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A study of tunnel demolition by hasty methods

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A STUDY OF TUNNEL DEMOLITION BY HASTY METHODS

BY

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A

THESIS

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INTRODUCTION

The use of explosives to construct obstacles which impede the enemy or close his routes of communication has long been employed by our armies. They have developed fairly effective methods for destroying bridges, setting up road craters and constructing abatis. However, one phase of obstacle construction, that of tunnel demolition, has been neglected in that no procedures or methods have been formulated which will aid in the proper destruction of tunnels.

At the present time, under the auspices of the Department of the Army, The Missouri School of Mines and Metallurgy is conducting a research program on tunnel demolition. The entire investigation is to cover both hasty and deliberate methods of tunnel demolition. Hasty demolition is that type of demolition which requires no previous preparation of the tunnel site before charge placement. Deliberate demolition requires time and effort in preparing the tunnel prior to the placement of the charge.

At the completion of the project, the Missouri School of Mines will recommend to the Department of the Army the most feasible approach to the theories and techniques for the destruction of tunnels by explosive charges. This recommendation will cover various types of charges placed in different types of tunnels for both hasty and deliberate demolition.

This paper is confined to the study of hasty demolition of tunnels and the degree of influence of various factors which may be encountered. The factors which were studied are:

1. Length of tunnel
2. Character and tightness of tunnel lining
3. Cross-sectional area of tunnel

4. Cross-sectional shape of tunnel

5. Various sizes of explosive charges

6. Different methods of charge placement

7. Different types of military explosives

The approach to the problem began by the construction of scale models to simulate tunnels under these varying conditions. By following the principles of similitude, it was possible to study the demolition effects of each of the above factors. A total of 21 tunnels were built and tested.

To the writer's knowledge, nothing has been published concerning research on tunnel demolition. However, because of a recognized need for effective methods of tunnel destruction, The Corps of Engineers decided to sponsor this research program.

To illustrate the importance of tunnels and to show how the loss of these tunnels might affect a nation, the following quotation is made:[(1)]

[(1)]Dotson, J. C., Tunnel Rehabilitation, Thesis presented to the School of Mines and Metallurgy of the University of Missouri, p. 3.

> Tunnels, unlike many surface structures, cannot be temporarily replaced by substitute structures. Furthermore, the time required to reopen a tunnel cannot be shortened simply by increasing the number of workmen that are employed. The confines of a tunnel will accommodate only a limited number of workmen if work is to be conducted efficie tly and safely. ...Many communities rely almost entirely on the use of tunnels for commerce, water supply, hydroelectric power, and utilities. Disruption of these vitally needed services may create a stab of panic. ...In theaters of military operations, destruction of communication tunnels and supply tunnels is a major objective of a retreating army as the attacking force cannot advance indefinitely without restoring routes of supply. Bridges, culverts, and road beds that are destroyed rapidly can be repaired or replaced, but the restoration of tunnels often imposes serious delays and to a large degree governs military strategy.

To further illustrate how critical and vulnerable tunnels can be in time of war, the following case history is presented from World War II. If the reader desires to read more accounts of tunnel demolition, he is referred to the case histories compiled in Tunnel Rehabilitation.[2]

(2) Dotson, J. C., op. cit., pp. 195-218.

THE DEMOLITION OF BEACON HILL TUNNEL,

KOWLOON-CANTON RAILWAY[3]

Beacon Hill Tunnel is a single track, standard-gauge, tunnel which pierces Beacon Hill, about four miles north of

(3) Walker, R. D., The Demolition of Beacon Hill Tunnel, Kowloon Canton Railway, The Railroad Gazette, Vol. 86, No. 20, May 30, 1947, p. 559.

the Kowloon terminal. The maximum cover above rail level is just over 1,300 feet, and the ground is mainly loose granite. The length of the tunnel, which is lined throughout with good brickwork, 33 in. thick, is 7,212 feet (1 3/8 miles). The southern end and approach is graded 1 in 100, and the northern 1 in 400; there is a short level portion of approximately 300 linear ft. in the centre. The tunnel took three years to build, and was completed in 1910. It is fairly dry, except near the northern end, where there is considerable percolation of water.

It was destroyed in the late afternoon of December 8, 1941, by the Field Company Engineers of the Hong Kong Volunteer Defence Corps, about 10 hours after the Japanese had attacked in force over the British-Chinese border, 18 miles farther north. It was the rearmost demolition of 18 major defensive road and rail obstructions blown by them.

Some of these demolitions were deferred; that is, they were charged many months before being fired. Others were prepared partially before the attack by the fitting of permanent structural devices to facilitate the placing of explosives to the best advantage. The limited structural gauge of Beacon Hill Tunnel, however, precluded the building in it of any preliminary aids, and a simple method of demolition had to be planned. This was provided by what was called a "wagon bomb."

The " agon bomb" consisted of a 30-ton covered goods wagon, inside which was built a wooden platform to enable explosives to be packed just under the roof, thus concentrating the maximum force of the explosion where it could do the most damage, just under the crown of the arch. It was charged at Kowloon Station directly when war had broken out, and then propelled to its firing position as soon as practicable. This position was at the central level portion of the tunnel. This gave the best tamping effect, as the explosive wave would strike the solid lining quickly. Slabs of gun-cotton, boxes of dynamite No. 1, and tins of ammonal were used to make up the 14-ton charge. Several electric detonators were embedded in the explosive, and electric leads were run out to a protected blast position near the southern portal of the tunnel.

Firing of the "wagon bomb" was by an exploder, and a most unusual spectacle was afforded the firing party. A tongue of whitish smoke, about a quarter of a mile long, shot out of the southern portal, and almost immediately was sucked in again. This unexpected effect, combined with a muffled rumble resembling distant thunder, was the meagre evidence vouchsafed the sappers of the damage they had done to the Japanese war effort.

Of the total length of Beacon Hill Tunnel, 2,646 linear ft., or 37 per cent, of brick arch were destroyed. In addition to this damage there were numerous arch cracks in the remaining 63 per cent. With the exception of a short length near the "wagon bomb," where all the lining of the tunnel was destroyed, the demolished brickwork was above the springing of the arch. The destruction was in discontinuous lengths, and there were many falls of rock where the tunnel passed through loose and shifting ground.

The Japanese cleared the debris, and reopened the tunnel, and the line, with a flourish of trumpets, in May, 1942. Their jubilation was short-lived, however, as it collapsed a few days afterwards. Several months of very heavy remedial work had to be undertaken before trains were allowed to pass through the tunnel at dead-slow speed--one hour to complete the journey of 1 3/8 miles.

During the period 1942-45, the Japanese erected 675 sets of heavy timber frames to shore the brick arches. They also built a short length of reinforced concrete arch which reduced the dimensions of the tunnel by one foot all round. Serious trouble because of falling rock occurred during the whole period of Japanese occupation, and the tunnel had frequently to be closed to traffic.

Permanent Remedial Work

One million, three hundred thousand red bricks are required to replace the missing brickwork, and a contract to effect the necessary repairs was signed in August, 1946. A cement gun will be used to grout the cracks in the arches, as soon as a suitable compressor can be obtained.

An idea of the immense amount of damage caused by this simple "bulk" type of demolition was gleaned by the writer, during the war, from remarks passed to him by Japanese Engineer officers, news items in the Japanese-sponsored press, by the questioning of local Chinese, and from Mr. K. L. Hu B.Sc., who is acting now as Engineer, Way & Works, of the Kowloon-Canton Railway (British Section). By an irony of fate, Mr. Hu, who is responsible for reconstruction of the tunnel, was the lance-corporal of Engineers in charge of the preparation of the "wagon bomb" used for its destruction.

TESTING SITE AND EQUIPMENT USED

TEST SITE

The entire testing program described herein has been carried out at the Missouri School of Mines and Metallurgy's Experimental Mine and Quarry Site. It is located approximately 2 miles southwest of Rolla, Missouri adjoining the Frisco Railroad right-of-way. The actual testing was carried out in two quarries where the relatively flat limestone floors made an ideal site on which to construct the model tunnels.

THE MODEL TUNNELS

The model tunnels were formed by using a combination of wood and steel forms. The wooden forms were made from one-half inch marine plywood backed up by 2 x 4 studs. The steel forms were bent from 18 gauge black sheet metal. All were made in 5 foot sections except the outside wooden forms. Figure 1 shows how the inside wooden forms were joined. The connection was made with two $\frac{1}{4}$ inch lag bolts. Figure 2 shows how the outside wooden forms were put into position and held there with 2 x 4 braces. F'gures 3 and 4 show how the inside metal arch forms were held in place. They were joined by welding $1\frac{1}{4}$ x $1\frac{1}{4}$ x 1/8 inch rolled steel angle braces to each end of the steel forms and then connected with 1/8 inch machine bolts.

After the concrete was placed between the wooden forms for the tunnel walls, the outside metal arch forms were put in position. Figure 5 shows the shape of these forms and Figure 6 shows the forms joined together in the same manner as the inside forms.

The concrete was mixed using one part quick setting cement and two parts coarse sand. During the placing of the concrete, six compression test cylinders were taken for each model tunnel. The cylinders were then

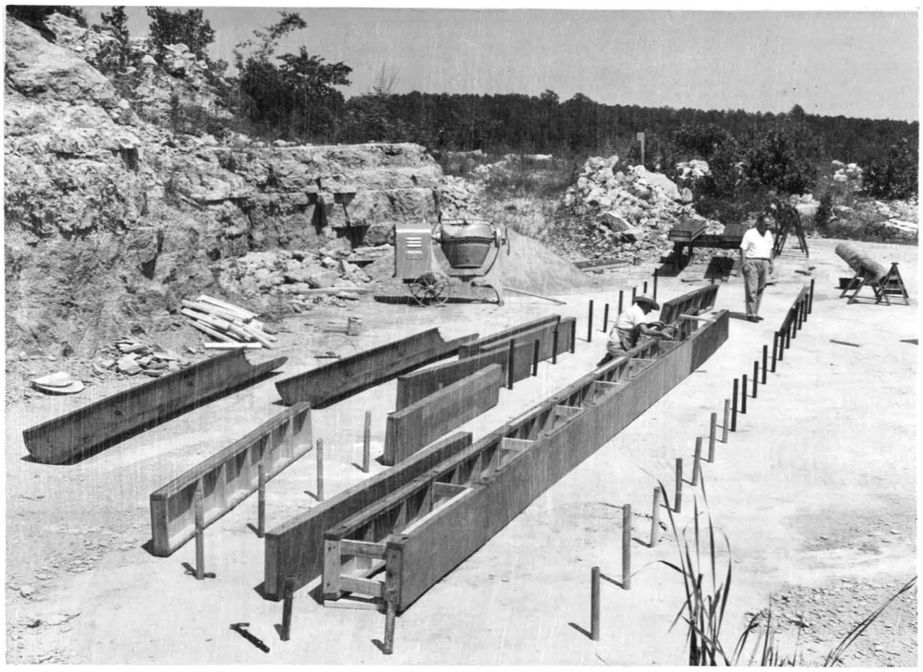


Figure 1. Lag bolts were used to join wooden forms

Figure 2. Wooden forms held in position with braces

Figure 3. Inside metal arch forms.

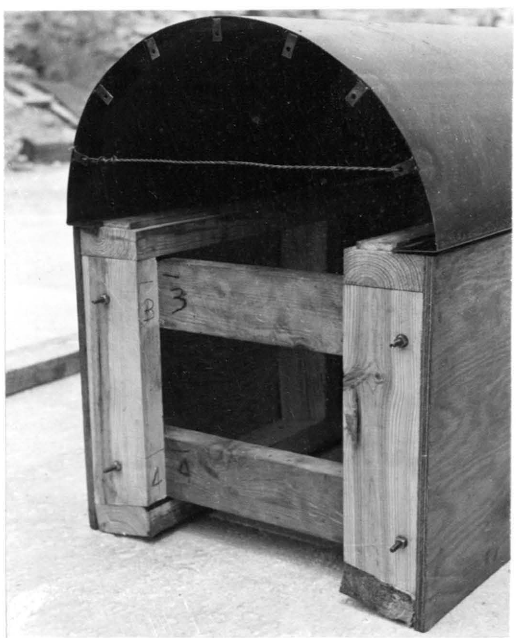


Figure 4. Inside metal arch forms.

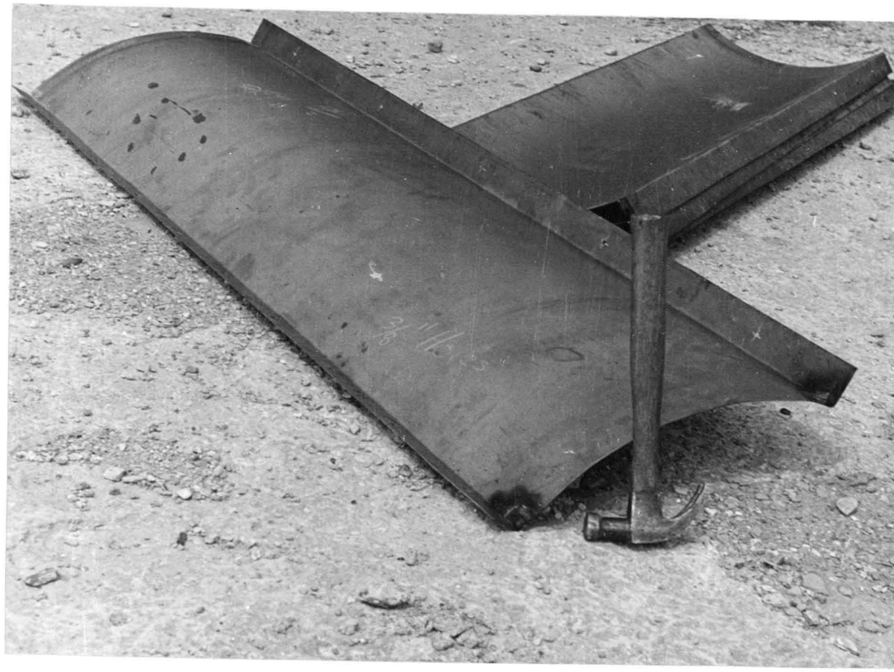


Figure 5. Outside metal arch forms.

Figure 6. Outside metal arch forms joined together with machine bolts.

tested periodically to determine the strength of the concrete. Figure 7 shows the Riehle Compression Testing Machine and a cylinder before testing. When the concrete reached a strength of approximately 3,500 p.s.i., the tunnel was tested.

For a few of the final tests, concrete tension blocks were taken to correlate the compression strength to the tension strength of the concrete. As will be discussed later, the model tunnels probably failed in tension. Figure 8 shows a tension block being tested in a Riehle Tension Block Testing Machine.

THE EXPLOSIVES AND PRIMER USED

The explosives used during the test program were Composition C-3, Nitrostarch and TNT. The characteristics and properties of these explosives are discussed in the following paragraphs.

Velocity tests were run on all types of explosives used by the D'Autriche Method. The results of these tests are shown in Table I. The primers used throughout the test program were Corps of Engineer special electric blasting caps.

TNT

Trinitrotoluene, commonly known as TNT, is a chief constituent of many explosives used such as amotal, pentolite, tetrytol, torpex, ednatol, composition B, etc., and is a very versatile explosive when used by itself. It is used as a standard of comparison in testing other military explosives and all tests are rated with TNT at 1.00. When properly purified, TNT is one of the most stable of the high explosives and can therefore be stored over long periods of time. Highly compressed TNT will detonate with a No. 8 blasting cap, but a Corps of Engineers special

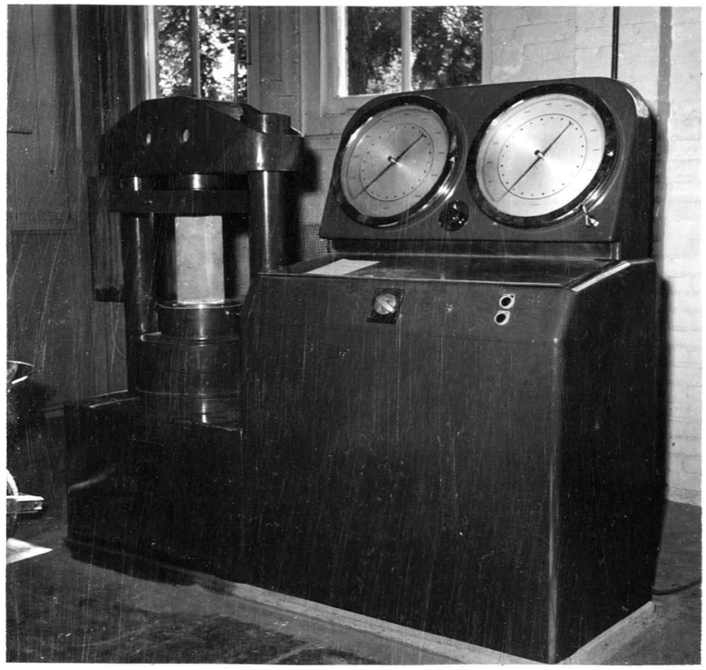


Figure 7. A Riehle Compression Testing Machine

Figure 8. A Riehle Tension Testing Machine

blasting cap is recommended. TNT is suitable for all types of military blasting and demolition work and produces approximately the same effect as an equal weight of 60 per cent dynamite. It has a detonation velocity of about 20,400 feet per second in the comp essed package form.

