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Delayed Blasting Tests To Improve Highwall Stability—A Progress Report

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UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	mm	millimeter
ft	foot	ms	millisecond
in	inch		

DELAYED BLASTING TESTS TO IMPROVE HIGHWALL STABILITY—A PROGRESS REPORT

By Virgil J. Stachura[1] and Larry R. Fletcher[2]

ABSTRACT

The Bureau of Mines conducted a series of delayed blasting experiments at a West Virginia contour coal mine that resulted in smoother highwalls. The highwalls were smoother due to reduced overbreak and inherently safer due to reduced likelihood of rockfall. Reduced overbreak was accomplished by an increase in the highwall hole delays, which changed the effective delay pattern geometry and the direction of burden movement. The blast delays in the highwall holes were 50 to 100 ms longer than the mine's nominal design pattern (flat V, 17- by 42-ms surface delays, 200-ms in-the-hole delay). The burden movement was effectively changed from a 45° angle to 90° with respect to the highwall.

The results of the blast delay changes were evaluated using terrestrial photogrammetry to generate vertical profiles at regular intervals. This evaluation showed that delay changes produced generally smoother vertical profiles.

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INTRODUCTION

Contour strip mining is a general term that applies to mining coal outcrops in areas characterized by steep slopes. Mining techniques such as haulback or lateral movement, mountaintop removal, block cutting, and modified block cutting are used. These techniques usually involve removing successive 20- to 40-ft benches in the overburden until the coal is reached. The resulting wall of rock on the inner flank of the working pit, which can be over 100 ft high, is commonly called the highwall. Personnel and equipment are in close proximity to the highwall and exposed to hazardous conditions during overburden stripping, coal removal, augering, or backfilling for reclamation. Rockfalls due to highwall failure rank highest as the cause of fatal accidents in surface coal mines (1).[3] Unstable highwall conditions are due, in part, to the adverse orientation of geological structures in the overburden. Furthermore, these unstable conditions are often aggravated by faulty blasting practices.

The Bureau of Mines is currently investigating more effective blast designs for improving highwall stability. This report describes blast delay changes, their effects on highwall smoothness, and a stereographic technique to illustrate irregularity as applied to a specific operating mine.

The Bureau sponsored a research contract by Engineers International Inc. (EI) to improve highwall stability by improved blasting practices (2). Almost all the mines visited by EI had highwall instability problems that were aggravated by poor blasting practices. Large variations in blasting competence of mining personnel were found, with the bigger operators usually using better blasting techniques. Highwall orientation and blasting practices were frequently established with little consideration given to the natural rock fracture systems at that mine. Large-diameter holes, usually 8 to 9 in, with short explosives columns resulted in very poor energy distribution. Inaccurate blast pattern layout and improper delay patterns were common. All of these factors contributed to poor fragmentation, overbreak, and damage to the highwall rock. EI conducted tests with eight production blasts at a contour strip mine. These tests showed that highwall stability could be improved with existing blasting technology while reducing costs. However, with the tests completed and the contractor off the site, the mine personnel reverted to their old blasting practices. Consequently, the tests reported herein emphasize simple, easily understood changes that minimize economic and procedural impact so as to maximize operator acceptance.

There is abundant literature describing various techniques for improving highwall stability. Most of these techniques deal with some variation of presplitting (3-7). Unfortunately, these methods add to the drilling cost and therefore are not universally accepted by the mining industry.

Improvements in highwall stability are best made by reducing the damage to the rock that bounds the excavation (8). Presplitting damages the rock slope the least. Line drilling is mentioned in the literature (8) but is expensive and not practical for mining applications.

Presplitting is occasionally used in contour mines to ensure stable walls above underground entrances or for cuts through ridges for permanent roadways. Presplitting is normally not used with production blasts for several reasons:

1. Numerous small blastholes are required, which is too expensive for small operations.

2. Contour mines have variable cover over the coal, which precludes a standard bench height. Presplit holes are limited

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

in depth to 50 ft or less, depending on drillhole accuracy (8).

3. The presplit drill cannot keep up with production hole drills, thereby slowing production.

Cushion blasting is similar to presplitting except the perimeter row of holes is shot after the main blast instead of before, and larger holes are often used. This method depends on closely spaced, lightly loaded holes up to about 6-1/2 in in diameter (3). Since the shearing action takes place between holes, boulder-size fragments can be formed in the burden, depending on the geology. Both presplitting and cushion blasting rely on reducing the amount of explosive per hole in the row of holes that form the final highwall. This decreases the damage to the remaining rock and increases stability.

The experiments described in this report are directed at reducing overbreak without costly special drilling. They use simple changes in timing to improve relief by changing the direction and time of burden movement. In this report overbreak is defined as excessive breakage of rock beyond the desired excavation limit (8).

ACKNOWLEDGMENTS

The authors acknowledge the generous cooperation of Barbour Coal Co. of Clarksburg, WV, for providing the field site and assistance in obtaining the data presented in this report. Martinez Mapping & Engineering Inc., St. Paul, MN, performed the photogrammetric analysis.

HIGHWALL EVALUATION METHODS

Three methods of highwall evaluation were tried: visual inspection, measurement of rockfall, and terrestrial photogrammetry. Core sampling and seismic techniques to determine degree of fracturing were not used since the concern was with blast damage causing rockfall and not total slope failure. Slope failure could be reduced by the blast designs in this report but was not evaluated in that context.

Visual inspection is the method used by blasters and mine inspectors to determine highwall condition. A smooth highwall at the engineered slope is considered to be a good highwall. The engineered slope is defined in the mine's ground control plan. Lack of overhanging or loose material enhances the safety of the work area below the wall. Visual inspection of highwalls is effective but not consistent because of differences in individuals, their interpretations, and their memories. In this study greater stability was assumed when the highwall was smoother and showed less loose material.

Personnel of Engineers International observed that most rockfalls occurred in the first 15 days of exposure (2). This is significant because most work below a highwall, such as stripping of overburden and removal of coal, occurs during this time. Other factors affecting rockfalls are rainfall and freeze-thaw cycles.

The mine at which the experiments were made was a contour strip operation which did not lend itself well to rockfall monitoring. A haulback method of mining was used which kept wall exposure time short. The terrain was such that permanent camera monitoring stations would not provide meaningful data.

Terrestrial photogrammetry is an analytical extension of the visual inspection method. This form of photogrammetry has been used in other applications such as geologic structure analysis (9-10) and for detecting and measuring slope failure displacements (10-11). It allows further analysis at a later date and a more direct comparison of different highwalls for surface roughness. Highwalls can be viewed stereoscopically in three dimensions when proper controls are used. Relative depth in the pictures can be calculated through measurement of parallax (the change in angle to an object as viewed in the left and right picture of a stereopair). Figure 1 shows the geometry involved in simple stereoanalysis. The 0 is a target on the highwall, and the L and R are left and right camera stations respectively. Derivation of the formula for depth differences in a stereopair requires only geometry and simple calculus and can be found in many references (12-14). This is shown below:

