.

Program IJUMP consists of four parts:

1) Input. The geometry, material properties and input forces are read. The masses are calculated, and all parameters are initialized a zero time.

2) Differential Equations. The differential equations for each mass are defined from the initial constants and the relative motion of adjacent masses.

3) Time Integration. This portion of the program handles the time integration for one time step to

the next by means of a Newmark-Beta integration scheme. The program loops through this integration until it reaches the final solution time.

4) Output. In addition to standard printed output, two subroutines have been written to provide plotted results. The first provides a time history plot of relevant parameters. These include displacement, velocity, relative displacement, and forces. Spatial plots are provided by the second plot package. The plots depict displacement versus distance along the retort axis, i.e., distorted shape profiles. Examples of both types of plots will be shown in the following sections.

Although Program IJUMP was implemented on a large scientific computer (CDC7600), the main program will run on most small computer installations. Only the plotting subroutines need to be changed for use on other computer systems.

CORRELATION

The validity of this type of analysis, which was based on engineering approximations, can be best verified by comparison with experimental results. A large amount of field test data has been obtained by Sandia National Laboratories during retort blast tests at the Geokinetics, Inc. site near Vernal, Utah. The field data used in this correlation were taken from high speed camera film.

The vertical motion of the overburden near the center of a retort blast is shown in Figure 7. The correlation with the calculated results is very good except at late times. The analytical unloading response at late times is not well defined, since the material properties are not changed in the model to account for degradation during loading. The actual field unloading behavior is likely quite different from that assumed in the analysis.

The locus of the vertical displacement along the longitudinal section of a typical retort at a set time is shown in Figure 8. This type of plot is commonly referred to as a "distorted shape plot", since it represents the ground shape at this time. Good correlation is evident in all regions except near the two ends. The discrepancies near the ends are expected because the analytical model does not account for gas moving laterally away from the explosively loaded region. This gas will result in a direct load which will cause calculated displacements near the ends to be lower than measured displacement.

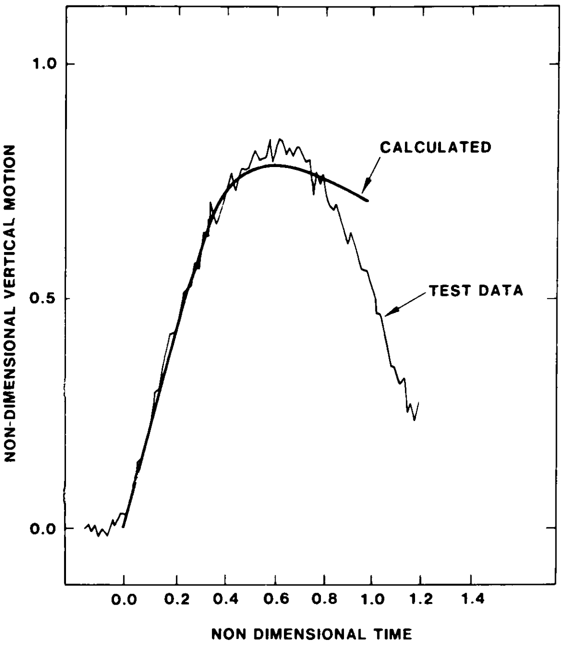


FIGURE 7. CORRELATION WITH VERTICAL MOTION OF OVERBURDEN

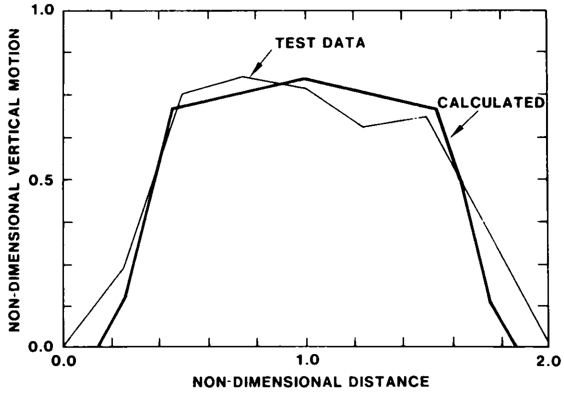


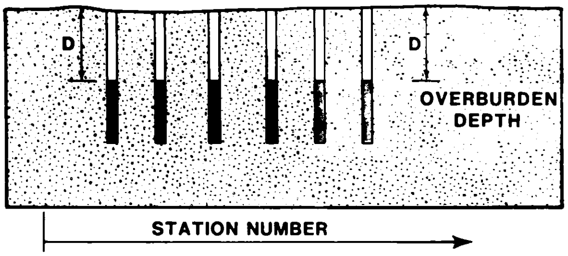
FIGURE 8. CORRELATION ALONG LONGITUDINAL SECTION

In general, the correlation of experimental and analytical data is good and justifies use of this method for studies associated with the type of blasting considered.

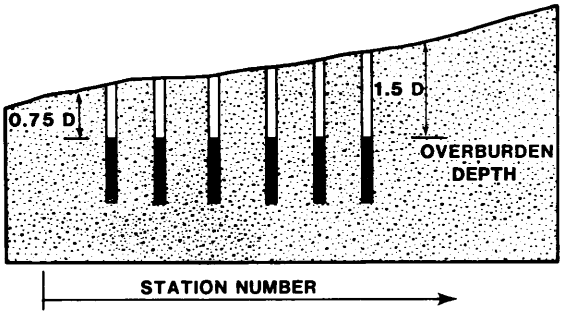
TYPICAL USES

The potential uses of the lumped mass method in blasting design and test are wide. Program IJUMP has been used to support blasting activities in several ways. During an experimental series, the program was used for pre-test predictions and evaluations. These studies provide a basis for logical test planning. IJUMP results have also been used to assist in the evaluation of post-test data.