Composition C-3

The plastic explosive, known as Composition C-3 which was much used during World War II and the Korean Conflict, was the principle explosive used in the testing program. Its principal ingredients are RDX (Cyclonite) explosive and plastic oils.[4] It is much more powerful than TNT, having

(4 Conference Notes, Characteristics and Equipment of Explosive and Demolition, Prepared at The Engineer School, for the Chief Engineer, Vol. CNXVII, 1 Jan. 1952, p. 7.

approximately 1.33 times as much total energy and about 1.25 times as much brisance. Brisance is the capacity of a detonated explosive to shatter its surrounding medium. It has a density of 1.6 and a velocity of detonation of approximately 26,000 feet per second. At normal temperatures it is plastic, or pliable, like putty. This makes it easily molded to obtain close contact with objects to be destroyed. At 20°F. below zero it becomes hard and brittle, and at high temperatures of about 120°F., it becomes extremely soft and oils ooze out if kept at this temperature. It is highly inflammable when exposed to an open flame, and the gas formed when C-3 is exploded is toxic. Its sensitivity to shock is about the same as TNT, and therefore a Corps of Engineers special blasting cap should be used for priming.

At the present time C-3 has been placed on limited standard issue in the Corps of Engineers. Its successor is C-4, another plastic explosive.

TABLE I

Results of D'Autriche Detonation Velocity Test

Test No.	Explosive Tested	Distance Between Marks on Lead Plate (in.)	Velocity of Detonating Cord (f.p.s.)	Calculated Velocity of Explosive (f.p.s.)	A erage Velocity (f.p.s.)
1	Composition C-3	2.10	20,574	29,391	
2	Composition C-3	2.50	20,574	24,689	26,599
3	Composition C-3	2.40	20,574	25,718	
4	Nitrostarch	7.00	20,574	17,635	
5	Nitrostarch	7.13	20,574	17,32	17,329
6.	Nitrostarch	7.25	20,574	17,027	
7	TNT	5.96	20,574	20,712	
8	TNT	6.13	20,574	20,138	20,406
9	TNT	6.06	20,574	20,370	

Nitrostarch

The explosive known as nitrostarch actually is only a nitrostarch base explosive. It contains approximately 50 per cent nitrostarch. It is much more sensitive to shock than TNT and therefore should never be crushed or cut with a sharp tool. It is only about 0.86 as powerful as TNT.

At the present time, nitrostarch is considered obsolete in the Corps of Engineers. However, it serves well for testing purposes since it is one of the slowest detonating military explosives. The D'Autriche tests (Table I) showed its velocity of detonation as 17,329 feet per second.

THEORIES AFFECTING THE PROBLEM AND THEIR APPLICATION

As is expected in most applied research, the problem is not confined to securing a workable end result, but is also concerned with the cause and effect relationship for all the events which occur.

While it is impossible to cover all of the related theories and problems that were encountered in conducting this research, the author feels that at least the most important subjects should be discussed. This will allow the reader to understand the basis on which the author makes his conclusions.

A GENERAL DISCUSSION OF WAVE MOTION

Whether it be the ripples that are emitted when a pebble falls into water, the vibrating strings of a violin or the phenomenon which follows an atomic blast, it all falls under the general subject of wave motion. Waves are set up by the vibrational motion of matter when it is displaced from its equilibrium. The displacement of one particle causes the displacement of a neighboring particle, analogous to the way a row of dominoes standing on end transmit the force to each other and are tipped over. One of the most common occurrences of wave motion is in the form of sound. Sound waves are audible to the human ear at frequencies between about 20 and 20,000 cycles per second (c.p.s.).

Probably the simplest form of vibration is that of a spring attached at one end to mass (m) with the other end stationary. When the spring is stretched or compressed through a distance (x), it must overcome some stiffness of the spring (s). The force required to return the spring to its equilibrium position is defined by Hooke's law:

$$F_s = -sx \qquad (1)$$

Simple harmonic motion occurs when the force continues to act directly on the mass and displaces it in the opposite direction an equal amount. The most important characteristic of this type of vibration is that the frequency is not proportional to the displacement, but to the ratio of he stiffness of the spring to the mass. Therefore, the displacement or amplitude remains constant.

However, if the force does not continue to act on the mass beyond the equilibrium point, then the free vibration will begin to decay exponentially and eventually the mass will come to rest. This is known as a damped system and can be shown graphically as in Figure 9. The attenuation of shock waves from the detonation of explosives occurs in very ch the same manner.

Now consider a system in which each unit of mass is separated by infinitesimal spaces so as to resemble a string in which it is no longer possible to pick out the mass-like or spring-like components. We now have a system in which wave motion can be transmitted only in one dimension.

If taut string has a driving force which is moved back and forth parallel to the length of the string, the waves are then produced longitudinally. If however, the driving force is moved at right angles to the stretched string, the waves are transverse. I both cases the amplitude and the frequency of the simple harmonic motion will be equal o those of the driving force. It will differ only in phase.

Figure 10 shows the motion of a two cycle transverse wave as it moves down a stretched string fixed at one end. Notice that as the wave hits the fixed end, it is reflected 180° out of phase with the original wave. Since they are 180° out of phase, they will cancel each other completely over the zone that they meet. Then the reflected wave will travel.

Figure 9. The diagram below shows the exponential decay of a damped wave system.

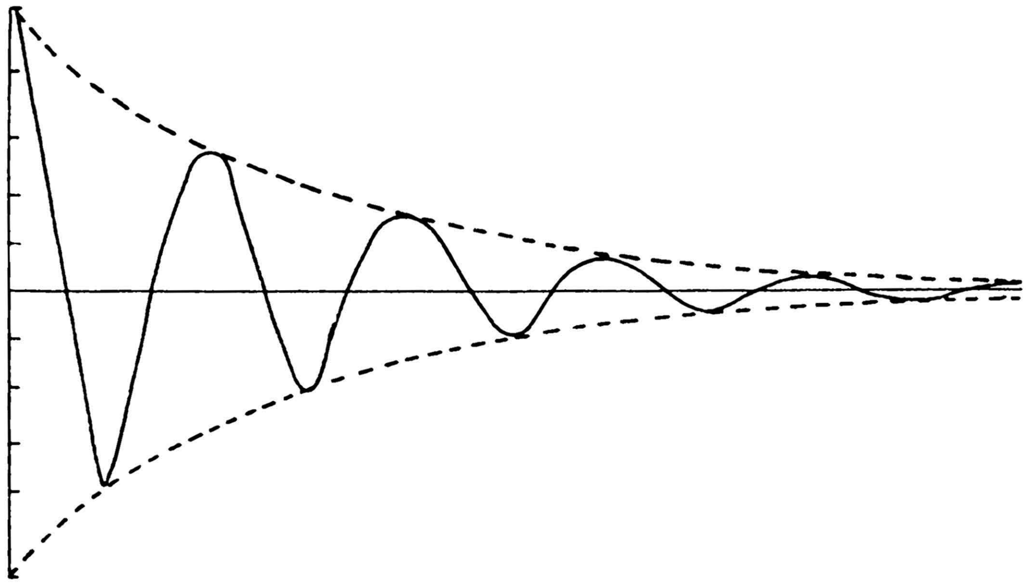
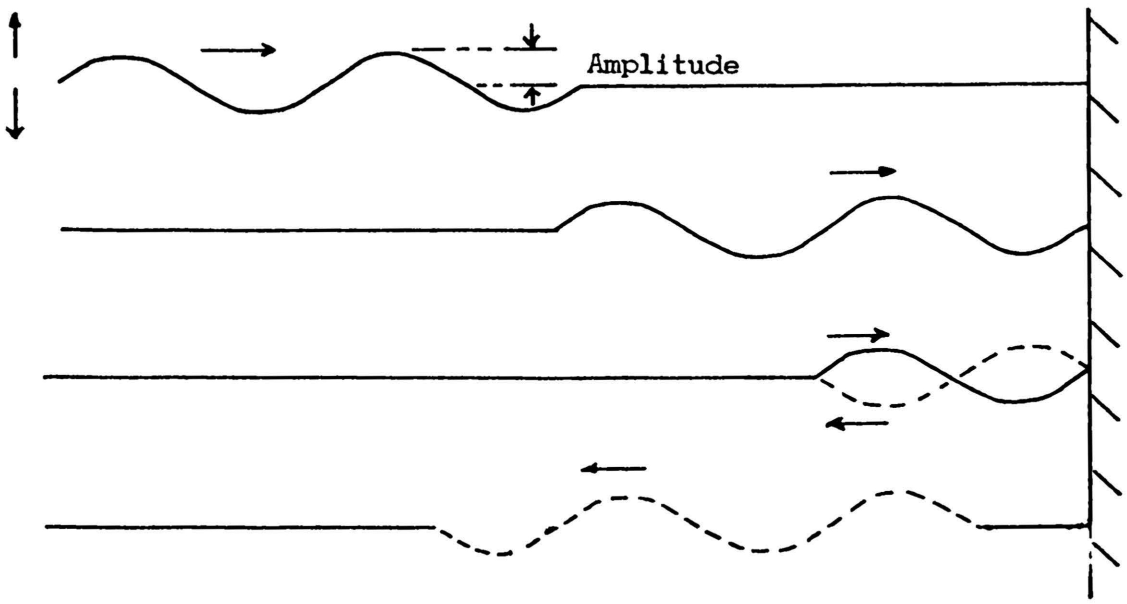


Figure 10. The diagram below shows the stages of progress of a two cycle transverse wave moving down a taut string and being reflected from a fixed end.



along unaffected by the meeting. If, however, the two waves meeting each other were 90° or 270° out of phase, it could be shown that they no longer cancel each other, but instead are additive.

Thus far the discussion has been limited to wave motion in a one dimensional system, and has dealt mostly with transverse waves. All that has been said of transverse displacement is equally true of longitudinal displacement. The principle difference being that longitudinal displacement acts as compression or tension on material, while transverse displacement acts as a bending or warping force. Another difference is that longitudinal compression waves always add to one another upon meeting. The effect of longitudinal waves meeting each other will be shown in a later paragraph under Phase VIII.

The discussion now turns to media such as a gas for which the longitudinal waves are to move. It immediately becomes apparent that there can be only the propagation of longitudinal waves since a gas cannot be bent, but can only be compressed or expanded. As a longitudinal wave moves through a gas, it displaces the gas particles from their position of equilibrium and causes regions of high and low pressures. This region of high pressure will hereafter be referred to as excess pressure. Excess pressure is proportional to the linear rate of change of the particle displacement. Therefore the maximum excess pressure will occur where the displacement is occurring more rapidly. This point is most important in the understanding of the peak pressures developed by the detonation of explosives.

Since both the density and pressure of air change with temperature, it is only natural that the velocity of wave propagation also changes with temperature. It is approximated that the velocity of sound increases one foot per second for every increased degree of Fahrenheit temperature. It is no wonder then that compressional waves are emitted at supersonic speeds from an explosion which occurs at temperatures of 3,000 to 4,000 degrees centigrade. It likewise follows from the previous paragraph that these high velocity waves create extremely large excess pressures immediately around the detonating explosive.

When the longitudinal wave motion is permitted to move in one direction, as it is in a long tube, then there is an analogy to the one dimensional motion of a stretched string. However, where there is one directional movement in a three dimensional medium, there is a moving plane wave. This plane wave is perpendicular to the general direction of wave propagation. Now instead of the wave having to displace an individual gas particle, it must move an entire plane of gas particles. A plane wave moving down a tube is analogous to a piston.

Now establish a condition in which the piston is being accelerated, and there are no longer continuous waves moving ahead of the pist n. Instead, a pressure front becoming steeper and steeper with time is developed. When the physical properties of the medium limit the rising pressure, a relatively stable front is reached. This pressure front is developed over a very narrow zone, and hence approximates a perfect discontinuity. Discontinuities in wave motion describe a shock wave. Once formed, the shock wave will travel at supersonic speeds, and will continue at the speed of the piston. However, when the piston decelerates, a rarefaction wave developes in front of it and moves with the velocity of sound relative to the medium. This rarefaction wave overtakes the compression wave and decays the shock front. Decay lowers the velocity of the shock wave and if deceleration is continued, the shock wave will fall to sonic velocity. This is essentially a word picture of the propagation and attenuation of shock waves set up by detonating an explosive in a tunnel.

THE DETONATION OF EXPLOSIVES

In the discussion of detonating explosives, it must first be assumed that the initiator will start a compressive wave of sufficiently steep pressure and temperature gradient to propagate the wave. This wave will be referred to as the detonation wave. The forward portion of this wave of extremely high pressure will be known as the shock front.

To evaluate the process of the detonation wave, a discussion of the classical hydrodynamic theory of detonation will be given. Figure 11 shows a rigidly confined column of unreacted explosive.(Zone A), the reaction zone (Zone B), and the gaseous products (Zone C). First assume that the shock front moves at a velocity D towards the unreacted explosive. This is somewhat easier to analyze if a moving co-ordinate system is used where the shock front is represented by the y-y'axis. To an observer standing in the y-y' axis it would appear that the unreacted explosives were moving through this co-ordinate system with a velocity of D. To a fixed observer in the reaction zone, the velocity of the gas would appear to be moving with a velocity W towards the unreacted explosive. This is known as the stream velocity of the gases. Therefore, the products of detonation will be moving with a velocity of D-W. In Zone A, p_1 v_1 T_1 and E_1 represent the initial pressure, specific volume, temperature and internal energy respectively. In Zone C, the same properties are denoted with a subscript 2.

Knowing that all the material moving into Zone B must also move out, the laws of the conservation of mass, momentum and energy may be applied. Thus,

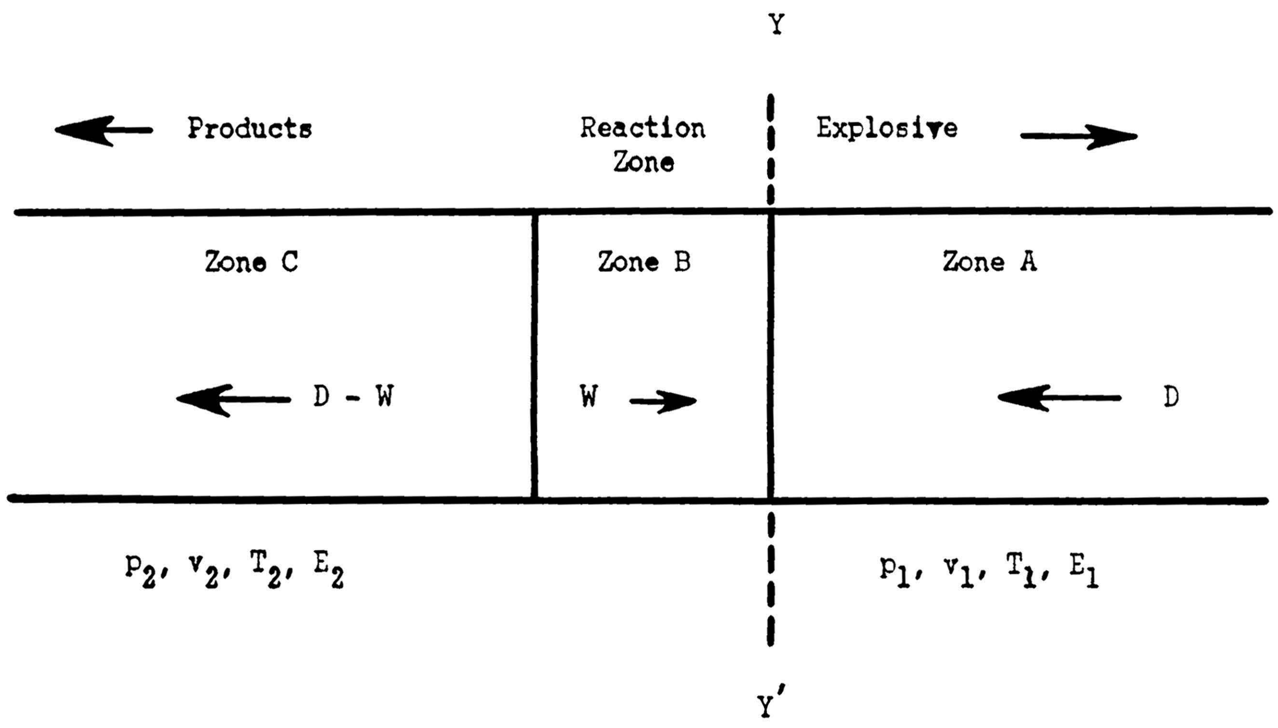


Figure 11. A shock front moving through a rigidly confined column of explosive.

$$\frac{D}{v_1} = \frac{D-W}{v_2} \tag{2}$$

$$\frac{D_2}{v_1} + p_1 = \frac{(D-W)^2}{v_2} + p_2 \tag{3}$$

$$E_1 + \tfrac{1}{2}D^2 + p_1\, v_1 = E_2 + \tfrac{1}{2}(D-W)^2 + p_2\, v_2 \tag{4}$$

Now solving for D and W in terms of p and v from equations 2 and 3,

$$D = v_1 \sqrt{\frac{p_2 - p_1}{v_1 - v_2}} \tag{5}$$

$$W = V_1 - v_2 \sqrt{\frac{p_2 - p_1}{v_1 - v_2}} \tag{6}$$

Then if we solve for the change in internal energy between Zone A and Zone C,

$$E_2 - E_1 = \tfrac{1}{2}(p_2 + p_1)\ (v_1 - v_2) \tag{7}$$

This then gives equations which define the velocity of detonation (D), the stream velocity of the gaseous particles moving in the relatively thin reaction zone (W) and the change in internal energy ($E_2 - E_1$). By choosing an equation of state that would hold over the wide temperature and pressure range, other properties such as temperature, pressure, and volume could be calculated. However, for the purpose of this general discussion it seems superfluous to do so.