$$\frac{X_L + X_R}{f} = \frac{B}{D}, \tag{1}$$

$$p = X_L + X_R, \text{ then } \frac{p}{f} = \frac{B}{D}, \tag{2}$$

$$p = \frac{fB}{D}, \tag{3}$$

$$\frac{dp}{dD} = \frac{-fB}{D^2}, \tag{4}$$

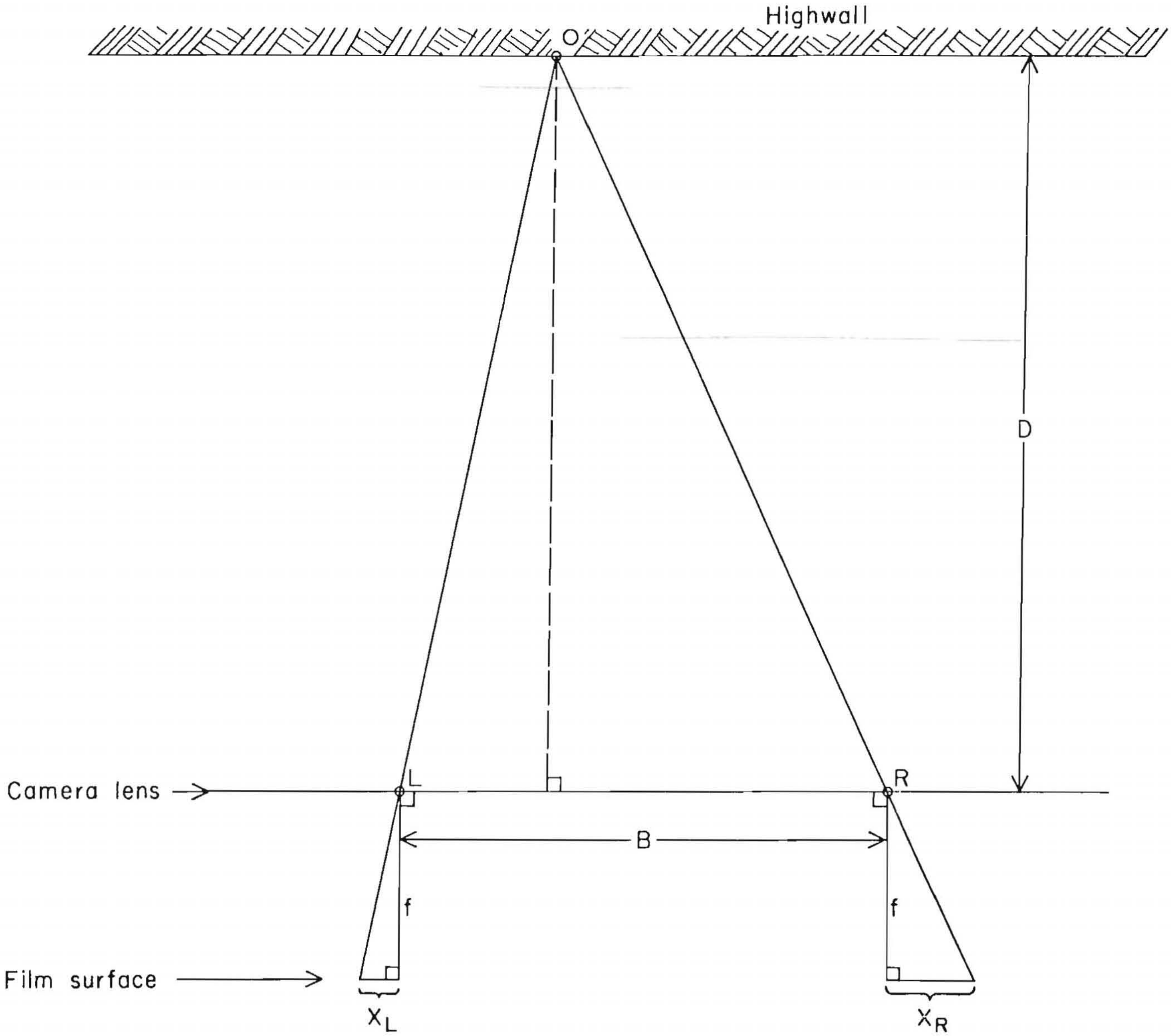

FIGURE 1. - Stereogeometry.

and $$\Delta D = \frac{-D^2}{fB} \cdot \Delta p, \quad (5)$$

where X_L = parallax left, mm,

X_R = parallax right, mm,

f = focal length of camera, mm,

L = left camera station,

R = right camera station,

D = distance from camera lens, ft,

B = baseline separation between camera stations, ft,

p = total parallax,

and Δ indicates a change in magnitude.

Simply stated, the change in distance is proportional to the change in parallax.

When the photographs are viewed in a stereoscope, the highwall is seen through both camera stations, thereby generating the perception of depth. Equation 5 can be used to measure relative depth differences between two objects in a stereopair if the photographs were taken as shown in figure 2. Typical

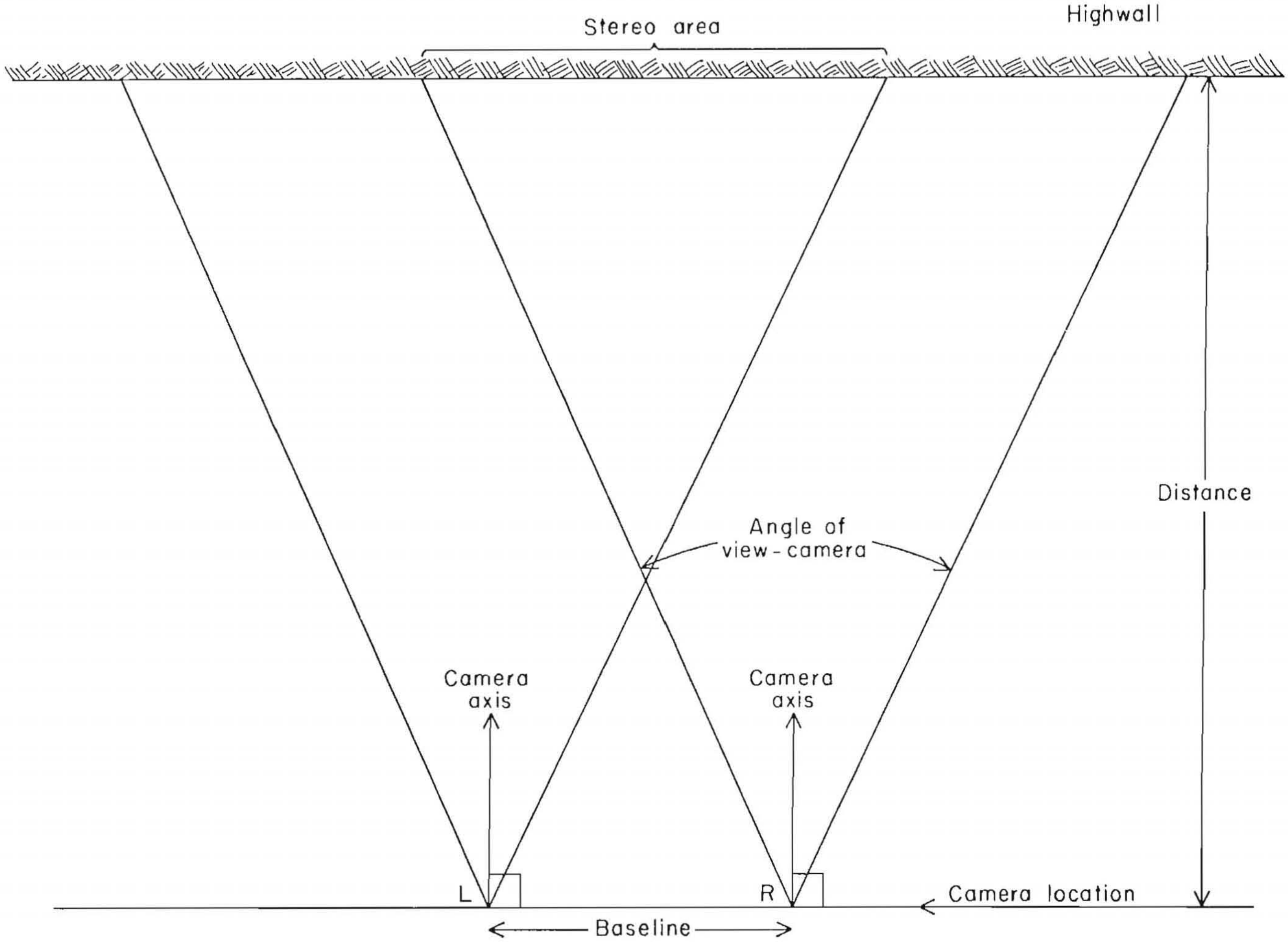

FIGURE 2. - Field procedure for general stereophotography.

accuracy of depth measurements based on the error in parallax measurements can be calculated using equation 5. Two examples follow:

Example 1

$$\Delta D = \frac{-D^2}{fB} \cdot \Delta p$$

If $D = 200$ ft,

$f = 80$ mm,

$B = 50$ ft,

and $\Delta p = \pm 0.05$ mm,

then $\Delta D = \pm 0.5$ ft.

Example 2

$$\Delta D = \frac{-D^2}{fB} \cdot \Delta p$$

If $D = 200$ ft,

$f = 80$ mm,

$B = 13.33$ ft,

and $\Delta p = \pm 0.05$ mm,

then $\Delta D = \pm 1.88$ ft.

Example 1 has a distance-to-baseline ratio of 4, and example 2 has a ratio of 15, with the greater accuracy for the wider baseline (example 1).

STEREOCAMERA

For the highwall monitoring in this report a Mamiya M 645[4] camera equipped with an 80-mm F/2.8 lens was used. This is a medium-format camera with a 60- by 45-mm negative, which produces sharper enlargements than a 35-mm camera. A specialized photogrammetric camera is expensive and requires special procedures; although not as accurate as a photogrammetric camera, the camera used was considered sufficient for the purposes of our tests.

SIMPLE STEREOPICTURE PROCEDURE

The initial field setup to obtain a stereopair is shown in figure 2. The base and distance were measured with a fiberglass tape measure, and the camera axis direction was estimated with a hand-held compass. A distance-to-base ratio of 4 or 5 was generally used. A common rule of thumb is that the distance to the object to be mapped should be from 4 to 15 times the length of the baseline (12, 15). A typical example is a base of 50 ft and distance to the highwall of 200 ft. The camera elevation was horizontal if terrain permitted. Malde (12) found that small errors (up to 2°) in camera aim could be tolerated if precision measurements were not required. In the present application, a relative measure of smoothness was desired rather than an accurate slope angle; hence small errors could be tolerated.

A Nikon reflex stereoscope with a parallax bar was used to measure relative changes in distance in the stereopairs. Initially, vertical profiles were calculated for the highwalls, but this proved to be time consuming and tedious. Equation 5 was used for this purpose with a correction for magnification because the photographs had been enlarged.