Parametric studies which assisted in the blasting design have been made using program IJUMP. One such series of parametric studies involved the examination of effects caused by non-uniform overburden thicknesses and explosive quantity. Cross-section views of two typical retort geometries are shown in Figure 9.



(a) UNIFORM DEPTH



(b) VARIABLE DEPTH

FIGURE 9. CROSS SECTION, TYPICAL RETORT

The first condition depicted is based on a uniform overburden thickness. In the second condition, the overburden thickness varies by a factor of two from one side of the retort to the other. The resulting distorted shapes are plotted in Figure 10. As expected, the shape for the non-uniform depth case is non-symmetric. The variation across the retort is not large, however, indicating that non-uniform overburden depth is not a severe problem for this geometry.

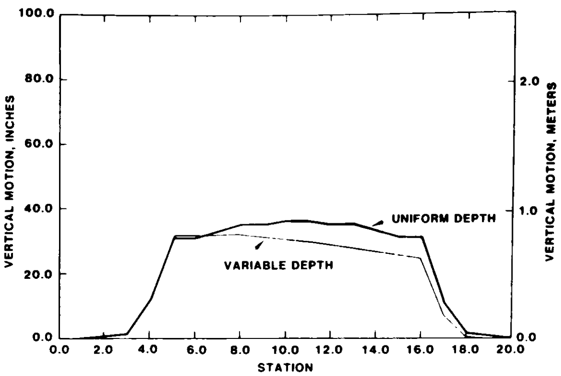


FIGURE 10. EFFECTS OF VARIABLE OVERBURDEN DEPTH

The effect of sequential timing of the explosive detonation was also studied. This case is representative of a rubbling concept in which rock is sequentially blasted into a cavity or partial void region created by the earlier explosive events which lift the overburden. A cross-section view through such a retort is shown in Figure 11. The detonation time was delayed along the section, as indicated. The resulting distorted shapes calculated at three times are shown in Figure 12. The non-symmetric behavior is obvious. The maximum vertical motion for the delayed initiation sequence is 28 inches (0.71 meters). By comparison, the maximum heave for uniform detonation is 38 inches (0.97 meters). This result indicates that a large portion of explosive energy is used in overburden distortion for the time delay case.

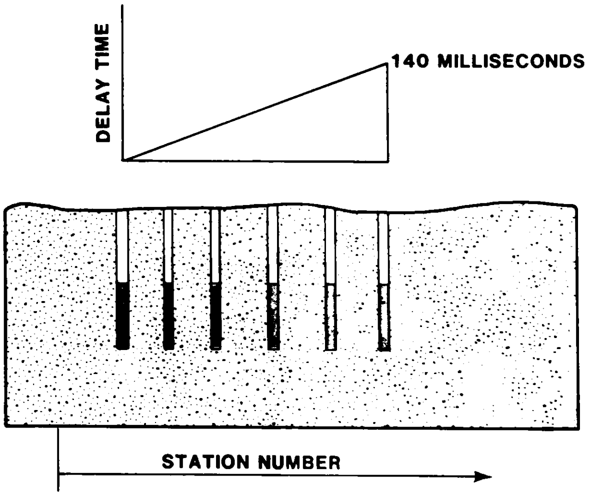


FIGURE 11. CROSS SECTION, TIMING STUDY

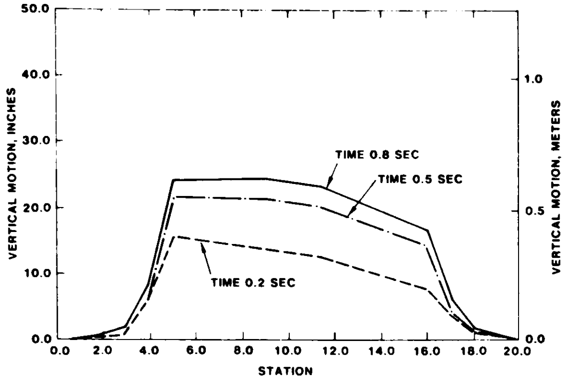


FIGURE 12. EFFECTS OF DETONATION TIMING

FURTHER EXTENSIONS

The lumped mass technique is capable of solving a large variety of problems. In particular, a large number of situations encountered in blasting can be analyzed using simple extensions of the analysis procedure presented in this report. Blasting situations which are dependent upon sequential burden movement or which involve interactive timing can be analyzed using this method.

Program IJUMP is being extended to include the horizontal motion of the broken rubble. This change will permit the study of the interaction of the vertical motion of the overburden and the rubblization and horizontal motion of the material in the blast zone. This work indicates that the lumped mass method can be used to analyze this interaction and to improve our predictive capability.

CONCLUSIONS

The in situ extraction of oil from oil shale is highly dependent upon explosive fracturing and rubblization of rock in a controlled and predictable manner. The rock material adjacent to the zone of desired explosive fracturing and the quality of rubblization are highly interdependent, and there is a need for better analytical tools to assist in blast design. A simple engineering technique based on lumped mass modeling provides an analytical method of predicting the rock motion in areas adjacent to a blast zone. A Fortran computer program (called IJUMP) has been written and the results compared to experimental field data; the correlation indicates that this technique can be used to analyze the overburden behavior during typical blasting operations.

IJUMP has been used in conjunction with experimental field operations. This report shows typical results from several parameter studies. The analytical method presented has potential in studies of other blasting situations and can be extended to include other parameters. In general, the lumped mass method has provided a simple engineering analysis tool which has been useful in our experimental blasting studies of oil shale.

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