According to the above theories, the detonation wave is a high pressure wave which moves through the explosives. It will be followed first by a relatively stable zone, and then by a zone of rarefaction. This detonation wave causes a series of collisions of high speed molecules hitting the explosive molecules. This in turn causes the explosive molecules to react at extremely high temperatures and in turn set their gaseous products into motion. Thus the detonation wave progresses through the column of explosives. Upon reaching the end of the column of explosive, a shock wave will be emitted to the surroundings at a velocity greater than the detonation velocity of the explosive.

After leaving the explosive, the shock wave will start to decay and will be overtaken by an expanding pressure wave known as a compression wave, resulting from the expanding gases. This pressure wave will also degenerate and form a sound wave. While it is more difficult to visualize, this compressive wave moves both in solids and gases.

Next to be considered is the case in which the explosive is unconfined and lies in a tube which is at least 20 to 30 times wider than the charge diameter. If the explosive is now initiated, it immediately emits an initial shock wave, followed by expanding gas compressive waves into the surrounding media, in all directions. Now instead of a simple plane wave motion, there is a three dimensional shock wave which becomes extremely complex. How soon the pressure wave overtakes the shock wave in this case is a point of question and is dependent upon the explosive used and the transferring media. At any rate neglect the force of the shock wave and consider only the compressive wave as the destructive force. (Justification for this will be shown in Phase IV of the model tests). Figure 12 illustrates the explosive detonating in a tube of this nature. It shows only the initial compressive waves and not the reflected waves. This is justified for the purpose of obtaining an approximation of the maximum forces that are developed within the tube and if the first compressive waves hitting the sides of the tube are of sufficient force to cause failure, then the reflected waves are of minor importance.

Another simplification made is to assume that the compressive wave moves down the length of the tube as a plane wave. If Figure 13 is observed, it will be realized that this simplification is also of minor significance since as the first compressive wave moves out in greater

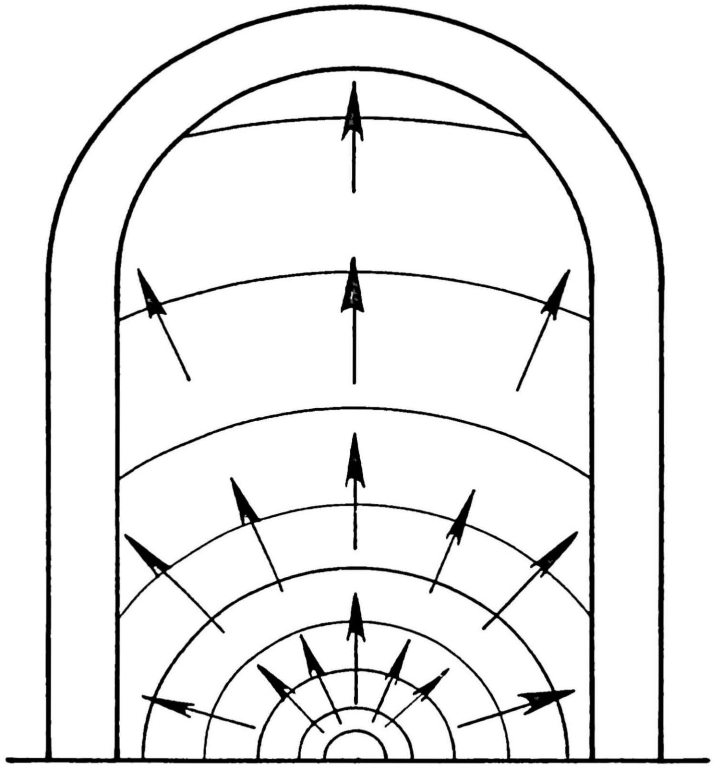


Figure 12. The spherical pressure front expanding within a tunnel.

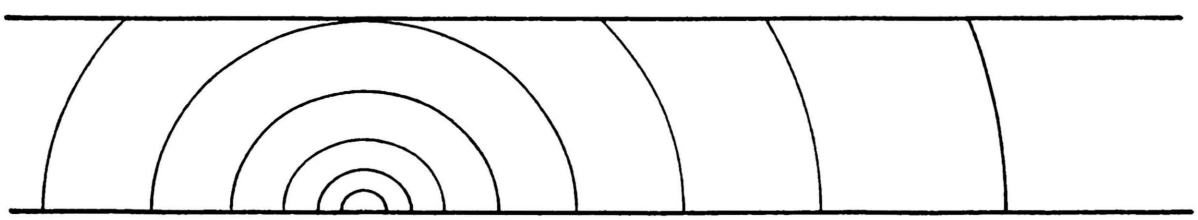


Figure 13. The spherical pressure front developing into a plane shock front as it expands in a tunnel.

and greater circles, the shock front moving down the tube appears as a plane wave. Here again, we are back to the situation where a piston-like wave is driving a column of air before it. Obviously, this air which is not in motion offers some small amount of resistance. The longer the column of air, the more the resistance. It therefore follows that the more resistance that is offered, the more confined in the tube the expanding gas will be. This is to say that the expanding gases will exert a greater force on the walls of the tube if they are not allowed to escape to atmospheric conditions quite so readily. By plugging both ends of the tube, the column of air could not escape and would be compressed. This then would offer a greater amount of resistance to our compressive wave. Likewise, this would cause a much larger force to be applied to the tube walls.

To further illustrate the shape of the pressure profile as this shock wave moves out, the author turns to a recent paper by Schardin.[4] By

(4) Schardin, Hubert, Measurement of Spherical Shock Waves, Transaction of Symposia in Applied Mathematics, Vol. 1, New York, Interscience Publishers, Inc., (1954) p. 224.

observing Figure 14 the reader can get a visual picture of the pressure profile at five different times. P/P_d is the pressure reading at any point divided by the detonation pressure. x/d represents the distance from the center of the charge divided by one-half the charge length. η is the time. The dotted line represents the boundary between the burnt-gas and air. To illustrate how the graph may be read, look at the curve where $\eta = 16$. First of all, it can be seen that the limit of this curve is at 49. This means that this is the leading edge of the shock front at this time. To the right of this is undisturbed air. Immediately

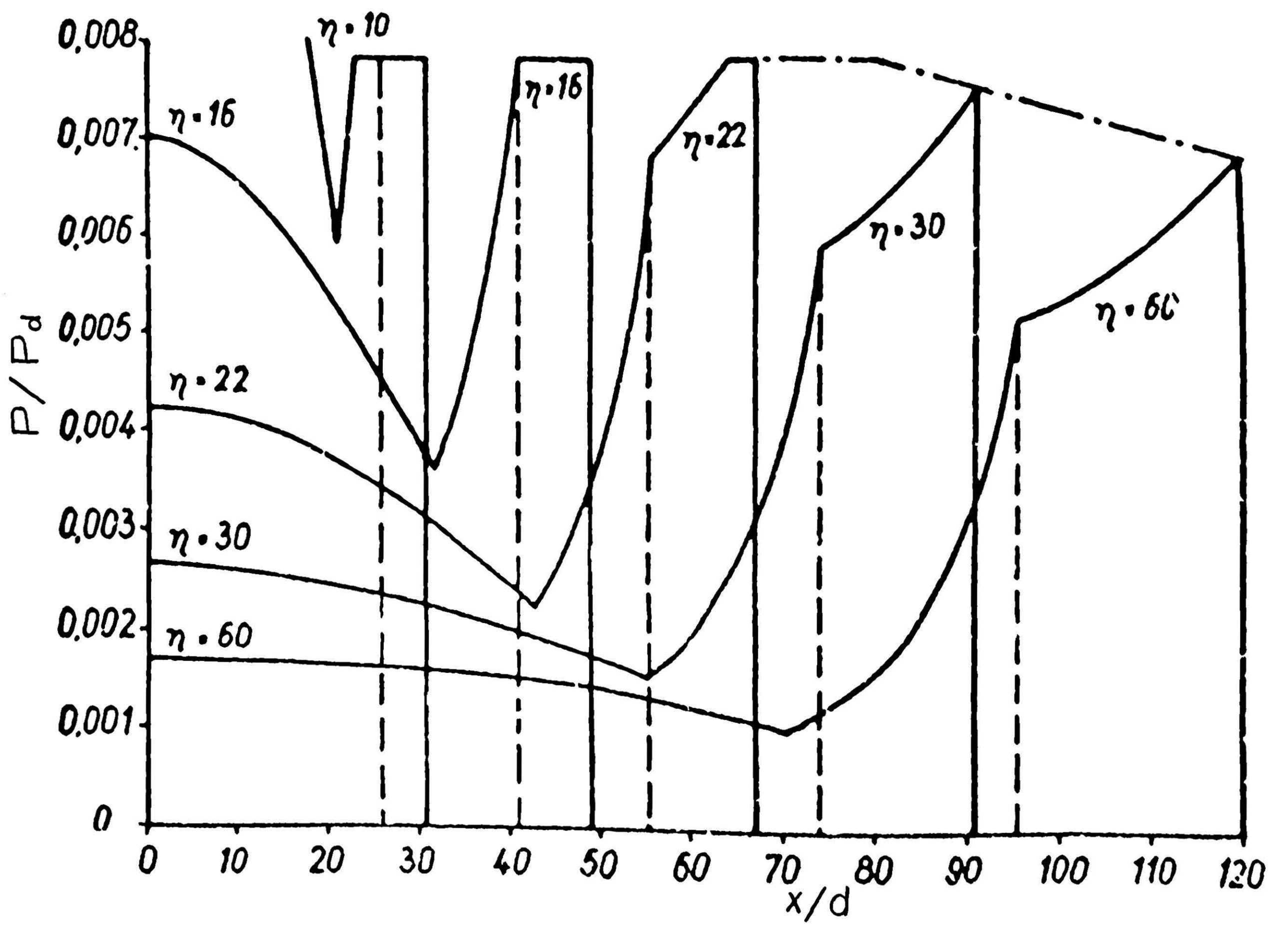


Figure 14. A one dimensional shock wave at five intervals of time. η = time, p = existing pressure, P_d = detonation pressure, x = the distance from the center of the charge, and d = half the length of a cylindrical charge of high explosive. The dotted line is the material boundary between air and burnt gas. (After Schardin).

behind this front there is a zone of constant pressure, followed by a rarefaction wave which is starting to decay the preceding wave. The minimum pressure of the rarefaction wave at this instant is located at 32. This distance ratio is more easily visualized if it is assumed that there is a charge of definite length, say four inches. Then this minimum pressure would occur at 64 inches away from the center of detonation. Following the rarefaction wave is the pressure wave of the expanding gases. Important things to be shown on these five curves are: first that there is a zone of constant pressure immediately behind the shock front; that the shock front starts to decay when the rarefaction wave reaches it; and that pressure waves of the expanding gases drop off very rapidly.

Concerning the zone of constant pressure, by checking the $\eta = 10$ curve it can be seen that this zone is quite wide. If again a four inch long charge is used for illustration then this peak pressure front is spread over approximately 18 inches. This is a very important occurrence since it adds a time duration to the peak pressure. Any force which acts over an interval of time has impulse. Schardin[(5)] states that:

[(5)]Schardin, Hubert, op. cit., p. 239.

"For the consideration of the destructive effect of the shock wave, the so called blast effect, the impulse is as important as the peak pressure, a fact which has been neglected often." From this point it may be concluded that even though the peak shock pressure is still very high between $\eta = 30$ and $\eta = 60$, it probably has very little destructive force. It is probable that the impulse of the following pressure wave is of more significance at this stage of the blast. Even though this pressure drops off as it expands, the duration of time in which there is a force acting on the surrounding media could cause considerable destruction.

MODEL SIMILITUDE

A discussion of the similarity between the problems and theories encountered in the study of tunnels and their models is now necessary. The advisability of using models for experimentation is apparent when the cost of demolition is considered. It is also true that more constant conditions will result from the use of models than real tunnels.

Whenever similar behavior is required of two bodies, they expect them to be geometrically similar (involving length ratios); kinematically similar (involving distance and time); and dynamically similar (involving mass, distance, and time).[6] However, it is seldom possible to

(6) McCutchen, Wilmot R., Similitude in the Study of Military Geology, The Military Engineer, Vol. XLI, No. 279, Jan.-Feb. 1949, p. 8.

achieve perfect similarity when dealing with explosives and materials of construction. In other words, it is highly impractical to try to reduce such things as the density and velocity of detonation of the explosive.

The model then is not a perfect model, but a distorted one. Distorted models are just as useful and as applicable as perfect models when the proper dimensional analysis has been applied to the relationships which exist between the model and the prototype.

If the linear dimensions of the model tunnel (1) are compared by ratios to the dimensions of the prototype tunnel (2), we have

$$\frac{L_1}{L_2} = \ell \; ; \quad (8) \qquad \frac{T_1}{T_2} = t; \quad (9) \qquad \frac{M_1}{M_2} = m; \quad (10)$$

where ℓ, t, and m are the length, time and mass ratios between the two tunnels. However, as previously stated, the density (D) ratio as well as the velocity (V) ratio are impractical to reduce to scale. This is to say that the properties of the explosive, as well as all the materials of construction, should be the same in both the prototype and the model. Thus

$$\frac{D_1}{D_2} = \frac{M_1 L_1^{-3}}{M_1 L_2^{-3}} = 1 \quad (11) \qquad \frac{V_1}{V_2} = \frac{L_1 T_1^{-1}}{L_2 T_2^{-1}} = 1 \quad (12)$$

Another fact that should be discussed at this time is the effect of gravitational acceleration. In many model studies where the gravitational force on the mass is of considerable magnitude, the ratio of all acceleration is considered to equal one. However, in this case where the explosive waves exert a force far greater than that of gravity, then the acceleration due to the earth's attraction is of minor significance and is ignored. From these fundamental ratios and basic principles, the ratios for other quantities such as force, acceleration, pressure, stress and energy can be obtained. Hence:

$$\text{Force ratio} = \frac{M_1 L_1 T_1^{-2}}{M_2 L_2 T_2^{-2}} = m\ell t^{-2} \quad (13)$$

$$\text{Acceleration ratio} = \frac{L_1 T_1^{-2}}{L_2 T_2^{-2}} = \ell t^{-2} \quad (14)$$

Thus by the same method, the ratios of other properties may be worked out. They are shown in Table II. Since the density ratio was unity, then $m\ell^{-3} = 1$, and $m = \ell^{3}$. Likewise, since the velocities were the same, $\ell t^{-1} = 1$, and $t = \ell$. Therefore all the dimensions involving m, ℓ, and t could easily be reduced to powers of the linear ratio. They are shown in Table II.

Since the density ratio = 1, then the weight ratio (W) is the same as the mass ratio and equals ℓ^3. Therefore, $\ell = W^{1/3}$. This is to say that if the linear ratio equal 0.100, then the weight ratio must equal 0.001. With this similitude factor, a 1,000 pound charge of Composition C-3

TABLE II

Dimensional Ratios

Mechanical Quantity	Distorted Model Ratios	Value of Ratios if $\ell = 0.100$
Length	$\ell = \ell$	0.100
Mass	$m = \ell^3$	0.001
Time	$t = \ell$	0.100
Density	$m\ell^{-3} = 1$	1.000
Velocity	$\ell t^{-1} = 1$	1.000
Acceleration	$\ell t^{-2} = \ell^{-1}$	10.000
Force	$m\ell t^{-2} = \ell^2$	0.010
Pressure, Stress, Strength and Modulus of Elasticity	$m\ell^{-1}t^{-2} = 1$	1.000
Strain	$1 = 1$	1.000
Work and Energy	$m\ell^2t^{-2} = \ell^3$	0.001

could be represented by a 1 pound charge of Composition C-3. The pressure exerted by these two charges are also similar. Since the pressure ratio equals one, then at similar points between the model and the prototype, the pressure will be equal. In other words, by again applying the 0.100 scale reduction, the pressure 100 feet from the 1,000 pound charge would be equal to the pressure 10 feet away from the 1 pound charge. This same pressure ratio has been worked out by other authors. Cole[7] states that

[7] Cole, R. H., Underwater Explosions, Princeton, New Jersey, Princeton University Press, 1948, p. 110.