Since more profiles were desired than could be readily done with the above system, a photogrammetric service company was hired for faster analysis. This changed the procedure somewhat. The new field setup is shown in figure 3. The stereopair has approximately 60-pct overlap, and the targets T_1, T_2, T_3, and T_4 are features that are visible in both pictures. A theodolite was used to

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

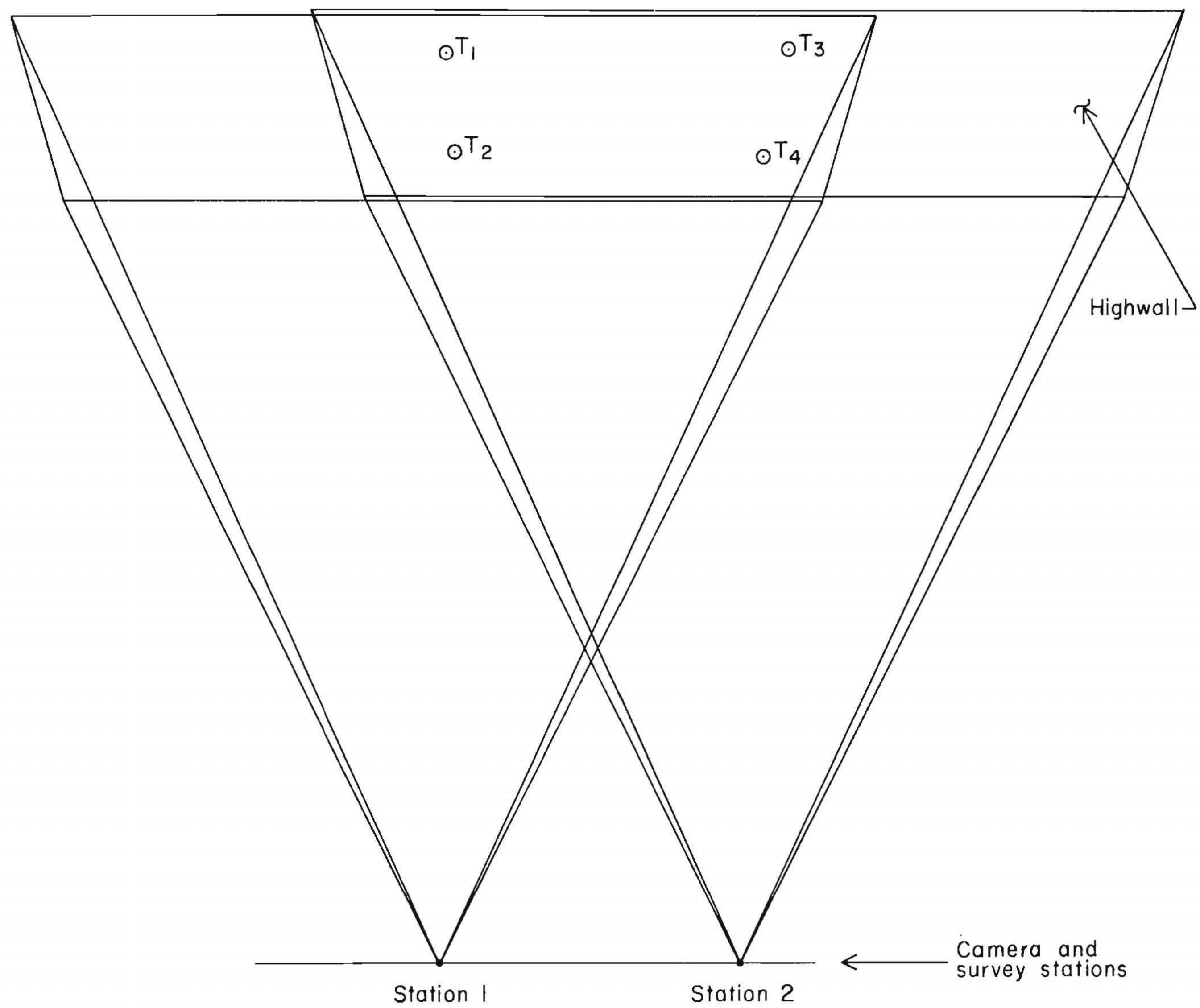

FIGURE 3. - Field procedure for stereophotography with control targets.

survey T_1, T_2, T_3, T_4, and station 2 from station 1 and T_1, T_2, T_3, T_4, and station 1 from station 2. At this point x, y, z coordinates were calculated for T_1, T_2, T_3, T_4, and station 2, using station 1 as a reference.

Once these coordinates are known, most photogrammetric engineering firms can do profile or contour analysis. With the aid of a computer, three-dimensional coordinates were compiled at 1/3-ft or less intervals for each vertical profile. In the two examples shown in the appendix, 40 and 70 profiles were calculated and plotted individually as seen in figures 6 and 9.

TEST HIGHWALLS

A typical highwall resulting from the mine's standard blast design is shown in figures 4 and 5. The affected area is from the coal seam (visible at midheight in figure 4) to the pit floor and the left and right limits of the photograph. Profiles 16 and 17 (fig. 6) were calculated through the area of greatest overhang. The affected part in the profiles is the lower 38 ft, labeled "Test area."

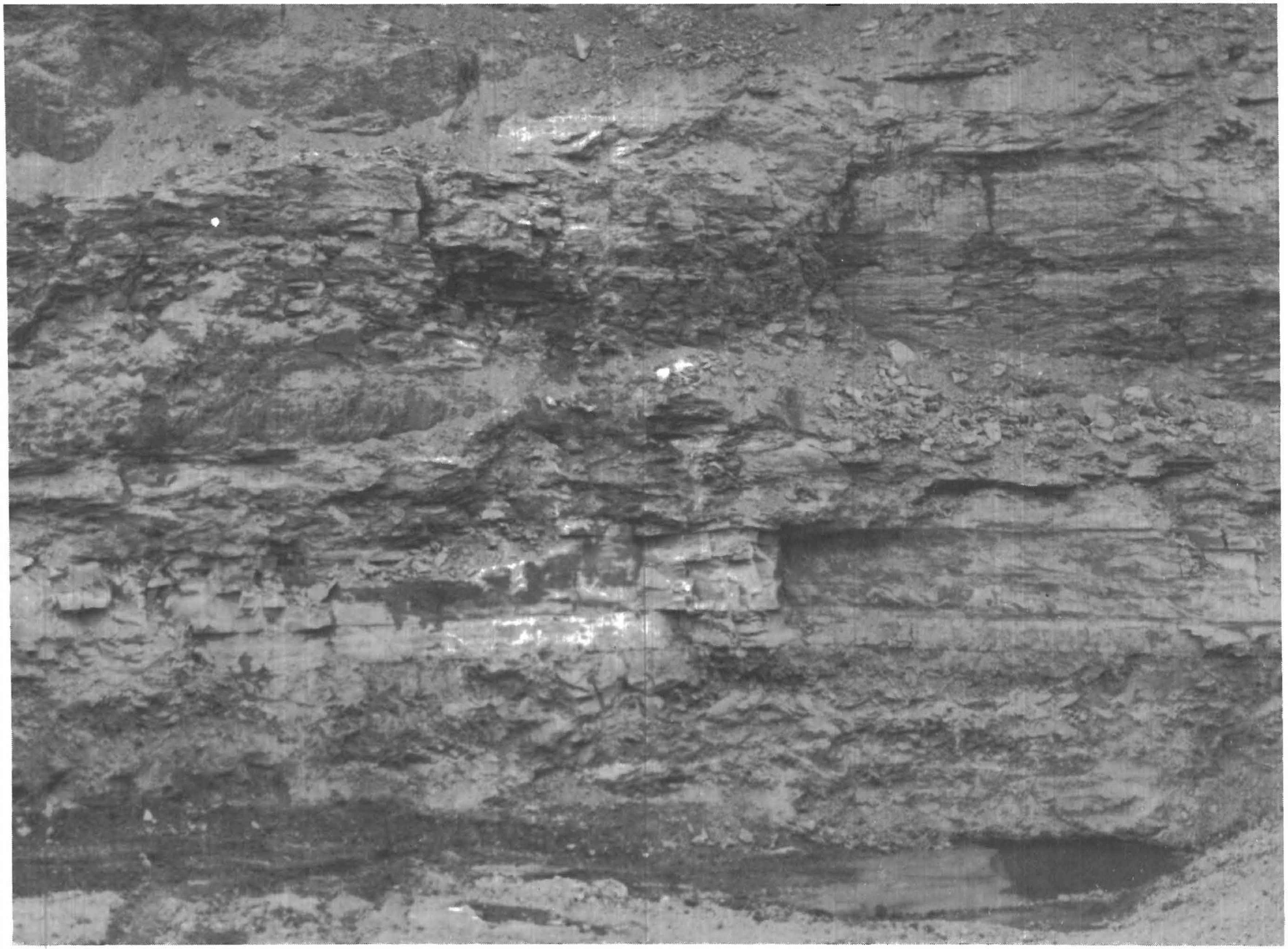

FIGURE 4. - Left stereomodel, test wall, no additional highwall delays.

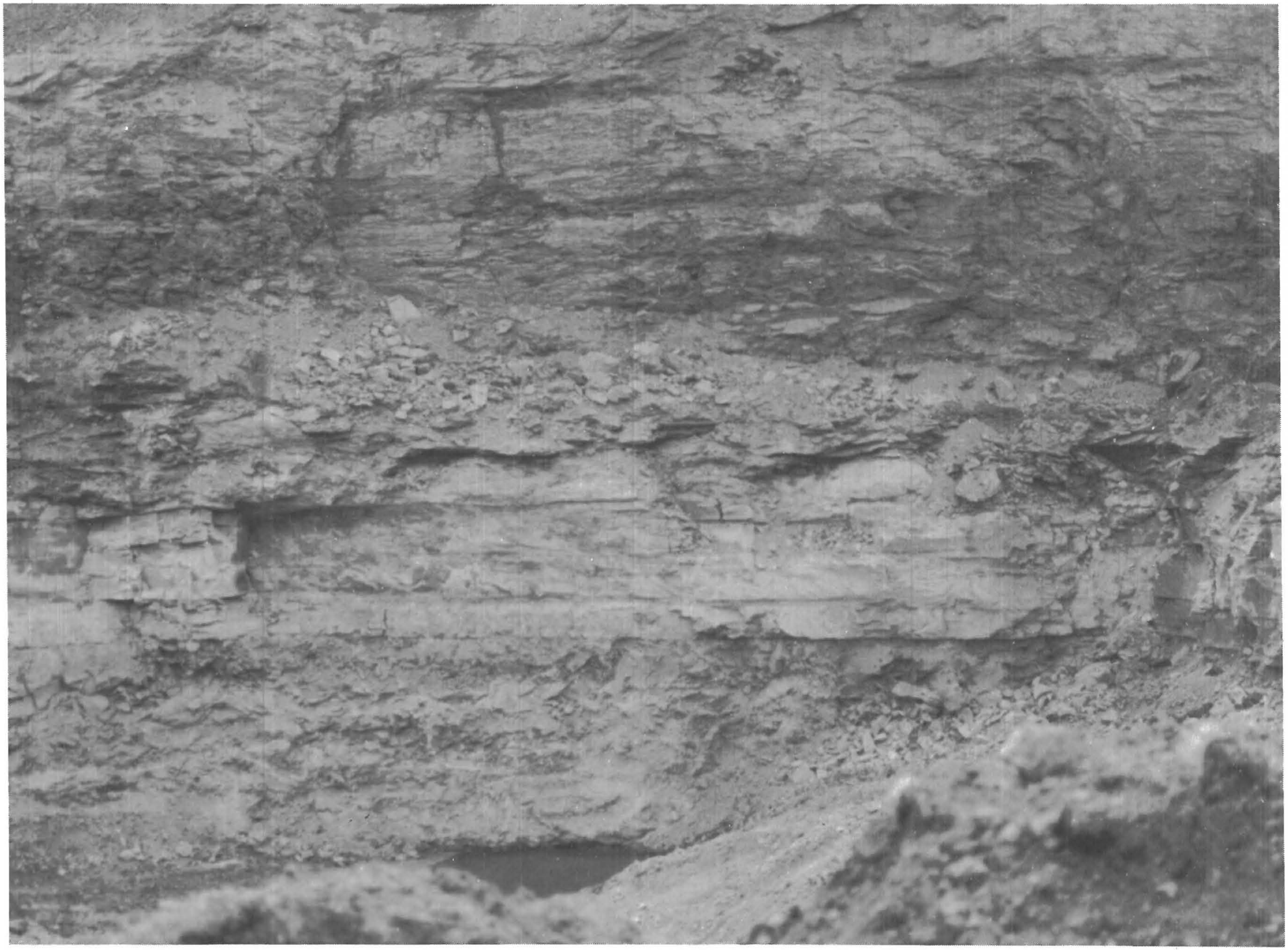

FIGURE 5. - Right stereomodel, test wall, no additional highwall delays.

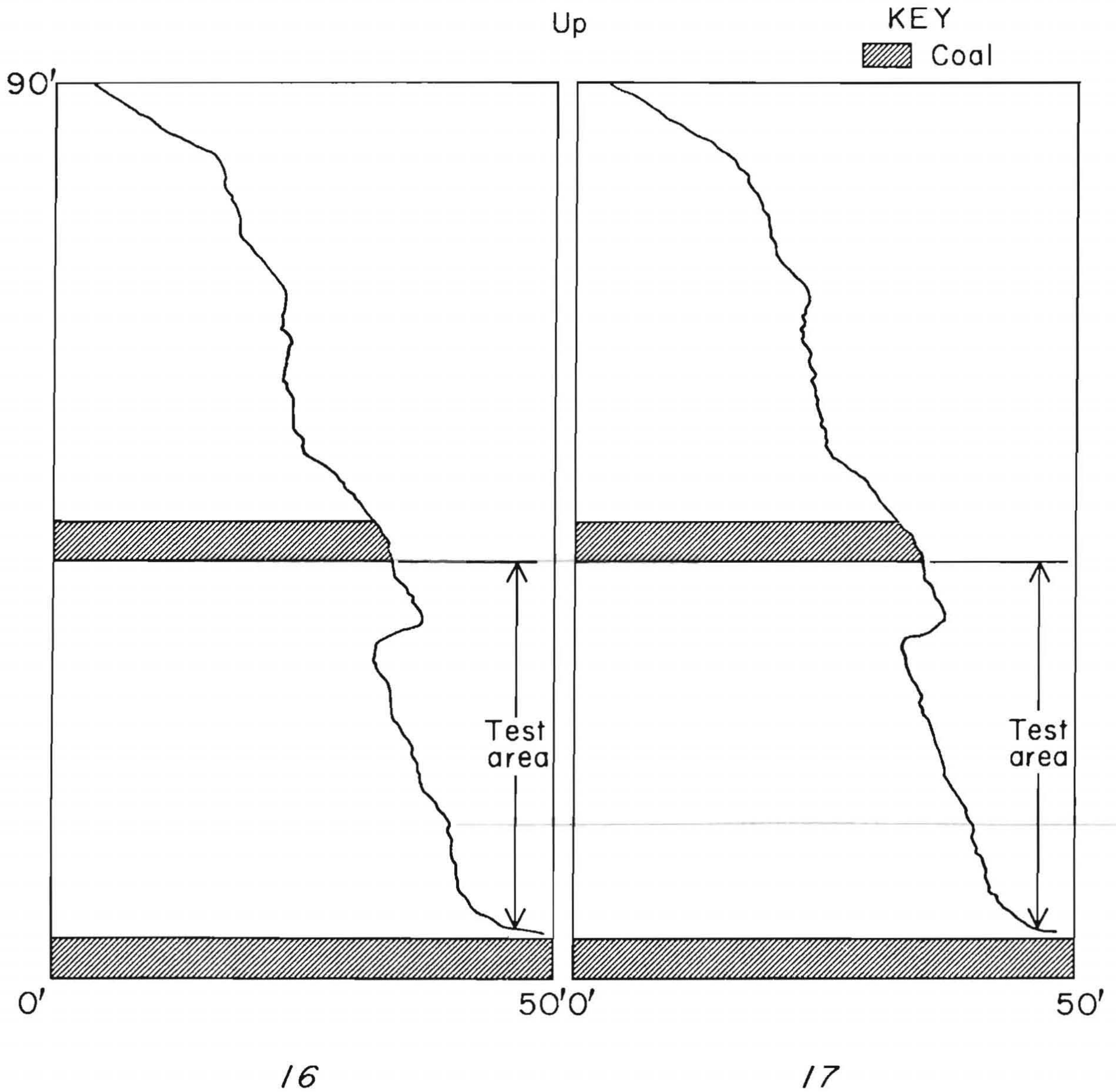

FIGURE 6. - Profiles 16 and 17, no additional highwall delays.

The overhang is more than 5 ft and is potentially dangerous because of the overbreak and overhanging rock in the area. A total of 40 profiles were calculated for this highwall at 2-ft horizontal intervals.

For comparison an adjacent blast used 250-ms delays as described in the "Blasting Tests" section. The resulting highwall can be seen in figures 7 and 8. The affected area is from the coal seam (at midheight in both photographs) to the pit floor and to the left and right limits of the photographs. The affected part of the profile is the lower 42 ft labeled "Test area" in figure 9. A total of 70 profiles were calculated for this highwall, also at 2-ft intervals. The most obvious difference when compared to the previous blast is the smoother profile. Another difference is the loose appearance of the highwall, which can be seen in the photographs but not in the profiles. More loose material can be seen in figures 4 and 5 than in figures 7 and 8. These two highwalls are side by side, have similar geology, and were

FIGURE 7. - Left stereomodel, test wall, 250-ms delays in the highwall holes.

FIGURE 8. - Right stereomodel, test wall, 250-ms delays in the highwall holes.