"the pressure and duration of the shock wave measured ten feet from a cubical charge one foot on an edge will be the same as the pressure and duration measured twenty feet from a charge two feet on an edge in units of time twice as large. The duration in absolute units is therefore doubled distance for the charge of twice the linear dimensions (eight times larger weight)."

He goes fur her and defines the peak pressure (P_m) as

$$P_m = K \left(\frac{W^{1/3}}{R}\right)^a \qquad (15)$$

where K and a are empirical constants and R is the distance from the charge.

In a paper by Stoner and Bleakney[8], they conclude:

[8] Stoner, R. G., and Bleakney, Walker, The Attenuation of Spherical Shock Waves in Air, Journal of Applied Physics, New York, N. Y., American Institute of Physics, Vol. 19, July 1948, p. 675.

"For similar charges of equal density, equal pressures are expected at distances proportional to the linear dimensions of the charges, and hence to the cube root of the charge weight. This scaling law has been shown experimentally to be valid over a large range of charge weights."

In building the model tunnels for these experiments, the linear ratio was established at one-tenth. Therefore, a wall thickness of 2 inches will represent a wall 20 inches thick in the prototype. Likewise, a model tunnel 50 feet in length will react similarly to a prototype tunnel 500 feet in length.

The explosive charges were likewise scaled according to the laws of similitude. From Table II we see that the mass ratio equals 0.001, therefore a 250 pound charge is represented by a 0.25 pound charge. By the same token, the 0.5 pound charges that were used were equivalent to 500 pound charges in the full scale tunnels.

The fact that equal pressures are found at similar points at scaled distances from equivalent charges has already been discussed, but the magnitude of the pressures has not been given. Several authors have approached this subject from both the theoretical and the experimental view point. Obviously, it is extremely difficult to measure any pressure which is very close to the charge because of the damage to the recording equipment.

In a paper by G. I. Taylor[9] there is included data obtained at

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[9] Taylor, G. I., The Formation of a Blast Wave by a Very Intense Explosion, Proceedings of the Royal Society of London, Vol. 201, March 1950, p. 172.

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the Road Research Laboratory on the pressures resulting from charges of a TNT-RDX explosive mixture at varying distances. The graph in Figure 15 is plotted from this information. While it is limited to a relatively small zone affected by the blast, it will suffice to give an approximation as to the pressure inside the model tunnels after the detonation of a small charge of high explosive.

From Figure 15, at a point 10 inches from a $\frac{1}{4}$ pound charge, the $R/W^{1/3}$ ratio would equal 1.32. This would give a pressure reading of 85 atmospheres or 1250 p.s.i. Likewise, at a distance 20.2 inches from the $\frac{1}{4}$ pound charge, the pressure drops to 20 atmospheres or 308 p.s.i. At 27.5 inches from the same charge, the pressure falls to 10 atmospheres or 147 p.s.i. These three distances were chosen because they represent critical points in a Type A tunnel. (The dimensions of this tunnel are described in detail on page 35.) If the charge is placed in the center of the tunnel floor, then the 10 inch distance is the distance from the charge to the wall; 20.2 inches is the distance from the charge to the spring-line of the tunnel; and 27.5 inches is the distance from the charge to the crown of the arch.

While the information would be extremely useful, the calculations involved in determining the stress concentrations set up within the tunnel lining in a three dimensional system would be highly complex and fall beyond the scope of this paper. However, after carefully studying motion

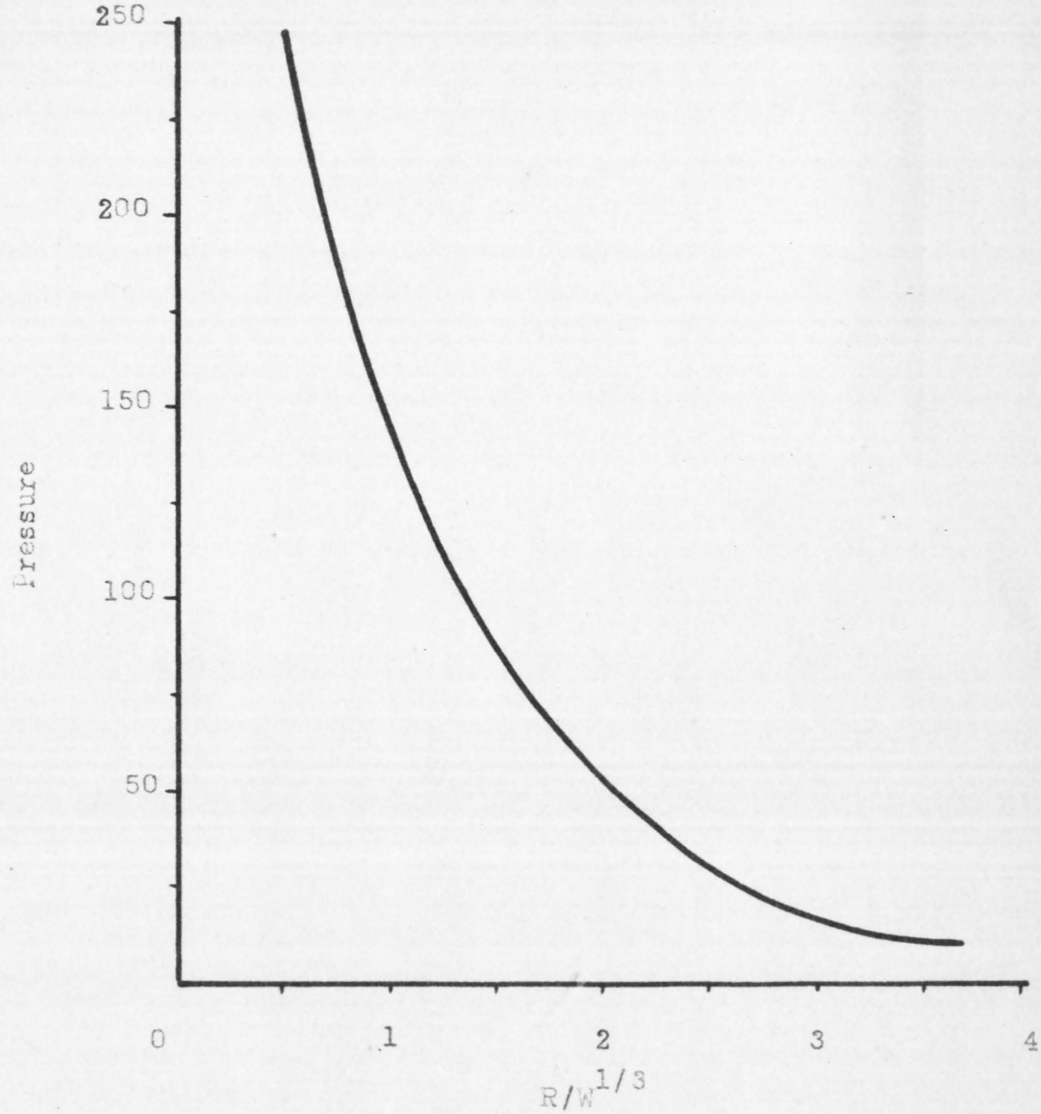

Figure 15. Pressure (atmospheres) at distance R (feet) from explosive of weight W (pounds) of TNT-RDX mixture. (After Taylor, G. I.)

pictures taken with a high speed camera, it is concluded that the tunnel linings failed in tension. Most of the tunnels that were tested had a tensile strength of approximately 350 p.s.i. By analyzing the magnitude of the pressures stated in the previous paragraph, it seems that in all probability the strength of the lining offers only minor resistance to a $\frac{1}{4}$ pound charge of high explosive placed within a Type A tunnel.

THE MODEL TEST

The primary purpose of this series of tests was to determine the blast effects of untamped charges when placed in tunnels under varying conditions. Twenty-one model tunnels were built and tested with a slightly different variable for each tunnel. It was the constant rule of the testing program that not more than one critical variable be changed between each test. This allowed for comparisons between tests to determine a cause and effect relationship.

In order to avoid repetitious description, the tunnels were classified into three basic types. Type A was model of a standard single track arch railroad tunnel, the linear scale relationship being reduced to one-tenth of the prototype tunnel. (See Figure 16). The inside dimensions of this tunnel were: width, 20 inches; height, $27\frac{1}{2}$ inches; arch radius, 10 inches; cross-sectional area, 3.52 square feet. The length and wall thickness varied with the different tests. The size of the prototype tunnel corresponding to this model would be 16.7 feet wide, 23 feet high, and with 1.7 feet lining thickness.

The Type B models were larger in size, but built in the same shape as Type A. (See Figure 17). The inside dimensions were: 28 inches wide; 38 inches high; arch radius of 14 inches; and a cross-sectional area of 6.81 square feet. The tunnel lining for all the Type B models was 3 inches thick. The prototype tunnel for this model would be 23.3 feet wide, 31.7 feet high at the crown of the arch and with a lining thickness of 2.5 feet.

The Type C tunnel was circular, 18 inches in diameter and with a 3 inch thick lining. (See Figure 18). The cross-sectional area was 1.77 square feet. The tunnel that this model would represent would be a 15

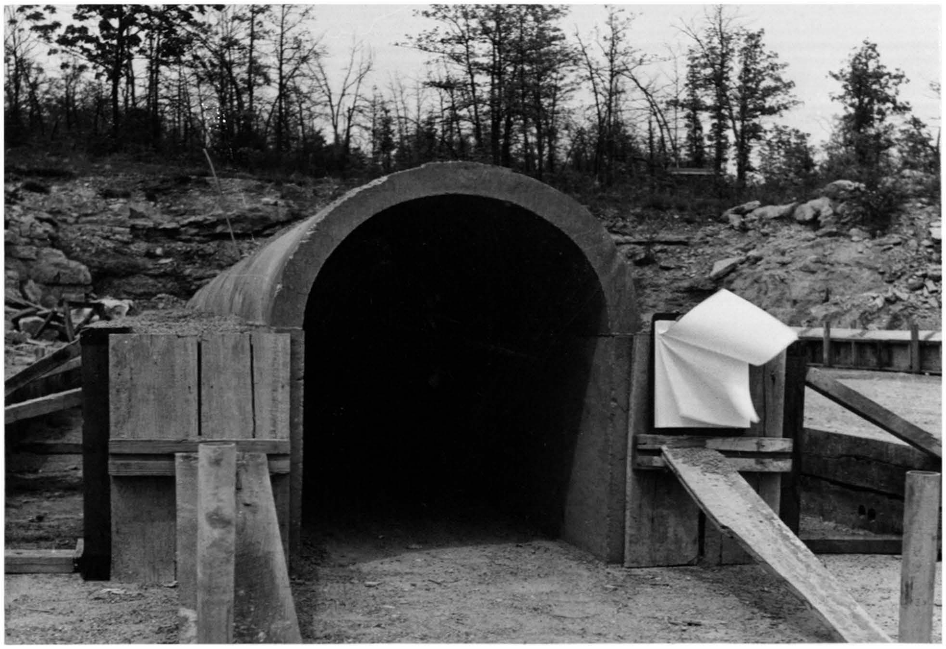

Figure 16. Type A tunnel.

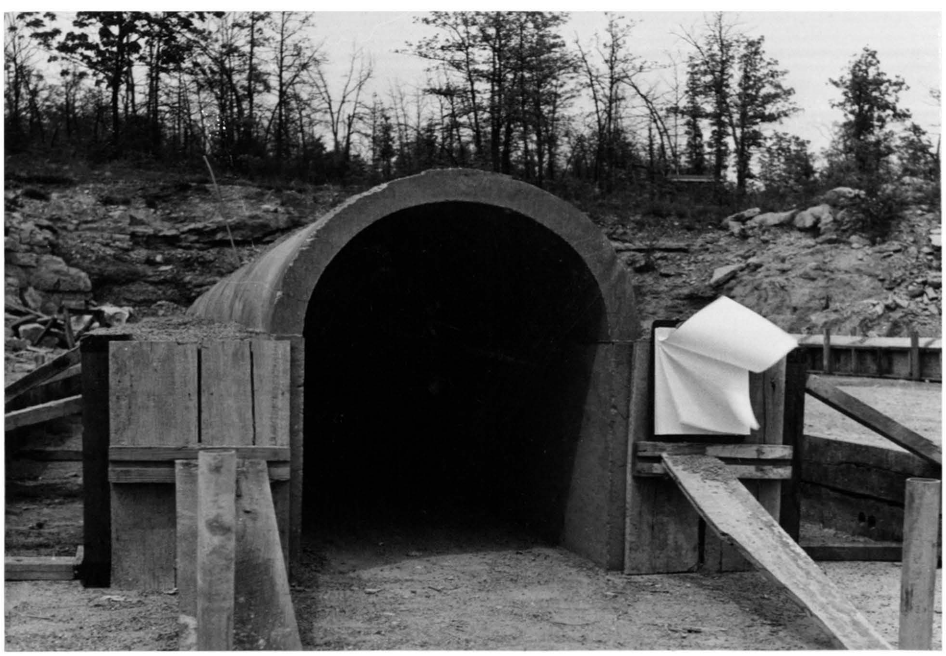

Figure 17. Type B tunnel.

Figure 18. Type C Tunnel

foot circular tunnel with a 2.5 foot thick lining.

All charges were detonated with Corps of Engineer special electric blasting caps except where otherwise designated.

PHASE I

The first series of tests were run to determine what effect the lining thickness had on the ease of destructability of tunnels. All the tunnels built for this phase were of Type A and were 10 feet in length. The tunnel linings were completely unrestrained.

Test One

This model was built with a lining thickness of 2 inches. The compressive strength of the concrete was 3305 p.s.i. (See Figure 19). The ¼ pound charge of C-3 shown in Figure 20 was placed untamped in the exact center of the tunnel floor.

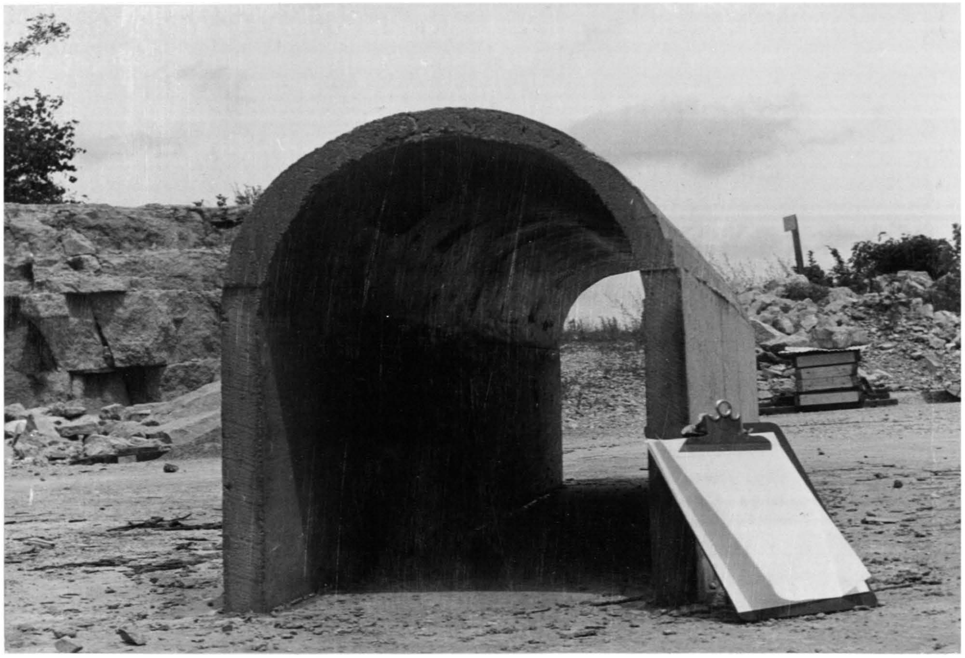

Figure 19. Type A tunnel constructed for Test One, Phase One.

Figure 20. A $\frac{1}{4}$ pound charge of Composition C-3 explosive.

The result of the blast effect after detonation of the charge is shown in Figure 21. Obviously the tunnel lining was completely destroyed. A point of interest is that the top portion of the walls moved out farther than the bottom of the wall which was displaced only a few inches.

Test Two

The model for this test had a lining thickness of 3 inches and a concrete compressive strength of 2915 p.s.i. (See Figure 22). Again a $\frac{1}{4}$ pound charge of C-3 was placed untamped in the center of the tunnel floor.

The results of the demolition were again complete destruction of both the arch and the walls. (See Figure 23). Careful examination showed that the top of the walls moved out more than the bottom portion.