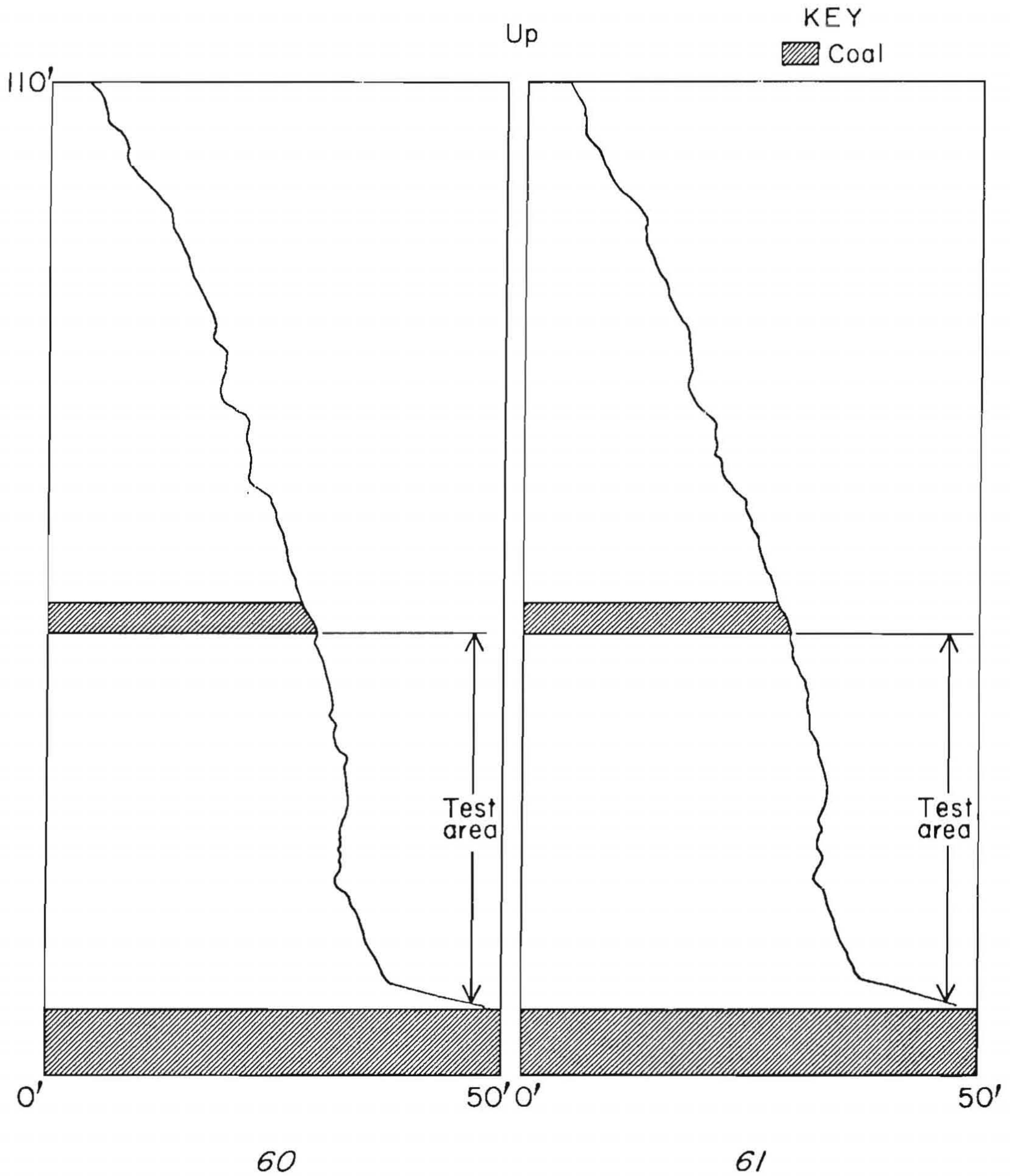

FIGURE 9. - Profiles 60 and 61, 250-ms delays in the highwall holes.

formed by similar blast patterns with the exception of the 250-ms delays. Many of the profiles from both highwalls are reproduced in appendix B.

TEST SITE

The test sites are in Barbour County, as shown in figure 10. The highwall profiles presented in this report are from site 2. The overburden is in the Monongahela Series, which is composed of green and gray, fine-grained sandstones, alternating with red and/or sandy shales and a few thin limestones. The most important coal seams are the Redstone and Pittsburgh seams.

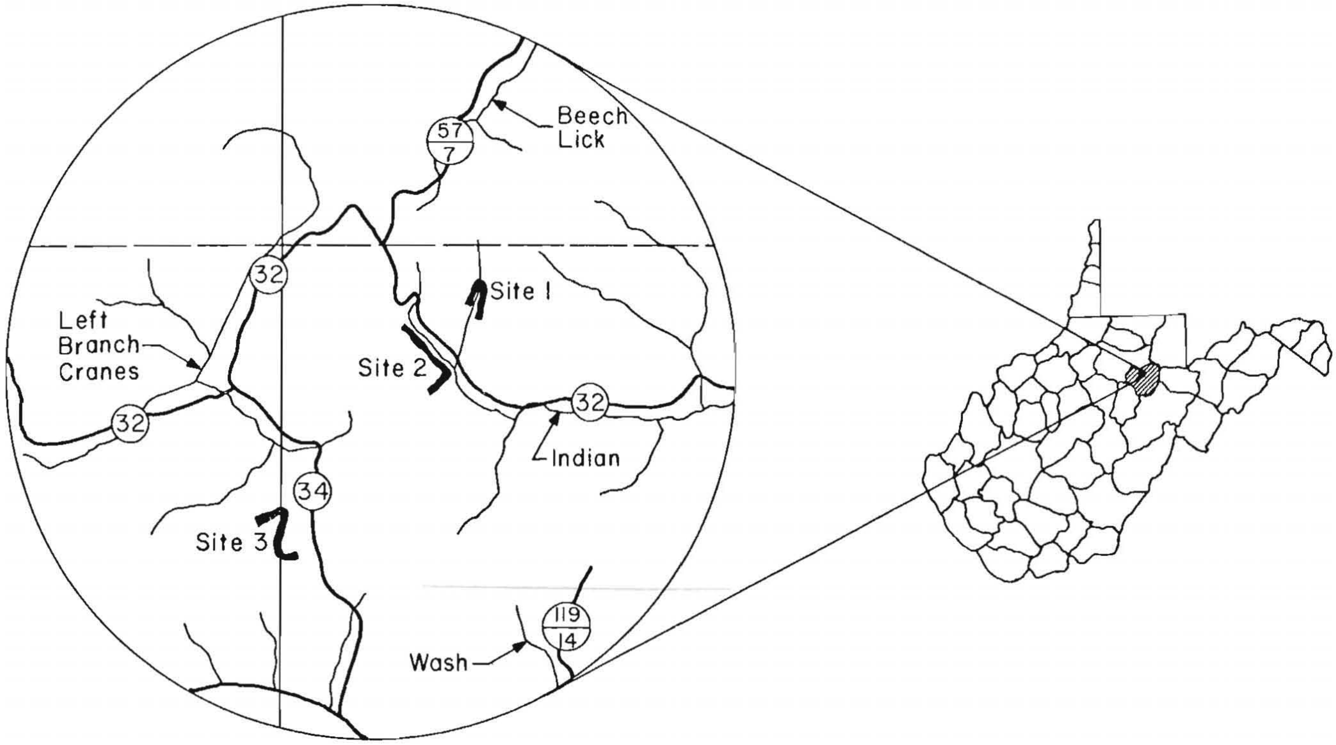

FIGURE 10. - Test site location.

BLASTING TESTS

When the blasting tests began, the mine was using hole diameters of 6-3/4 in and 9 in with burdens and spacings of 12 by 12 ft and 15 by 15 ft respectively. Stemming heights ranged from 7 to 16 ft. Bench heights ranged from 25 to 50 ft. All dry holes were loaded with bulk ANFO. Wet holes that could be dewatered were sleeved and loaded with bulk ANFO. In cases where the hole was making water so fast that dewatering was impossible, loading with cartridged ANFO was required. All holes were initiated with a cast primer on a detonating cord downline. Delaying was accomplished with surface delays, with 17 ms used between holes and 42 ms used between rows (fig. 11). At this mine, the rows of blastholes are perpendicular to the highwall, rather than parallel to it as in most mines.

The rock area affected by each hole (fig. 12) was determined by observation of shots in which some holes were not loaded. Note that distance a in the center of the burden area is longer than distance b on the sides. Since the explosive's energy will work toward the areas of least resistance, which are on the sides (b), excessive overbreak will occur there. The overbreak is primarily of concern when it affects the highwall.

The break line at 85 ms is shown in figure 13.

Based on the rule of thumb of 1 ms of delay per foot of burden, in-the-hole delays are recommended for the entire shot. As the figures show, the delay between rows is about 3 ms per foot of burden, and cutoffs can be expected with surface

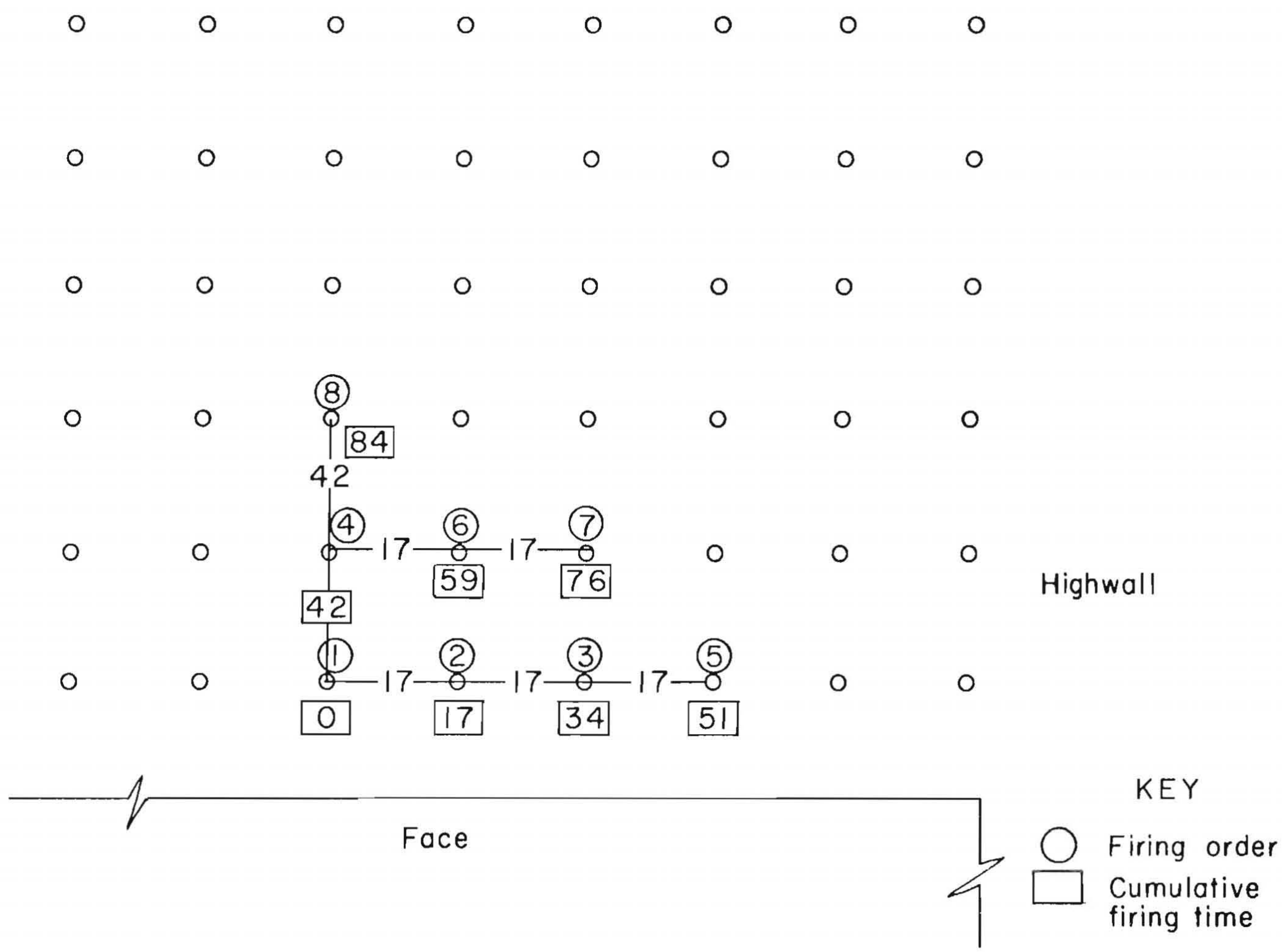

FIGURE 11. - Surface delay system used by mine. The number between holes is the delay period in milliseconds, the number below the hole is the firing time in milliseconds, and the number above the hole shows the firing order of the holes.

delays. After a few test shots the company started using a 200-ms in-the-hole delay in all holes. This allowed the surface delays to progress four rows into the shot before any rock movement occurred. The use of in-the-hole delays did not affect the break line at the time the first highwall hole was fired (fig. 14).