Figure 21. The results of demolition in Test One, Phase One.

Figure 22. Type A tunnel constructed for Test Two, Phase One.

Figure 23. The results of demolition in Test Two, Phase One.

Figure 24. Type A tunnel constructed for Test Three, Phase One.

Test Three

This time, the lining thickness was increased to 6 inches. (See Figure 24). The concrete strength was 3610 p.s.i. in compression. The same type charge was placed in this tunnel as the previous two.

Upon detonation, the tunnel completely collapsed. However, because of its greater mass and lining thickness, the concrete had less chance to be displaced and could thereby be more easily studied. (See Figure 25). The walls appear to have collapsed outward allowing the top to drop.

Analysis of Phase I

Since the scale reduction is one-tenth, a model having a 6 inch lining thickness represents a prototype tunnel lining of 5 feet. It was decided that tests of greater thicknesses would be impractical.

From the above three tests, the following may be concluded:

Figure 25. The results of demolition in Test Three, Phase One

1. That the unrestrained tunnel lining offers little resistance to the blast effect within the range of the thickness tested.
2. That the unrestrained lining will usually break along the spring-line. This allows the top to go up and the walls out.
3. That there is a greater destructive force at the top of the wall than at the bottom.

PHASE II

The second phase of the testing program was to determine the combined effects of tunnel length and degree of confinement in relation to the destructive force of the blast. All the tunnels for this phase were of Type A.

The first two tunnels of this phase were tested without any confining material around them. The next three tunnels were partially confined by placing sand against the walls. Then two were tested while completely

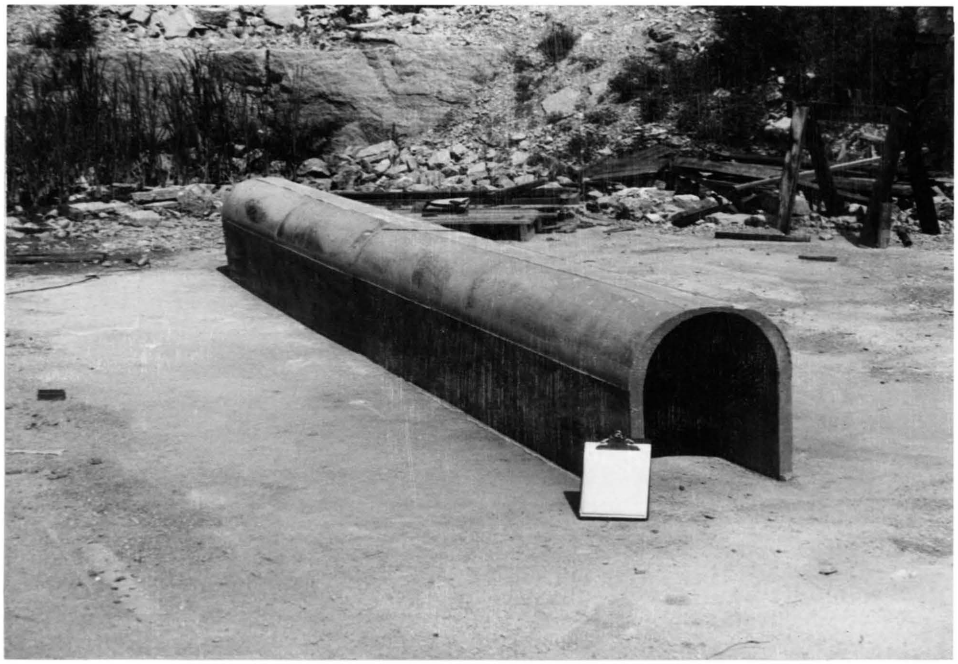

Figure 26. Type A tunnel constructed for Test Two, Phase II.

covered with sand, and the last tunnel was rigidly confined with concrete every 10 feet.

Test One

The reader is referred to Test One of Phase One for a 10 foot tunnel without any form of confining material.

Test Two

This tunnel was constructed 20 feet long. (See Figure 26). There was no confining material placed around the lining. Because of an error in building this tunnel, the concrete at the top of the arch was only about 1 inch thick, while the haunch of the arch was about 3 inches thick. It was allowed to come up to 3930 p.s.i. to give it additional strength before testing.

A $\frac{1}{4}$ pound charge was placed 5 feet in from the east portal, in the

Figure 27. The results of demolition in Test Two, Phase II

center of the tunnel on the floor.

Upon detonation of the charge, the tunnel was totally destroyed. By comparing Figure 27, the results of this test, and Figure 21 we can see that the destructive force was ore efficient in the 20 foot tunnel. Proof of this statement is that not only was twice as much tunnel destroyed with the same amount of explosive, but also the displacemen of the lining fragments was much greater. Around the point of detonation, the lining was thrown at least 6 feet in Test Two. Even at the far end of this tunnel, the walls were displaced a foot. But in Test One, the left wall was merely turned over with little displacement.

Test Three

In this test the walls were backed with 1 foot of sand. The tunnel was again 10 feet in length with a 6 inch lining thickness so that a

Figure 28. Type A tunnel constructed for Test Three, Phase II.

comparison between partial confinement and no confinement could be made. (See Figure 28). The concrete strength was 3020 p.s.i. in compression. Detonation was produced in a ¼ pound charge of C-3 placed in the exact center on the floor.

When the charge was fired, a break developed above the springline on each side of the tunnel. The walls bulged out about 1 inch at the bottom and about 2½ inches at the top. Vertical cracks developed in both walls at the point of detonation as well as a minor crack across the arch. As can be seen from Figure 29, the tunnel was left standing for its full length.

Test Four

For this test, a Type A tunnel 20 feet in length was constructed with a 2 inch wall thickness. The walls were backed with 1 foot of coarse

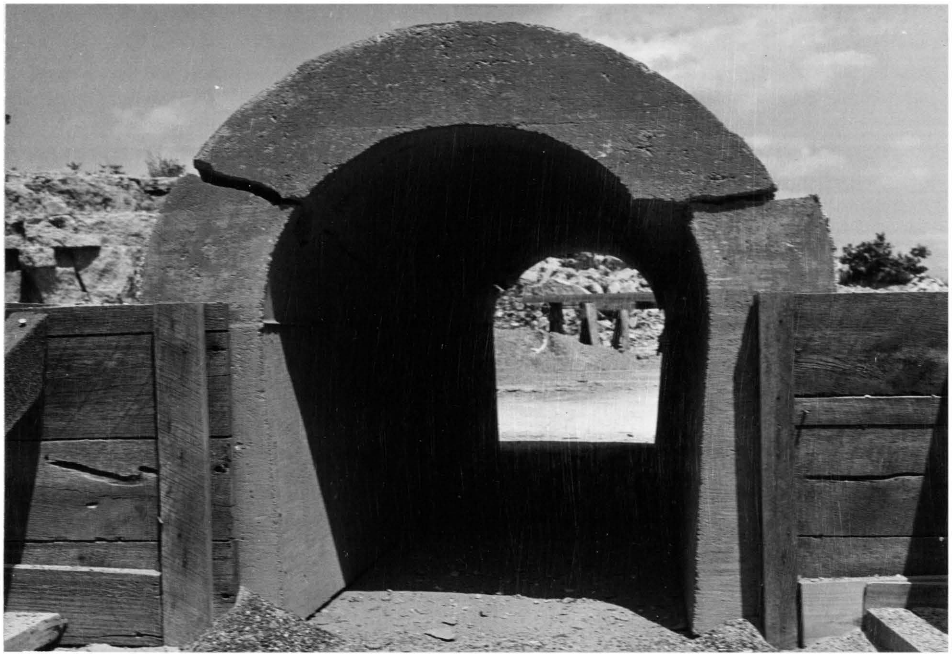

Figure 29. The results of demolition in Test Three, Phase II.

Figure 30. Type A tunnel constructed for Test Four, Phase II.

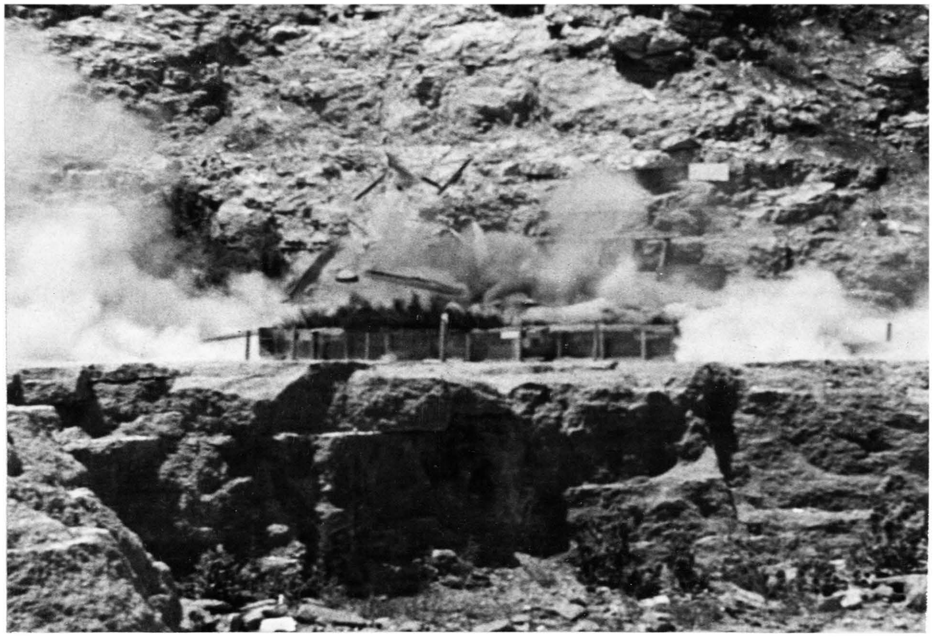

Figure 31. A $\frac{1}{4}$ pound charge being detonated in Test Four, Phase II.

sand. (See Figure 30). The compressive strength of the concrete was 3708 p.s.i.

A $\frac{1}{4}$ pound charge of C-3 was placed in the tunnel 5 feet from the west portal on the floor and detonated. An excellent photograph of this tunnel being exploded was taken and is shown in Figure 31.

As a result of this explosion, 60 per cent of the arch was destroyed. (See Figure 32). The walls were left standing but were slightly displaced.

Test Five

For this test a 50 foot tunnel of Type A, with a 2 inch lining thickness was constructed. The walls were backed with 12 inches of coarse sand. (See Figure 33).

Upon detonation of a $\frac{1}{4}$ pound charge placed in the same manner as in the previous test, 100 per cent of the arch was destroyed. Figure 34

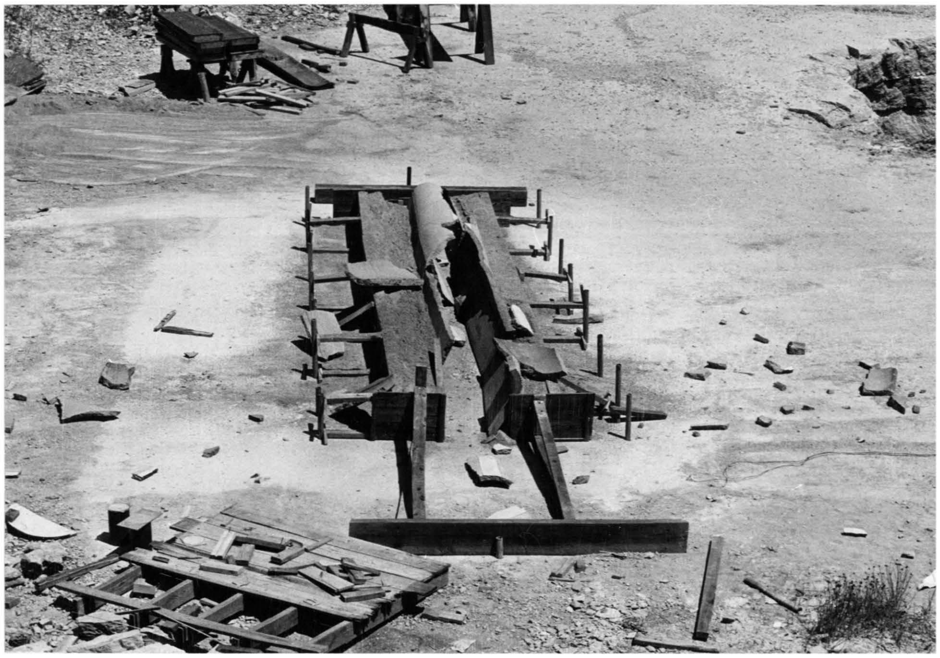

Figure 32. The results of demolition in Test Four, Phase II.

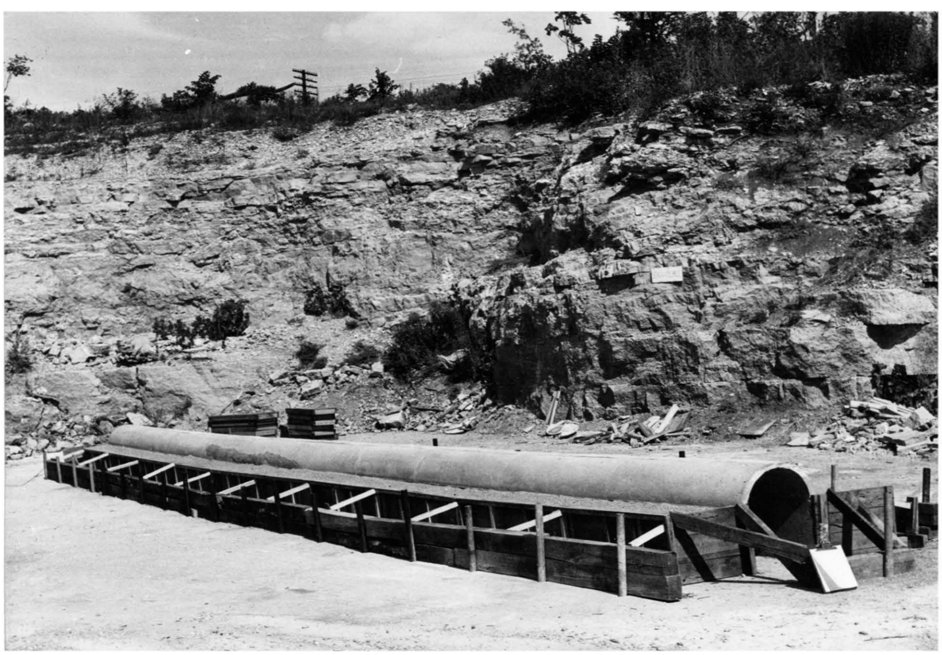

Figure 33. Type A tunnel constructed for Test Five, Phase II.

Figure 34. A $\frac{1}{4}$ pound charge being detonated in Test Five, Phase II.

shows the blast going off. The results of that explosion are shown in Figure 35.

Figures 35 and 32 illustrate the difference in the results of demolition between the 20 foot and the 50 foot tunnels. More effective utilization of the same size charge was obviously gained in the 50 foot tunnel. In the longer tunnel there was at least three times as much damage as in the 20 foot tunnel. The effect of the sand confinement on the structures is very noticable when Figure 32 is compared with Figure 27. The latter shows complete failure of the tunnel walls and arch, while Figure 32 indicates practically no wall damage. Figure 36 also shows how the walls of the model in Test Five were le practically undamaged even with 100 per cent arch failure.

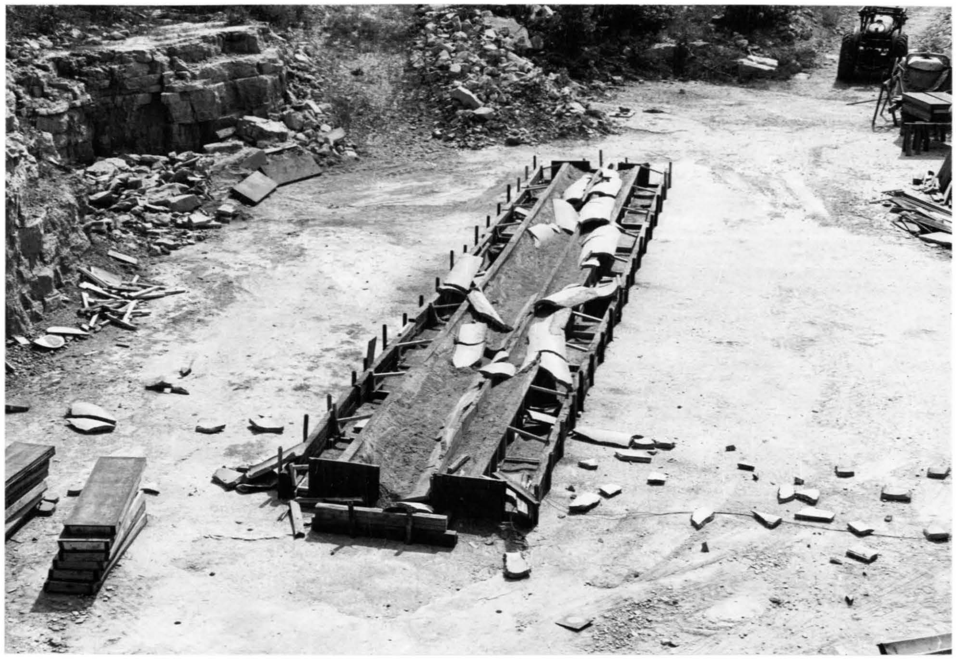

Figure 35. The results of demolition in Test Five, Phase II.

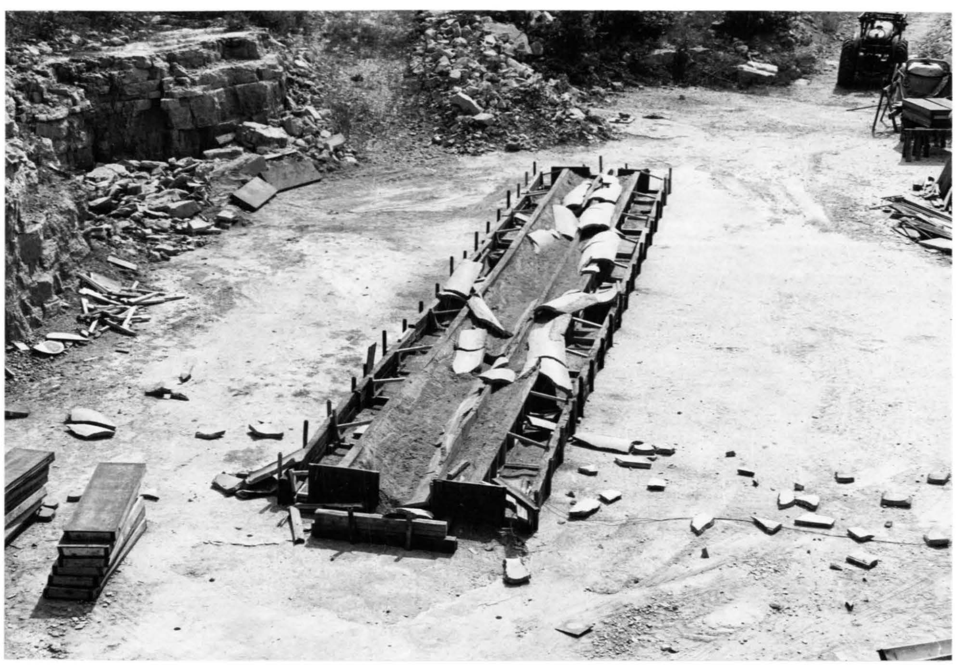

Figure 36. The walls were left practically undamaged in Test ive, Phase II.

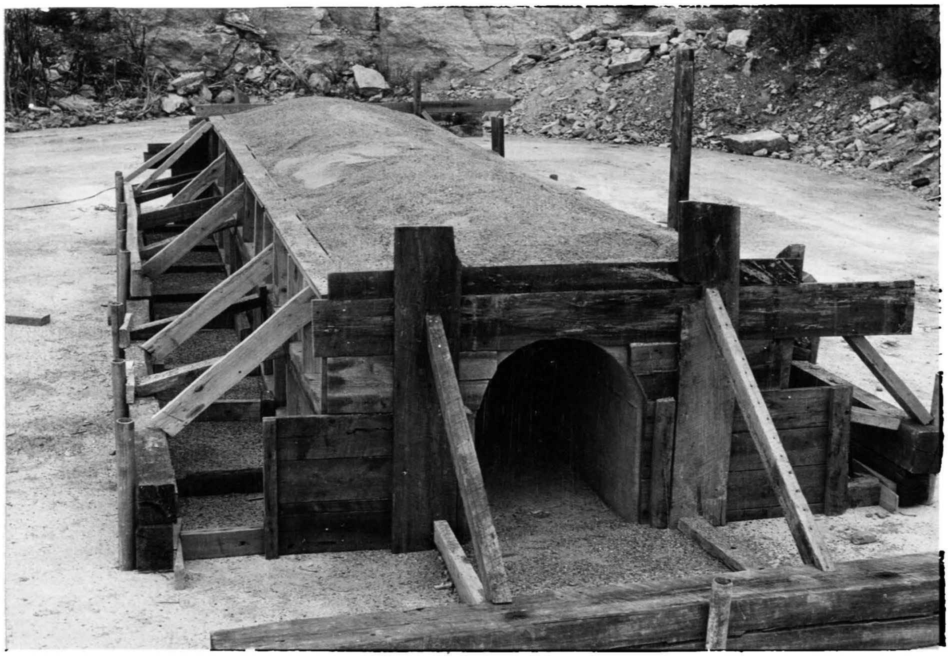

Figure 37. Type A tunnel constructed for Test Six "A", Phase II.

Test Six "A"

A type A tunnel, 20 feet long with a 2 inch lining thickness and covered completely with coarse sand, was constructed for this test. The walls and top were covered with 12 inches of sand and the haunch of the arch was covered with 18 inches. (See Figure 37 . The compressive strength of the concrete was 3575 p.s.i.

A $\frac{1}{4}$ pound charge of C-3 was placed 5 feet in from the west portal on the floor. The results of the detonation of that charge are seen in Figures 38 and 39. The former was taken from the west portal and the latter from the east portal.

The west half of the arch was badly cracked but was keyed in place and therefore nothing could fall. The east half of the arch had only the one main crack running down the approximate center.

Figure 38. The results of demolition in Test Six "A", Phase II. The picture taken from the west portal.

Figure 39. The results of demolition in Test Six "A", Phase II. The picture taken from the east portal.

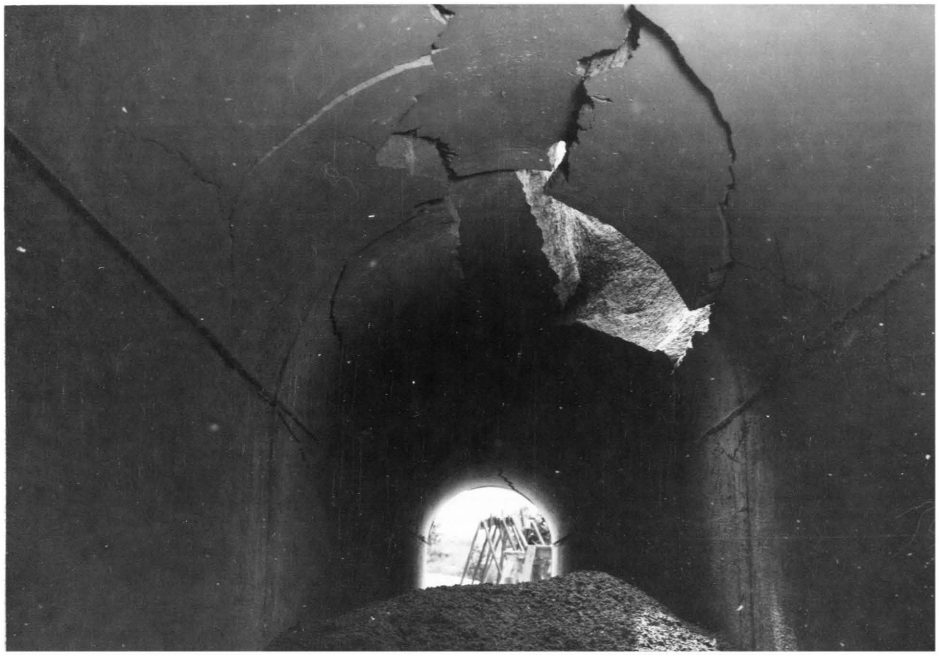

Figure 40. The results of secondary demolition in Test Six "B".

Test Six "B"

Since the tunnel was still standing and in usable condition, it was decided to submit the already broken structure to further demolition and determine what further damage could be inflicted. A duplicate of the charge used in test Six "A" was placed and fired. As can be seen from Figure 40, a hole approximately 1 foot in diameter was breached in the arch at the point of detonation.

Test Six "C"

Since the tunnel could be made passable with little effort, a third charge was used. This time a ½ pound charge of C-3 was placed in the same spot as the previous two shots and fired.

The west half of the tunnel completely collapsed from this charge, while the east half remained, but was badly cracked.

Figure 41. The results of demolition in Test Seven "A", Phase II. The picture was taken from the west portal.

Test Seven "A"

A Type A model tunnel 50 feet in length and with a 2 inch lining thickness was constructed. The tunnel was completely covered with sand as in Test Six.

A $\frac{1}{4}$ pound charge of C-3 was placed 5 feet in from the west portal on the floor and exploded. As usual, it was untamped and primed with a Corps of Engineers special electric blasting cap. The results of the blast to the west half of the tunnel are shown in Figure 41. The damage to the arch was severe, but due to the weight of the sand, the broken pieces remained keyed in place. By comparing this photograph with Figure 38, it can be seen that more damage was done to the longer tunnel. Figure 42 shows the slight damage done to the east portion of the model.

Figure 42. The results of demolition in Test Seven "A", Phase II. The picture was taken from the east portal.

Test Seven "B"

To follow the pattern of testing set up in Test Six, a second charge of the same size as the first was placed in the same spot and detonated. Figure 43 shows the results of that blast. A hole about one foot in diameter was breached in the arch over the point of detonation, and about 3 feet of the west portal caved. Springline cracks opened up on both sides of the tunnel throughout its length, extending to within about 6 feet of the east portal, where they curved to the floor. The remaining portion of the tunnel stood intact.

Test Seven "C"

The tunnel was still considered passable with very little reconstruction, so the third charge was placed in it. As in Test Six "C", a a $\frac{1}{2}$ pound charge was used for the third charge, this time being placed

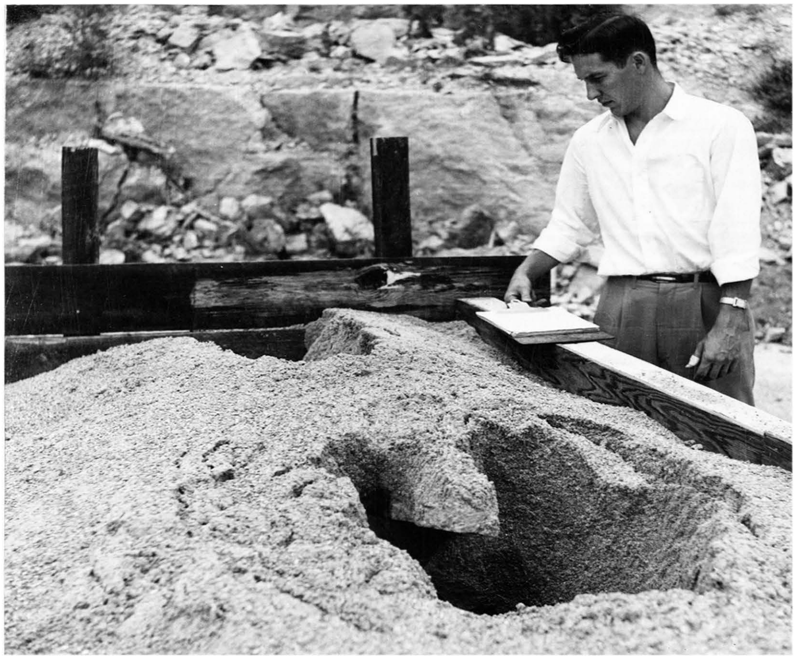

Figure 43. The results of the secondary demolition in Test Seven "B", Phase II.

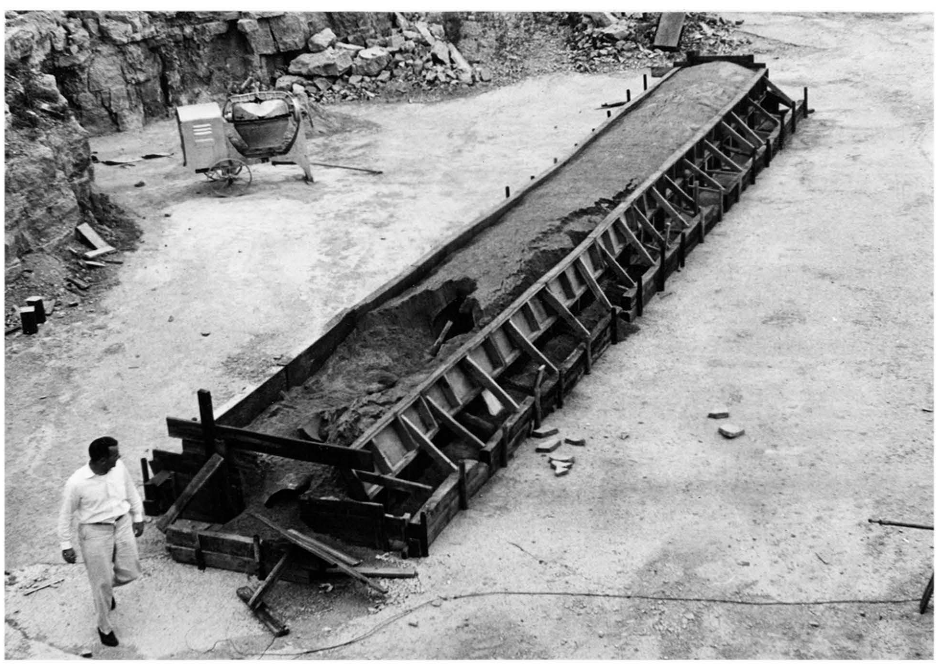

Figure 44. The results of the tertiary demolition of Test Seven "C", Phase II.

Figure 45. The tunnel which was constructed for Test Eight, Phase II.

on the floor, 10 feet from the west portal. The results of this explosion closed the west 15 feet of the tunnel. (See Figure 44).

Test Eight

The tunnel for this test was a Type A model constructed 50 feet long and with a 2 inch lining thickness. The confining media for this tes consisted of large solid masses of concrete built over the tunnel every 10 feet. (See Figure 45). The lining confinements were 12 inches thick, 60 'nches wide, and 49½ inches high. Between these masses of concrete, the tunnel walls were backed with sand. Because of a delay incurred in obtaining high speed camera equipment to record the action of the blast, the compressive strength in this model was allowed to go to 4720 p.s.i., which was higher than in previous tests. A ¼ pound charge of Composition C-3 was placed on the floor, 5 feet from the south portal.

Figure 46. The results of the demolition in Test Eight, Phase II.

When the charge was detonated, the arch between the first and second concrete blocks was blown off at the springline. (See Figure 46). The walls of this section contained several vertical cracks but remained standing. The next 10 foot section had a double crack running down the arch, but nothing caved. The remaining 30 feet of tunnel had minor cracks running down the arch. There was a crack near the springline of the west wall which ran all the way down the 40 foot portion of the tunnel which did not cave.

To illustrate the effect of having rigid wall confinement every 10 feet, compare Figure 46 with Figure 35. Figure 46 shows about 20 per cent of the arch destroyed, while Figure 35 shows that 100 per cent of the arch failed.

Analysis of Phase II

From the foregoing tests, the following conclusions are drawn:

1. That the $\frac{1}{4}$ pound charges were used more efficiently in the 20 foot tunnel than in the 10 foot tunnel. Likewise, that the same size charge was more effective in the 50 foot tunnel than in the 20 foot tunnel. This then leads us to the conclusion that the longer the tunnel, the more efficiently the air blast effect will be utilized to destroy the tunnel, other conditions being equal. It is probable, however, that there is some great length where this generalization does not hold true. This is to say that the tamping effect of an additional length of air column for very long tunnels is practically negligible.
2. That the confinement of the walls with sand protects these walls from almost all damage for the explosive charges tested. However, it adds almost no protection to the arch.
3. That when the tunnel is completely confined with sand, the tunnel is greatly strengthened. Even though the sand above the arch is free to move, its weight causes the broken sections to key back in place after the $\frac{1}{4}$ pound charges are detonated.
4. That where the lining is placed against solid concrete or rock and is rigidly confined, the amount of damage which can be caused by air blast from untamped charges is very limited. In fact, the severe damage will be limited to the zone in the immediate area around the charge where the lining is free to move.
5. That when the tunnels are completely covered with sand, small charges fired one after the other in the tunnel are very inefficient in destroying the tunnel, even though the tunnels are

previously cracked and broken. This is to say that detonating two $\frac{1}{4}$ pound charges, one after the other, is not as efficient as detonating one $\frac{1}{2}$ pound charge.

PHASE III

This phase of testing was carried out to determine the effects of charge size in relation to the destructive force of the blast. This phase also includes the effects experienced when one end of the tunnel is closed by sand bags before demolition.

Test One

The reader is referred to Test Six A of Phase II for a Type A tunnel completely covered with sand and charged with a $\frac{1}{4}$ pound charge of C-3.

Test Two

As in previous tests, a Type A tunnel was built 20 feet long with a 2 inch lining thickness and completely covered with sand. The demolition that was placed within the tunnel was $\frac{1}{2}$ pound of C-3.