Normal burden movement is at a 45° angle from the highwall. If the burden movement of the highwall hole were changed to a 90° angle and relief were increased, better shearing of the rock would occur, resulting in much less overbreak in the highwall. To accomplish this, a 250-ms delay was used in all highwall holes. The break line at the time the first highwall holes were fired is shown in figure 15; it can be seen that normal burden is more uniform and relief became more adequate. These shots did provide a smoother highwall with much less overbreak, as can be seen in the section on "Test Highwalls." To determine if additional relief would further improve highwall conditions, 300-ms

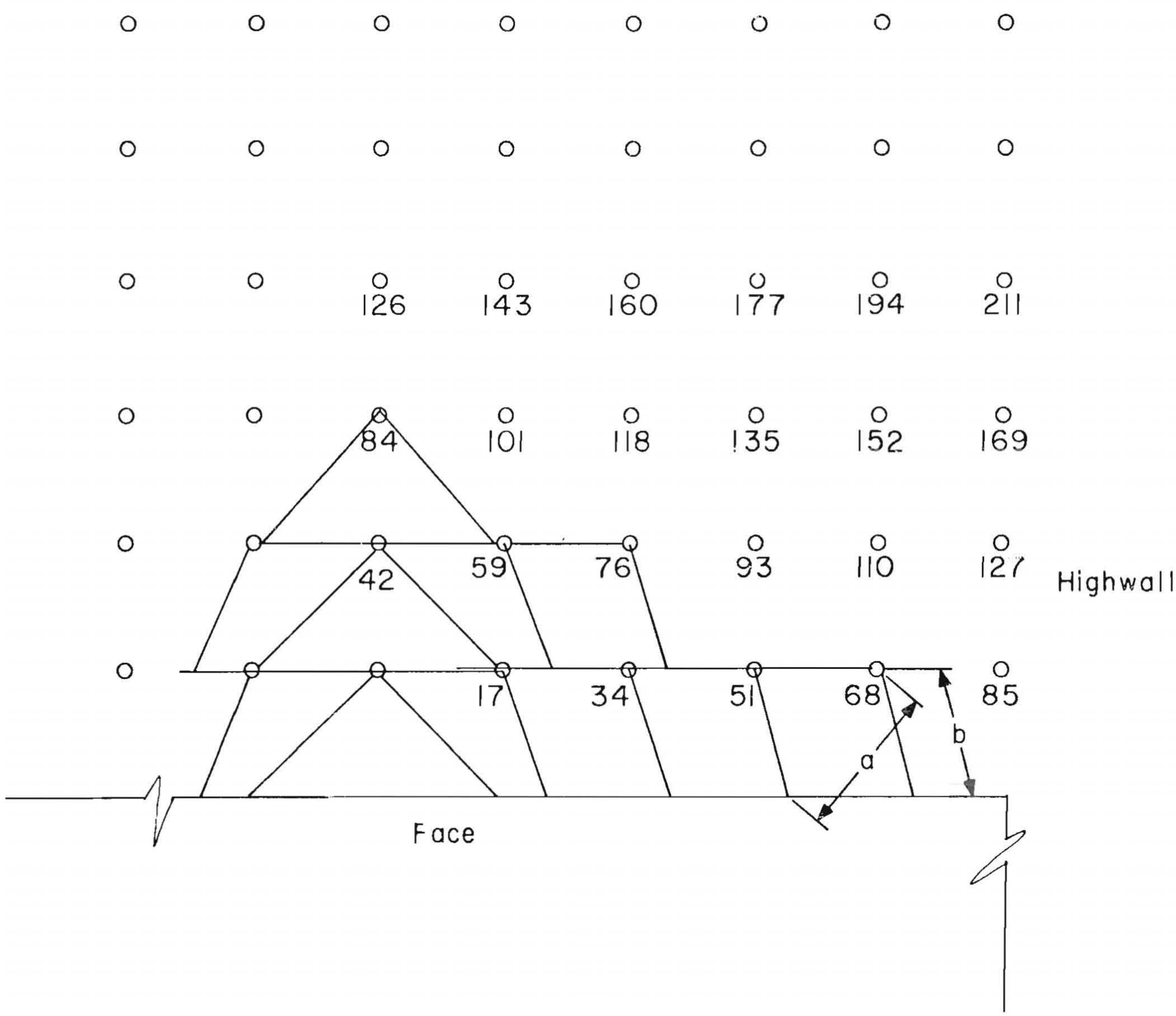

FIGURE 12. - Area of rock affected by each blasthole.

delays were used in the highwall holes. Figure 16 shows that the break line at the time of firing for the 300-ms delays has moved deeper into the shot, providing more relief. However, there was no observed improvement over the use of 250-ms delays.

CONCLUSIONS

The results of this research project showed that greater highwall stability can be achieved by turning the burden movement to a direction perpendicular to the plane of the highwall. These changes can be implemented without increasing

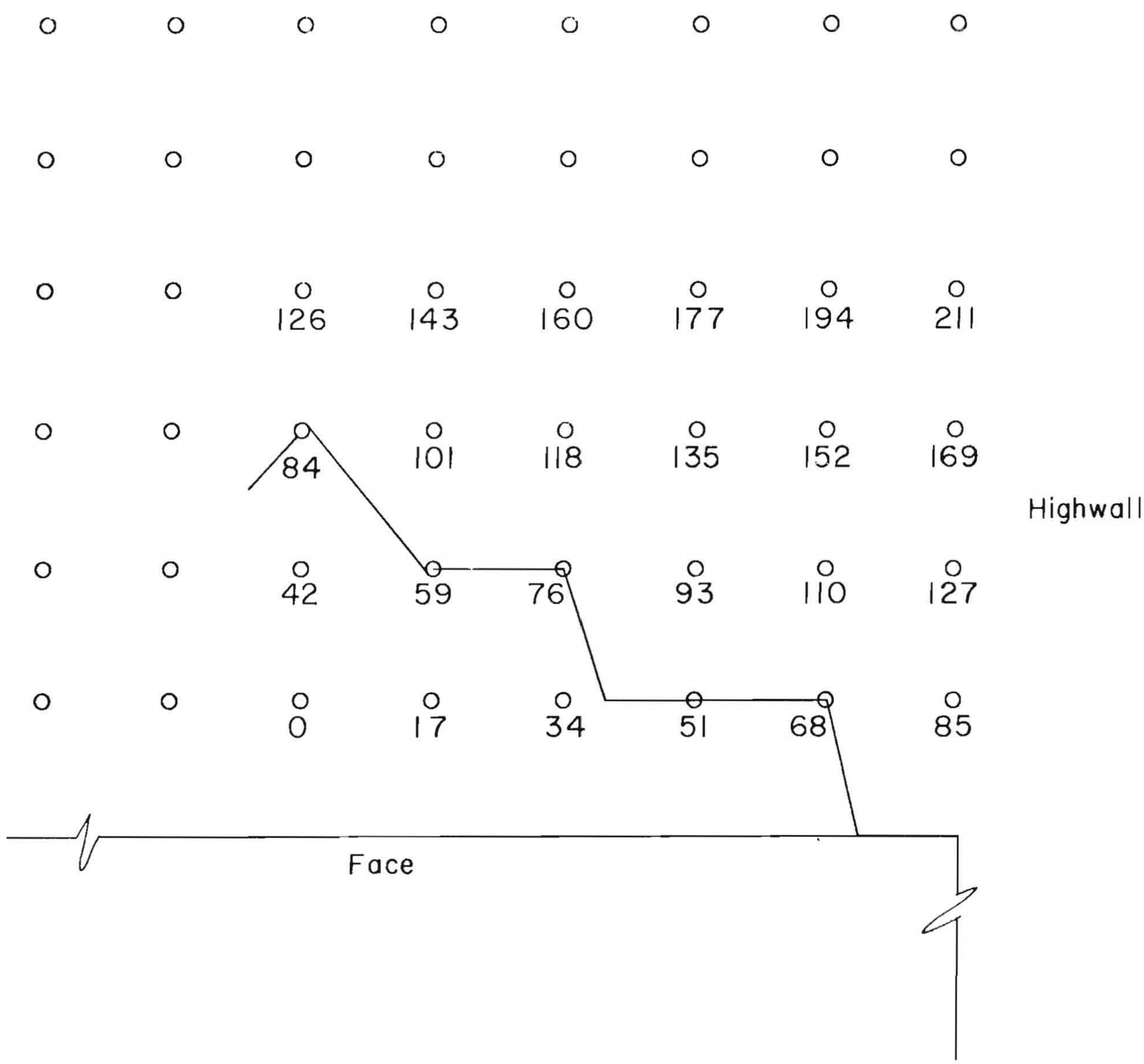

FIGURE 13. - Break line at 85 ms.

cost or technical complication. Redirecting the burden movement was accomplished by using a delay in all highwall holes of 50 to 100 ms longer than those previously used in the delay pattern. The lengthened delay at this location allowed more time for the burden to move, thus reducing the overbreak which causes irregular and unstable highwalls. The use of in-the-hole delays in the entire shot prevented cutoffs that could have adversely affected the highwalls. The mine operator felt that the highwalls looked better and required less cleanup by his bulldozers.