The results of the detonation of that charge are shown in Figures 47 and 48. The west half of the arch collapsed into the tunnel. The east half of the tunnel remained open but was badly cracked. To appreciate the effects of doubling the charge weight under these conditions, compare Figures 39 and 48. Both pictures were taken from the east portal after Test One and Test Two respectively.

Test Three

The reader is referred to Test Seven A of Phase II for an example of a $\frac{1}{4}$ pound charge bei g detonated in a 50 foot Type A tunnel, completely covered with sand.

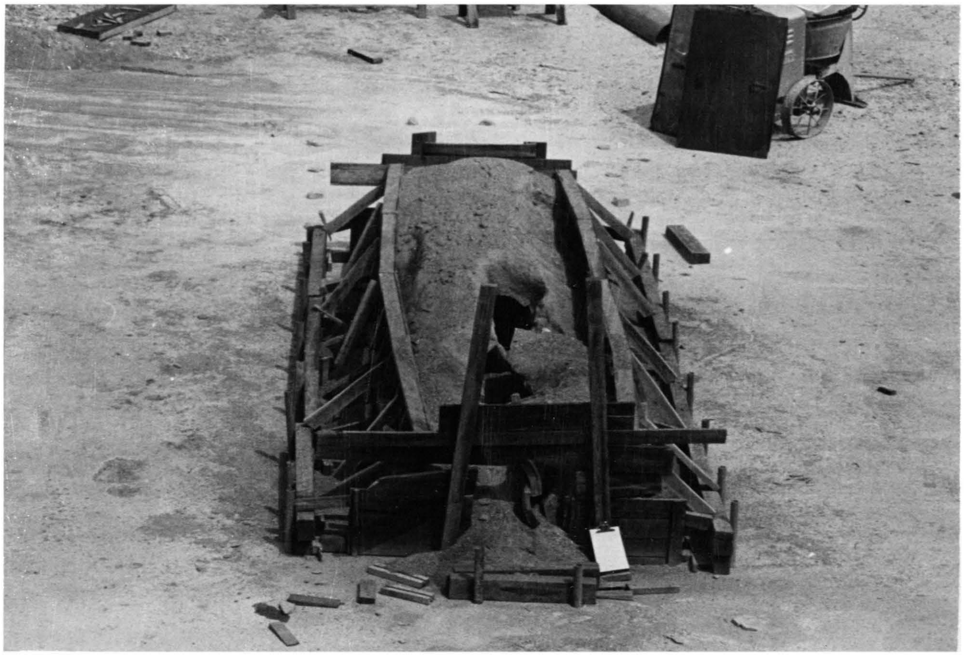

Figure 47. The results of demolition in Test Two, Phase III.

Figure 48. The results of demolition in Test Two, Phase III.

Figure 49. The results of demolition in Test Four, Phase III.

Test Four

This time a $\frac{1}{2}$ pound charge of C-3 was placed in a tunnel identical with Test Three. The results of that charge are shown in Figure 49. As can be seen, there was a cave-in starting 1 foot from the west portal and extending about 9 feet. The next 15 feet eastward had a single crack at the crown, followed by 15 feet of double cracks which left a center piece of the crown keyed in place. The remaining 10 feet had a single crack in the arch. There was practically no wall damage except for a springline crack on both sides and a vertical crack at the point of detonation.

Some comparison can be shown between the results of Test Three and Test Four by comparing Figure 41 with Figure 50.

Figure 50. The results of demolition in Test Four, Phase III.

Figure 51. Sand bags approximately 18 inches thick closed the portal in Test Five, Phase III.

Test Five

A Type A tunnel was constructed 50 feet long with a 2 inch wall thickness and completely covered with sand, as previously described. The charge employed was $\frac{1}{4}$ pound of C-3, which was placed on the floor, 5 feet from the west portal. The charge itself was left untamped. However, the west portal was closed by placing sand bags approximately 18 inches in depth across the portal. This is shown in Figure 51.

Upon detonation of this charge, there was a cave-in starting five feet from the west portal and continuing about $2\frac{1}{2}$ feet. The next 1 foot of the arch was keyed in place, but the next $1\frac{1}{2}$ feet caved in. Th's destruction is illustrated in Figure 52 and Figure 53. The next 5 feet had a single crack running down the center of the arch which opened into a double crack for the next 10 feet. The remaining 25 feet had a single crack running down the arch. The walls were cracked vertically in several places, but there were no horizontal cracks.

It is worth noting that this was the first time in the testing prog am that the Type A tunnel, completely covered with sand, was breached with a $\frac{1}{4}$ pound charge of C-3. The effects of closing the portal before demolition can be seen by comparing Figure 42, in which the portal was not closed, with Figure 53 of this test. Obviously, considerably more damage was done in the latter.

Test Six

The tunnel construction and the method of charge placement and closing the portal was the same in this test as in the previous one. The only difference was that a 1 pound charge was detonated instead of a $\frac{1}{4}$ pound charge. Also, the tamping and the charge were placed in the east end of this tunnel instead of the west.

Figure 52. The results of demolition in Test Five, Phase III.

Figure 53. The results of demolition in Test Five, Phase III.

After the explosive was detonated, the tunnel completely collapsed from the east portal down to within 15 feet of the west portal. This remaining 15 feet was partially caved but portions of it remained standing. For all practical purposes the tunnel would be considered completely destroyed.

Figures 54 and 55 show how complete the destruction was. Notice that in Figure 54, on the east end of the bottom sand forms that are still vertical, a 2 x 4 brace has been driven through the plywood forms. Notice also how the upper sand forms have been displaced. Figure 55 shows that even the walls of this tunnel were badly broken and displaced.

A comparison of the destructive effect of a charge four times larger than another charge placed in like manner 's seen when Figure 52 is compared with Figure 54. It is estimated that approximately eight times as much damage was caused by the 1 pound charge.

Analysis of Phase III

From the above test, the following conclusions may be derived:

1. From the tests on the 20 foot tunnels which were completely confined with sand, it was estimated that doubling the charge weight from $\frac{1}{4}$ to $\frac{1}{2}$ pound caused approximately eight times as much damage to the tunnel.
2. From Tests Three and Four in which two 50 foot tunnels were confined with sand, it was estimated that doubling the charge weight from $\frac{1}{4}$ to $\frac{1}{2}$ pound caused approximately four times as much destruction.
3. From comparisons of Tests Three and Five, it was estimated that by closing one portal with sand bags, approximately two times as much damage could be caused with $\frac{1}{4}$ pound of C-3.

Figure 54. The results of demolition in Test Six, Phase III.

Figure 55. The results of demolition in Test Six, Phase III.

4. By comparing Test Five with Test Six, it was estimated that at least eight times as much damage was done to the 50 foot tunnels with one portal closed when the charge size was increased four times.

PHASE IV

This phase of the program consisted of only one test. The object was to determine whether the shock wave moving through the air in the form of air blast (pressure wave) or the shock wave (stress wave) moving through the lining was causing the destruction of the tunnels.

The model for this test was a Type A tunnel, 50 feet long with a 2 inch lining thickness. However, placed within the concrete lining 20 feet from the west portal was a piece of ½ inch sponge rubber held between two pieces of ½ inch plywood. This joint was made the exact shape of the tunnel.

A ½ pound charge of Composition C-3 was placed 5 feet from the west portal on the floor in the center of the tunnel. After detonation of this charge, the tunnel arch failed for its entire length. As can be seen in Figure 56, most of the arch was blown off and the walls were pushed in by the weight of the sand. The shock proof joint seemed to have little effect on the destruction. In fact, the joint was also split at the crown of the arch. (See Figure 57).

Analysis of Phase IV

From the results of the foregoing test, it is concluded that the force which is causing destruction, when the charge is placed in the described manner, is largely the air blast from the explosion. This does not mean that a shock wave moving through the lining is not capable

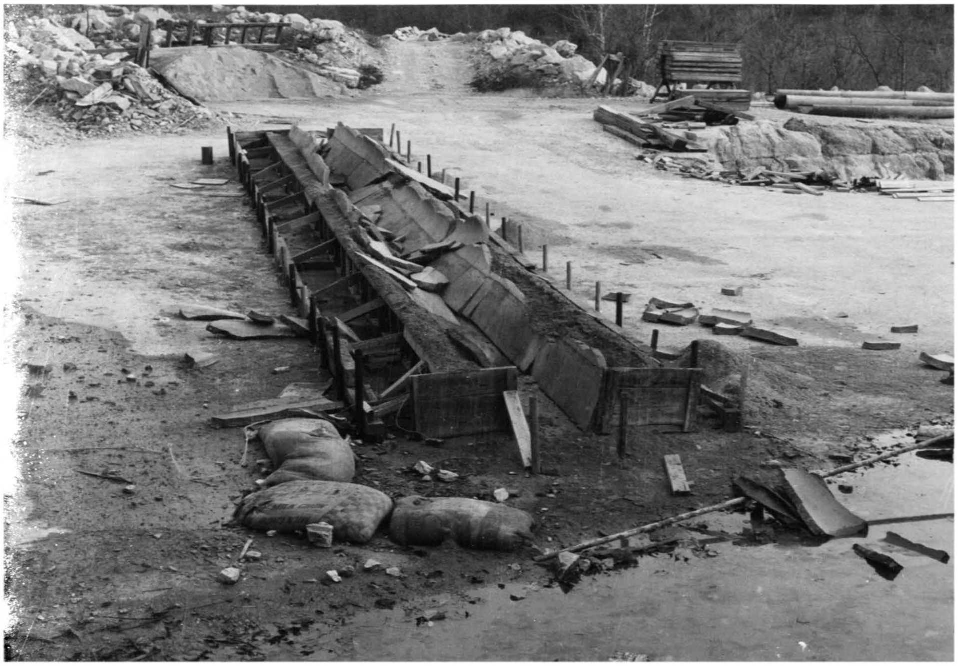

Figure 56. The Phase IV tunnel after demolition.

Figure 57. The Phase IV tunnel after demolition.

of causing destruction. In all probability, it contributed somewhat to the destruction of he first 20 feet of the tunnel. However, it was found that the air blast effect was of sufficient force to cause failure without the shock wave moving through the lining.

PHASE V

These tests were run to determine what effect the size of the tunnel had on the destructive force of the explosive. Only two sizes of the same type tunnel were tested.

Test One

For this test, the reader is referred to Test Five, Phase II. Here a Type A tunnel, 50 feet in length, was completely destroyed with a $\frac{1}{4}$ pound charge of Composition C-3.

Test Two

For this test, a Type B tunnel, 50 feet in length, was constructed. (See Figure 58). The walls of the tunnel were partially confined with 12 inches of sand. A $\frac{1}{4}$ pound charge of Composition C-3 was placed 5 feet from the east portal in the center of the tunnel floor. Because of the necessity to delay the test until high speed camera equipment arrived to record the blast, the concrete strength increased beyond that of previous models. Although the compressive strength was 4750 p.s.i., it is felt that had little effect upon the similitude between Test One and Test Two. The tensile strength of the tunnel in Test Two was approximately 380 p.s.i., while the Test One tunnel had a tensile strength of about 290 p.s.i. However, it is believed that the tensile stress which could be set up by the explosive is a great deal larger than either of these, therefore the 90 p.s.i. difference is of minor significance.

Figure 58. The Type B tunnel constructed for Test Two, Phase V.

Figure 59. The damage resulting from the demolition applied to the tunnel in Test Two, Phase V.

The detonation of this charge caused very little damage. One main crack developed that ran down the crown of the arch for the full length of the tunnel. Figure 59 shows this crack pattern after it was painted to distinguish it.

A very small piece of concrete slabbed out over the point of detonation. It was only about 12 inches long and 3 inches wide. The east 10 feet of the tunnel had a double crack in the arch which allowed a portion of the arch to bulge about 2 inches.

Analysis of Phase V

From the foregoing test, it can be seen that increasinq the size of the tunnel, which in turn increases the inside volume, is a very critical factor when using this method of tunnel demolition. In the introduction of this section on the model test, it was stated that a Type A tunnel was 20 inches wide and had a cross-sectional area of 3.52 square feet. The Type B tunnel was said to be 28 inches wide and had a cross-sectional area of 6.81 square feet. This means that the linear ratio is increased 1.4 times, the area ratio by 1.96 times and the volume ratio by 2.74 times. That is, the bubble of expanding gas as well as the growing spherical shock wave had to be 2.74 times larger before they could effectively cause damage. As was discussed earlier, the attenuation of this shock front in air is very rapid. In Test Two, the air blast was sufficiently strong to break the tunnel down the crown of the arch, but it had decayed to the extent that it lacked the force to displace any of the arch. This then leads to the conclusion that an increase in tunnel size must be accompanied by a comparable increase in charge weight, following the law of similitude established.

PHASE VI

It has been established that an increase in tunnel size must be accompanied by an increase in the size of the explosive charge. The theories which govern the increase in charge size were covered in the section, Model Similitude. However, because of the importance of these theories to the application of the knowledge gained in this testing program to full scale tunnels, it was deemed necessary to test the similitude ratios established to determine if they are valid.

In Phase V, the tunnel used in Test Two was 1.4 times as large as the tunnel used in Test One in all linear dimensions except the tunnel length. The larger tunnel would have had to be 70 feet long to be in proper proportions. As it was, the Type B tunnel would represent a Type A tunnel 36.5 feet long. The mass of the charge would have to be increased by the cube of the linear ratio or 2.74 times. Since 0.250 pounds of explosive were used in the small tunnel, 0.686 pounds would have to be used in the larger tunnel to obtain comparable results.

A second Type B tunnel was constructed for this phase exactly like the one for Test Two of Phase V. The compressive strength of the concrete was 4120 p.s.i. A 0.686 pound charge of Composition C-3 was placed 7 feet from the east portal on the floor and detonated.

After the detonation of the charge, approximately 75 per cent of the tunnel arch was destroyed, with about 12 feet of the entire length remaining keyed in place. (See Figure 60). By referring to Test Four, Phase II, it is seen that the 20 foot Type A tunnel had about 60 per cent of the arch destroyed, while the 50 foot Type A tunnel had 100 per cent of the arch destroyed. By interpolation, a Type A tunnel, 36.5 feet in length, should result in 82 per cent destruction of the arch. This then is a difference of only 7 per cent of the actual results found from the test of this phase. Therefore our similitude ratios proved accurate with less than 10 per cent error.

PHASE VII

The object of this phase of testing was to determine the different effects caused by detonating equal charges in tunnels of different shapes. The two shapes compared in this phase are those of a Type A tunnel and a Type C tunnel.

Test One

For the description of the destruction of a 50 foot Type A tunnel charged with $\frac{1}{4}$ pounds of Composition C-3, the reader is referred to Test Five, Phase II.

Figure 60. The results of demolition in Phase VI.

Test Two

For this test a Type C tunnel was constructed with a 3 inch lining thickness. Since this tunnel is round in shape, it was decided that the best method of construction was to use 4 foot sections of prefabricated concrete tile, 18 inches in diameter. Each section had a tongue and groove joint to provide an effective seal with grout. The compressive strength of the concrete in all the Type C tunnels was approximately 3600 p.s.i. The tunnel was constructed 48 feet in length, with the sides backed with a foot of sand. (See Figure 61). A ¼ pound charge of Composition C-3 was placed on the floor 5 feet in from the east portal.

After the charge was detonated, the roof above the sandline, 12 feet from the east end of the tunnel, was completely blown off. (See Figure 62). About half of the roof of the next four foot section was destroyed.

Figure 61. The Type C tunnel constructed for Test Two, Phase VII.

The major breaks in the top of this section seemed to occur in a criss-cross pattern. Dual cracks traversed the top of the next section and crossed about 1 foot from the end. (See Figure 63). Damage to the bottom portion of the tunnel was slight except in the first two eastern sections, where wall and floor fracturing occurred in several places.

Analysis of Phase VII

By comparing the results of the two tests of this phase, it is evident that approximately 3 times as much damage was caused to the Type A tunnel as was caused to the Type C tunnel with the same size charge.

The tests in Phase V proved that less damage is produced on the tunnel walls when the cross-sectional area is increased. The lessening of the damage results from the attenuation of the air blast as it passes over the increased distance. Yet in this phase, the damage was more severe to the Type A tunnel, which had a cross-sectional area of 3.52 square feet, than to the Type C tunnel which had a cross-sectional area of 1.77 square feet. This leads to the probable conclusion that the shape of the tunnel may be a more critical factor than its size, and that round tunnels appear to offer more resistance to air blast than do arch type tunnel.

PHASE VIII

The primary purpose of this phase was to ascertain the effect of placing a charge at each end of the tunnel, thus allowing the shock front of each charge to collide in the center of the tunnel. The theory on longitudinal compression waves and how they add to one another on colliding was discussed under the theories of wave motion. The phase consisted of only one test.

Figure 62. The results of demolition, Test Two, Phase VII.

Figure 63. The results of demolition Test Two, Phase VII.