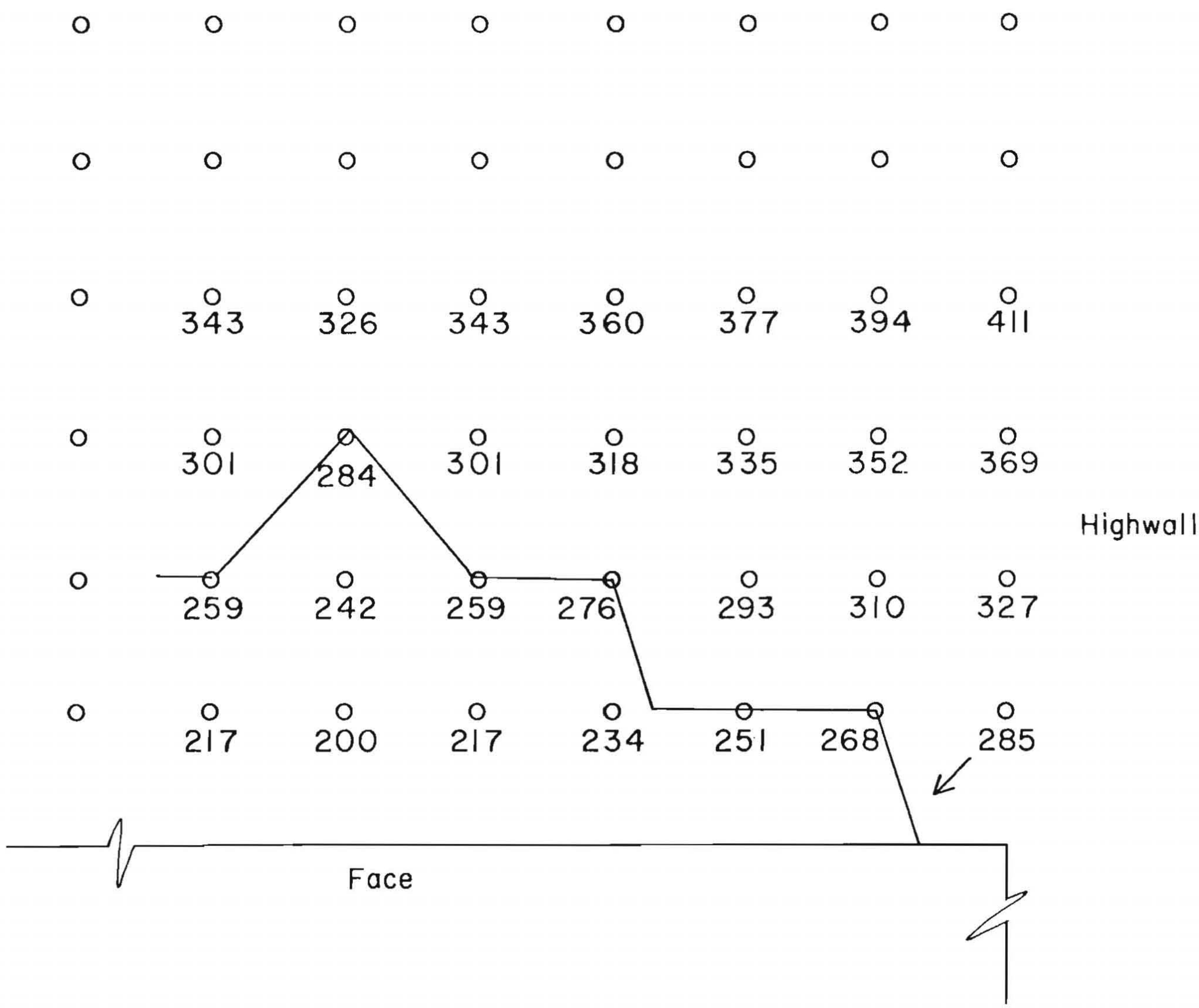

FIGURE 14. - Total delay with 200-ms in-the-hole delays.

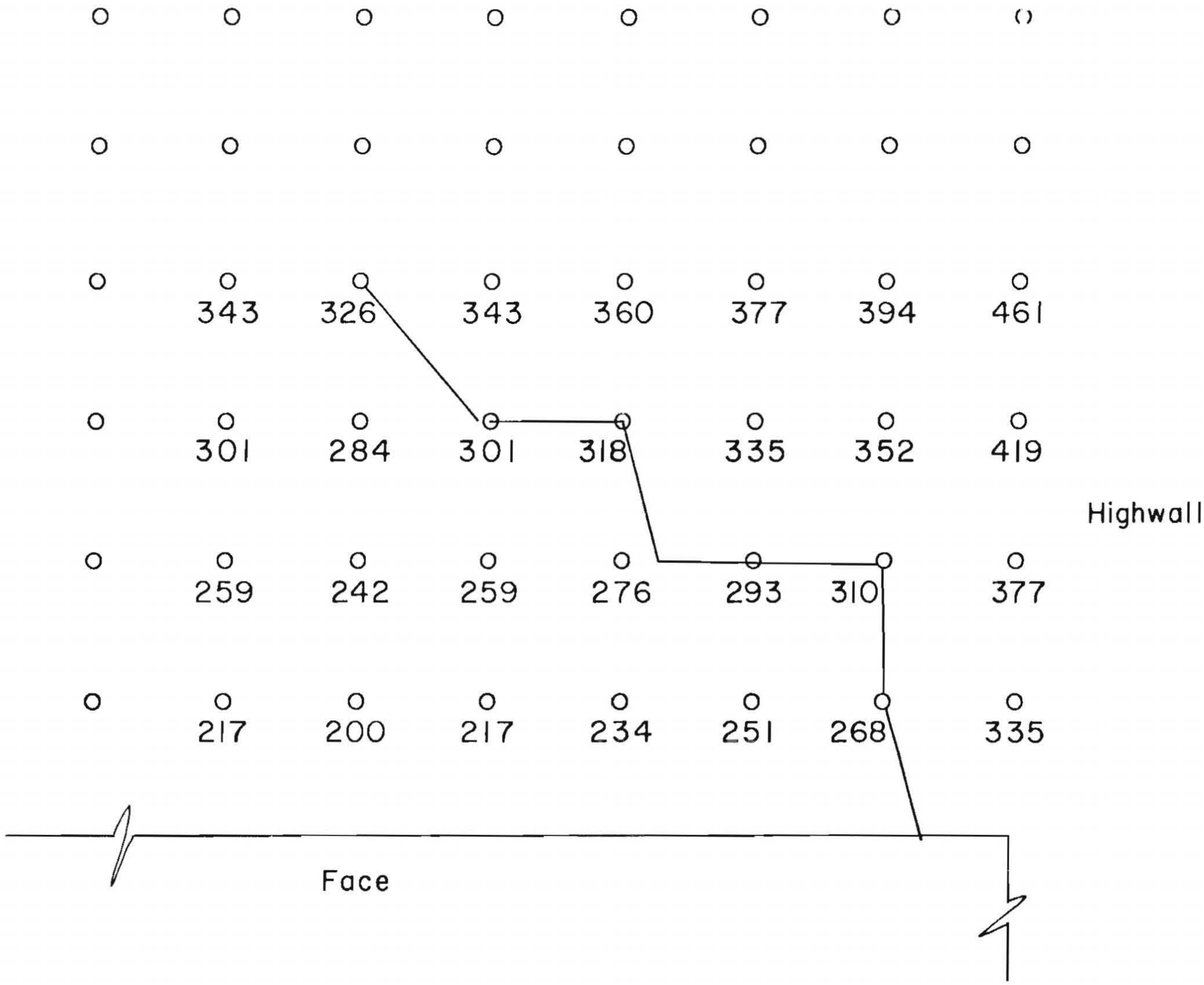

FIGURE 15. - Break line at 335 ms with 250-ms delays in the highwall holes.