For this test a Type A tunnel, 30 feet in length, with a 2 inch lining thickness, was constructed and then completely covered with sand. A $\frac{1}{4}$ pound charge of Composition C-3 was placed 5 feet from each portal in the middle of the tunnel floor. To insure that the charges were detonated simultaneously, two equal lengths of detonating cord were taped to one electric blasting cap. To the other end of each strand, a Corps of Engineers special non-electric blasting cap was crimped and then inserted into each charge.

After the two charges were detonated, the force of the colliding pressure fronts caused about 12 feet of the east half of the tunnel to collapse. (See Figure 64). The east portal did not cave, but was very badly broken. In the west half of the tunnel, about 2 feet of the arch caved a distance of 7 feet from the portal. While most of the west half did not cave, the damage would be considered extremely severe. (See Figure 65). The weight of the sand pressing on the broken fragments kept them keyed in place, even though the walls had horizontal breaks in them about 7 inches from the floor. This is the most severe wall damage that occurred in any of the tests in which the walls were backed with sand.

Analysis of Phase VIII

The results obtained from this test indicate that the colliding shock fronts from explosive charges can be very effective in causing tunnel lining damage. The effectiveness of this method of charge placement as compared to placing the whole charge at one end of the tunnel, readily appears in a review of Tests Two and Four of Phase III. In these tests, both a 20 foot and a 50 foot tunnel were charged with the same amount of explosive as was the tunnel in Phase VIII. However, in neither of the Phase III tunnels was the damage so complete. The tunnel in Phase VIII

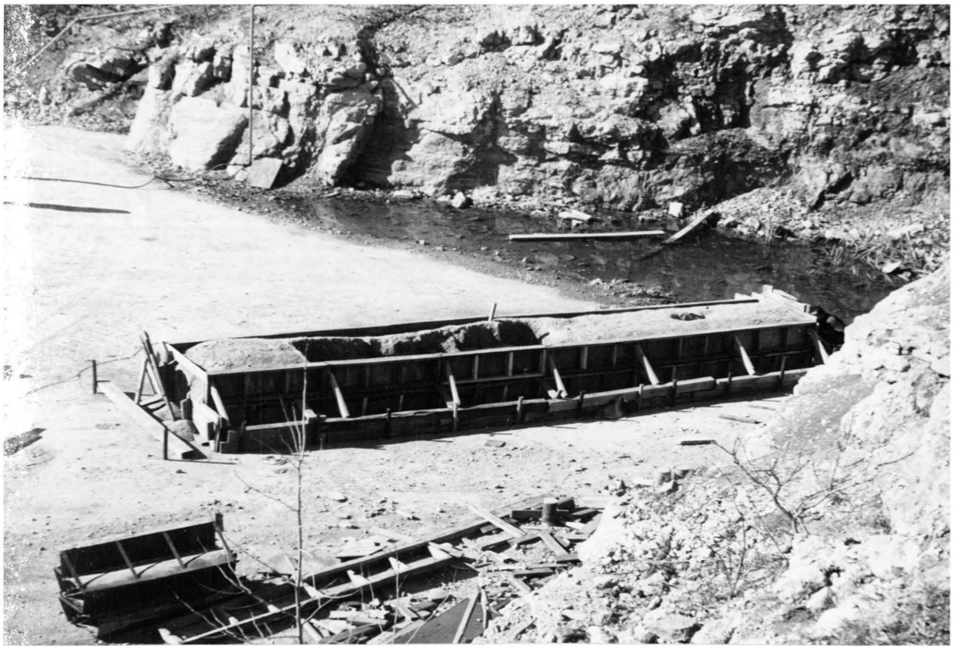

Figure 64. The results of the damage in Phase VIII.

Figure 65. The results of the damage in Phase VIII.

would require at least 75 per cent rehabilitation before it could be used.

A casual analysis of the destruction resulting from a division of the charge between two points might indicate that a collision of the shock waves from the two charges creates a greater pressure than the one large charge. The truth of this assumption depends on the distance between the two charges. Figure 15 illustrates how rapidly this pressure front drops off. If two $\frac{1}{4}$ pound charges of C-3 were separated by 20 feet, then each shock front would have to travel 10 feet before colliding with the other. While the graph shown in Figure 15 does not cover the pressure 10 feet away from a $\frac{1}{4}$ pound charge, it is estimated that the pressure would fall to approximately 70 p.s.i. This being the case, the collision would cause a pressure of only 140 p.s.i. A $\frac{1}{2}$ pound charge detonated in the exact center of the tunnel would exert 250 p.s.i. on the crown of the arch and 1650 p.s.i. on the walls of the tunnel at the point of detonation. Therefore, it is not proved that a greater pressure caused he damage after the collision.

A second assumption might be that an increase in impulse occurred which caused more damage when the waves collided. To study the shape of the one-dimensional plane wave some distance away from the charge, turn to Figure 14. When two longitudinal waves of equal magnitude collide, they are reflected as if they had struck an elastic wall. Then try to imagine the wave in Figure 14, when $\eta = 30$, suddenly reversing its direction. It will first move back through the extremely high pressure zone, then the rarefaction zone, and then the zone of nearly constant pressure. The first effect that this action will have is to double the duration of time that the high pressure will act on the lining between x/d equals 73 and 91. This will greatly increase the impulse of the force in that area. As the reflected peak pressure front moves back through the zone of nearly constant pressure, it will also increase the impulse of the force in this area. If one would superimpose and $\eta = 60$ curve between 0 and 91, with the peak pressure front arriving back at $x/d = 0$, on top of another $\eta = 60$ curve as it is in the diagram, then it would immediately become apparent that the zone of nearly constant pressure would not only have higher pressure but would also have the impulse required for most destruction. Here, then, seems to be the valid explanation for the increased amount of damage caused by colliding waves over the damage resulting from a single large wave.

PHASE IX

This phase of the testing program was conducted to correlate the effects of the three military high explosives and determine which one was the most effective in destroying tunnel lining by hasty methods of demolition. The explosives used were Composition C-3, Nitrostarch, and T.N.T. All the tunnels of this phase were Type C models and were constructed as described in Test One.

Test One

The reader is referred to Test Two of Phase VII, for a Type C tunnel charged with $\frac{1}{4}$ pound of Composition C-3.

Test Two

In this test, the Type C tunnel was charged with $\frac{1}{4}$ pound of Nitrostarch explosive. As in the previous test, the charge was placed on the floor of the tunnel, 5 feet in from the east portal.

The damage that was caused by the detonation of the charge is shown in Figures 66 and 67. The explosion caused complete arch failure of the

Figure 66. The damage resulting after demolition in Test Two, Phase IX.

Figure 67. The results of demolition in Test Two, Phase IX.

first two four-foot sections at the east end. The third section had the crown of the arch displaced about 6 to 12 inches. About $2\frac{1}{2}$ feet of the arch of the fourth section was blown off leaving an opening 14 inches wide. The remaining portion of this section was only cracked down the crown of the arch. The fifth section did not cave, but had a crack running down the center of the arch. The sixth section had practically the whole top removed. The bottom portion of the tunnel had two major cracks running lengthwise through the first three sections and only one major crack running down the next three sections.

Test Three

The explosive used in this test was a $\frac{1}{4}$ pound charge of TNT. The tunnel was constructed in the same manner as the previous two, and the charge was placed on the floor of the tunnel 5 feet in from the east portal and detonated.

After the explosion occurred, the top of the tunnel above the sand was completely blown off for five sections on the east end. (See Figures 68 and 69). The remaining sections were left undamaged. The damage to the bottom portion of the tunnel was fairly severe only in the first two sections.

Analysis of Phase IX

The results obtained in this phase of testing appear at first to be very unusual. From the earlier discussions on the characteristics of these three explosives, it was stated that if TNT had a rating of 1.00, then C-3 would be 1.33 times as powerful, and Nitrostarch would be only 0.86 times as powerful. This is essentially true when the shock wave moving through a solid media is the force that is causing the damage.

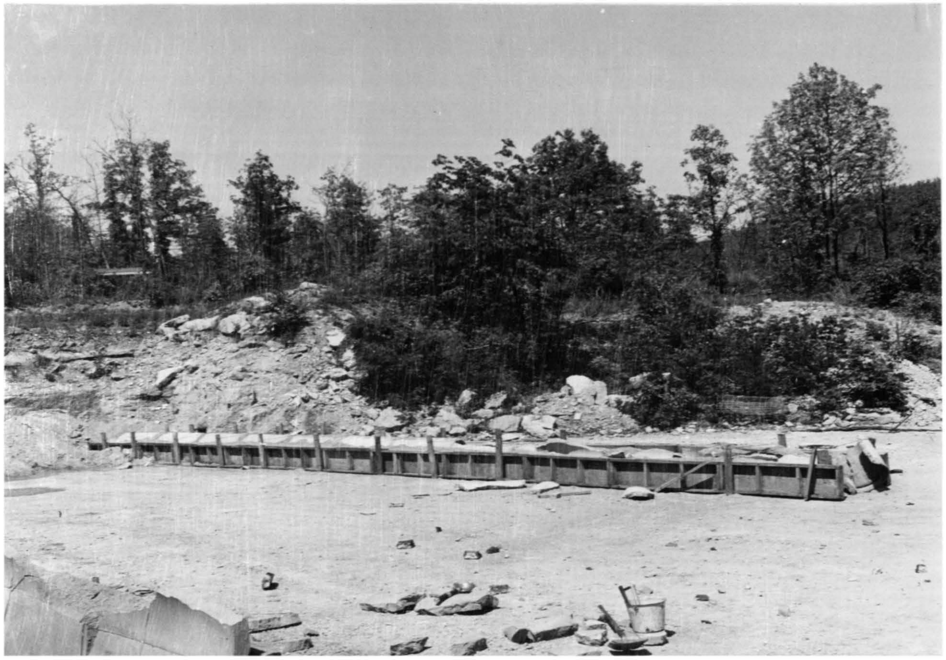

Figure 68. The results of demolition in Test Three, Phase IX.

Figure 69. The results of demolition in Test Three, Phase IX.

However, when the pressure developed from air blast is expected to do the damage, the above ratings do not apply. In fact, as can be seen from the three tests of this phase, the situation is nearly reversed. The C-3 charge took the top off of three sections, partially off of the fourth section, and only cracked the fifth section. The TNT charge removed the top off the tunnel for five complete sections. The Nitrostarch charge removed some portion of the arch for the first four sections, left the fifth section cracked and took the top off of the sixth section.

If the destruction criteria is correlated with the velocity of detonation of the explosive, then the slower detonating explosives produce a far more reaching air blast effect than the faster detonating explosives. This at least holds true over the limited range of velocities tested. The author's theory behind this phenomenon is suggested by the words of Schardin[10] when he stated that when considering the blast effect, the impulse is as important as the peak pressure. While it is true that the explosives with higher detonating rates produce larger air blast pressures, it is likewise true that since the shock front is moving at a higher velocity it will have less impulse than the slower detonating explosives.

If the photographs of these three tests are studied carefully, it will be noticed that the zone immediately around the charge shows greater damage by the faster detonating explosive, even though the slower explosives cause damage at greater distance. This then leads to the following conclusions:

1. That when only medium tunnel damage is required over a long

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[10] Schardin, Hubert, op. cit. p. 239.

length of the tunnel, Nitrostarch explosive is preferable to C-3, or TNT.

2. That when very severe damage is required over a fairly short length of the tunnel, C-3 is preferred to Nitrostarch or TNT.
3. That when severe damage is required over a fairly long length of the tunnel, TNT is preferred to either Composition C-3 or Nitrostarch.

CONCLUSIONS

The foregoing information has been gathered and studied in an effort to establish some of the fundamental principles which are necessary in formulating methods for hasty demolition of tunnels. Each of the variables listed in the introduction have been studied and tested.

LENGTH OF TUNNEL

From the analysis of Phase II, it was found that the destruction caused by air blast from untamped explosives is much more efficiently utilized in long tunnels than in short ones. For example, more damage will result in a 50 foot model tunnel than in a 20 foot model by untamped explosive charges of equal size.

CHARACTER AND TIGHINESS OF TUNNEL LINING

From Phase I it was concluded that concrete linings between 2 to 6 inches in thickness in model tunnels offer practically no resistance to the force of the air blast if the linings are unconfined and free to move. Since masonry structures are in general weaker in tension than concrete structures, they offer even less resistance than concrete. Reinforced concrete offers a greater resistance to fracture than plain concrete, depending upon the amount and type of reinforcing.

From Phase II it was established that the tightness of the tunnel lining is one of the most critical variables encountered when the air blast effect is expected to cause the damage. It was found that if damage was to occur from air blast, that portion of the lining which is expected to fail must be free to move out to some extent when the pressure wave passes over it. The following conclusions may be derived: If the lining is rigidly confined its full length, the air blast will have little destructive effect on it; if the lining is free to move a distance less than the lining thickness, fracturing, but not caving, will occur; if the lining is partially confined with some media such as sand, crushed rock, or rubble, which will move but offers a great amount of resistance, then the amount of damage will depend directly upon this resistance and the amount of explosive used; if the lining is free to move in the area around the charge, but is rigidly held in place at other points, the damage beyond these points will be minor compared to the zone near the charge, even though it may be free to move.

CROSS-SECTIONAL AREA OF TUNNEL

From Phases V and VI it was found that an increase in the cross-sectional area of the tunnel must also be accompanied by an increased charge size to obtain comparable damage. The explosive increase was found to vary as the cube of the linear ratio. In applying the whole model study or any part of it to full scale tunnels, the similitude scaling ratios must be followed. If any new critical variable is introduced in the prototype tunnel which was not in the model, then the similarity laws will no longer hold.

CROSS-SECTIONAL SHAPE OF TUNNEL

From Phase VII it may be concluded that arch type tunnels are much more easily destroyed with air blast than round tunnels. In the test of this phase, at least three times as much damage resulted to the arch type tunnel as the damage caused to the round tunnel with the same size charge. Yet the arch type tunnel had twice the cross-sectional area and should have been more difficult to destroy.

VARIOUS SIZES OF EXPLOSIVE CHARGES

From the Analysis of Phase III, it was concluded that by doubling the explosive charge in a 20 foot tunnel, eight times as much damage resulted. Four times as much damage was caused by doubling the size of the charge in a 50 foot tunnel. Eight times as much damage was caused to a 50 foot tunnel with one portal closed when the explosive charge was increased four times. It was also concluded from Phase II that detonating two or three small charges one after the other is not as effective as firing the total amount of explosive at one time.

DIFFERENT METHODS OF CHARGE PLACEMENT

From Phase IV it was established that the pressure of the air blast from unconfined explosives was, in all probability, the force which was causing the damage to the tunnel linings. Since it is air blast which is causing the damage, the charge placement which will cause maximum air blast becomes a critical variable. From the theories developed on page 19 it was generalized that the longer the column of air being pushed by the shock front, the more pressure and impulse would be exerted on the tunnel walls. Therefore, it is concluded that the most efficient charge placement with respect to the tunnel length would be in the exact center of the tunnel. It is also believed that the maximum air blast effect is obtained by placing the charge on the floor of the tunnel rather than in the air or against the lining. By placing it on the solid floor, most of the force of the explosion is either directed or reflected up toward the arch.

From Phase VIII, a very efficient method of charge placement was devised. Here it was found that by dividing the charge in half and separating each half so that when both charges are detonated simultaneously, the colliding pressure fronts caused very severe damage. This method of hasty tunnel demolition seems very effective and would warrant further study to determine how far apart the charges should be placed to obtain maximum air blast damage.

From Phase III, a still more efficient method of tunnel destruction was utilized. It does, however, hinge between hasty and deliberate demolition. By blocking one portal with sand bags and placing the charge close to this end, a very efficient air blast charge was developed. If both ends were blocked the explosive charge should be even more effective. The ends of full scale tunnels could be effectively closed by blasting down the portals, by using a bulldozer to push material into the portals, or by placing a sand bag wall about 15 feet thick in the portals.

DIFFERENT TYPES OF MILITARY EXPLOSIVES

It was determined that all of the three military explosives tested were effective in causing air blast damage to tunnel linings. However, when severe destruction is required over a fairly long length of tunnel, TNT is preferred to either Composition C-3 or Nitrostarch for best overall results.

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VITA

Richard L. Bullock, son of Royce F. Bullock, Sr. and Ruby Lee Bullock, was born July 24, 1929, at Kansas City, Missouri. He received his elementary and high school education in Houston, Missouri.

He enrolled at the University of Missouri, School of Mines in 1947, and received a B. S. degree in Mining Engineering in 1951. After graduation, he was employed by the New Jersey Zinc Company at Gilman, Colorado, as a mining engineer.

In 1952 he was inducted into the United States Army. After four months of Infantry training, he was assigned to the Corps of Engineers at Fort Belvoir, Virginia, where he served for the next 20 months as an instructor in The Engineer School. He taught courses in pit and quarry operations as well as explosives and demolition. On January 16, 1954, he was released from active duty as a Corporal.

He returned to the Missouri School of Mines on February 1, 1955, for graduate work. At that time he was granted a Research Fellowship in the Department of Mining Engineering.