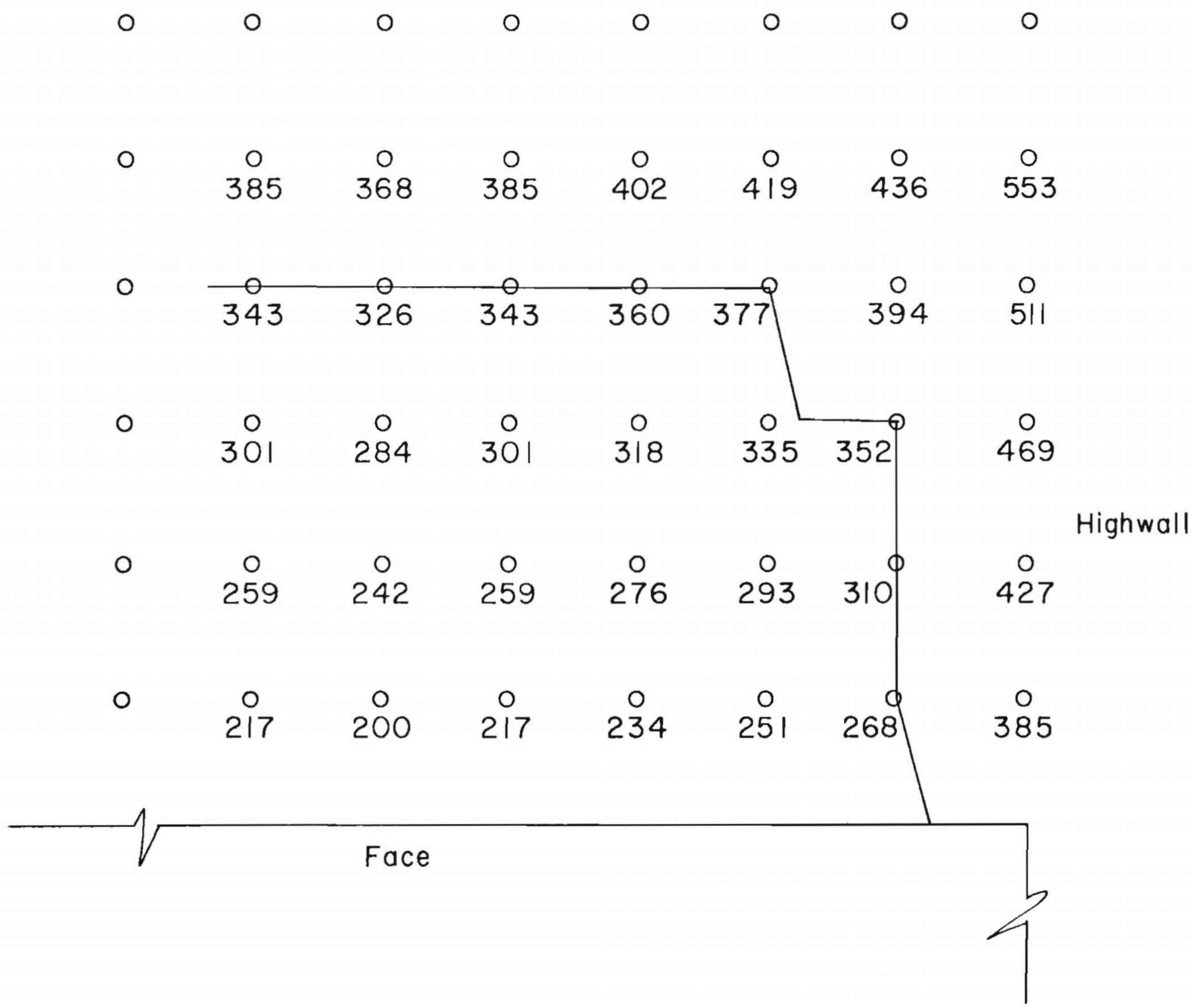

FIGURE 16. - Break line at 385 ms with 300-ms delays in the highwall holes.

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APPENDIX A.--PHOTOGRAPHS--STEREOPAIRS

These stereopairs of test highwalls should be viewable with a simple stereoscope. The separation should be about 2.4 to 2.5 in as printed center to center.

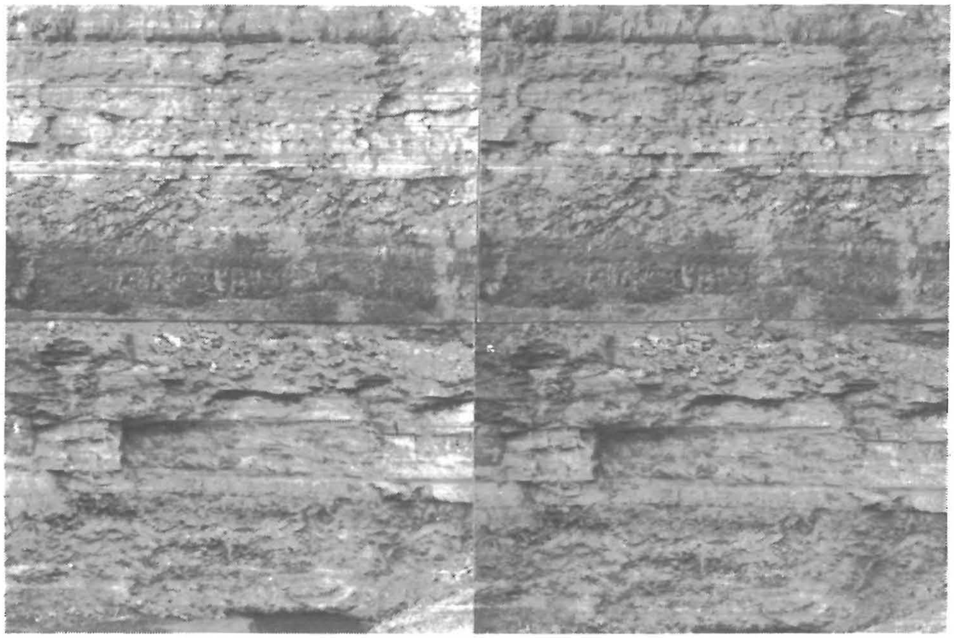

FIGURE A-1. - Stereopairs of test highwalls.

APPENDIX B.--PROFILES OF TEST HIGHWALLS

Figures B-1 and B-2 are oblique drawings of the two test highwalls presented in the text. The profiles were originally taken at 2-ft intervals but are shown here at 4-ft intervals for clarity.

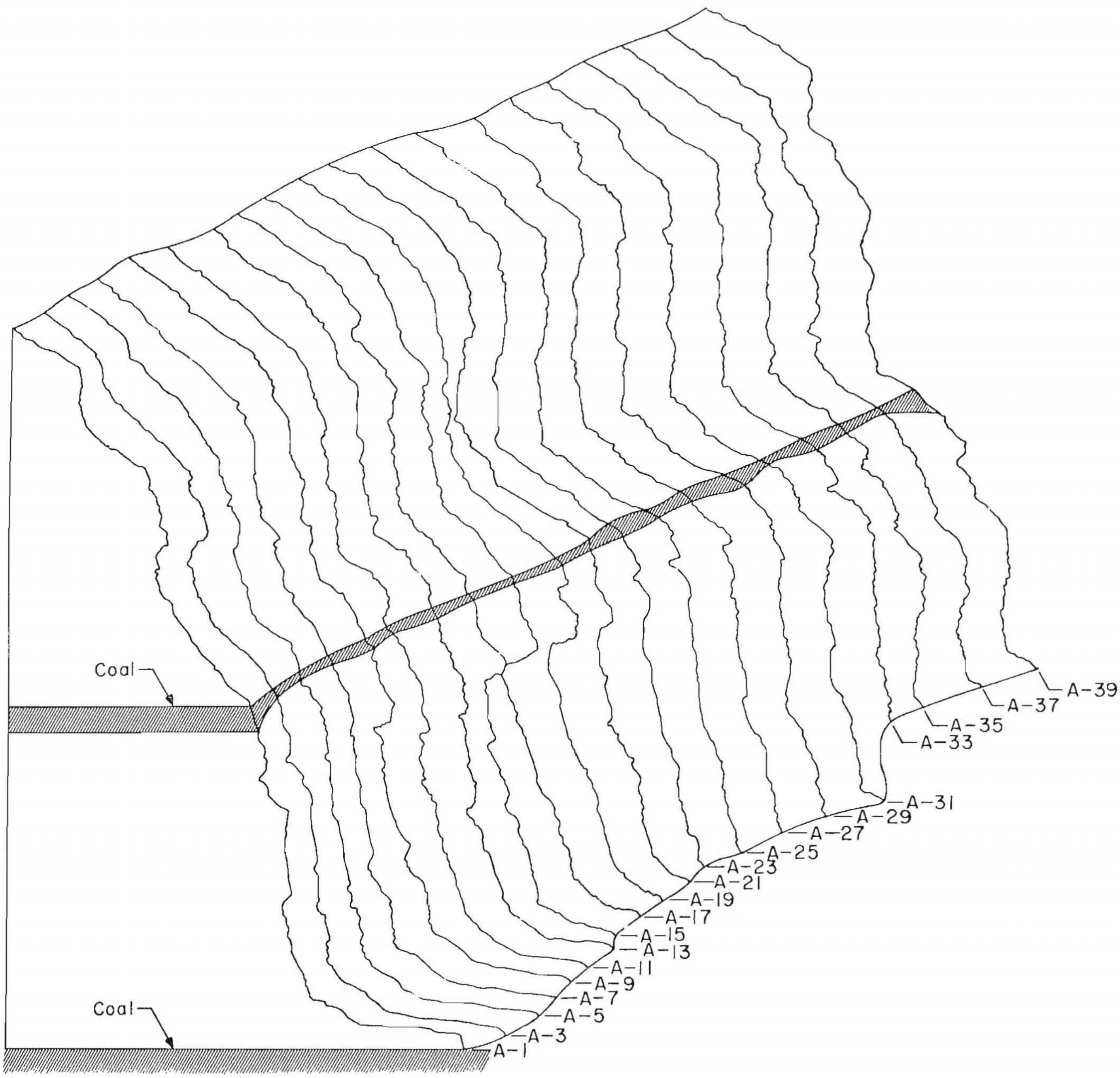

FIGURE B-1. - Test highwall profiles, no additional delays.

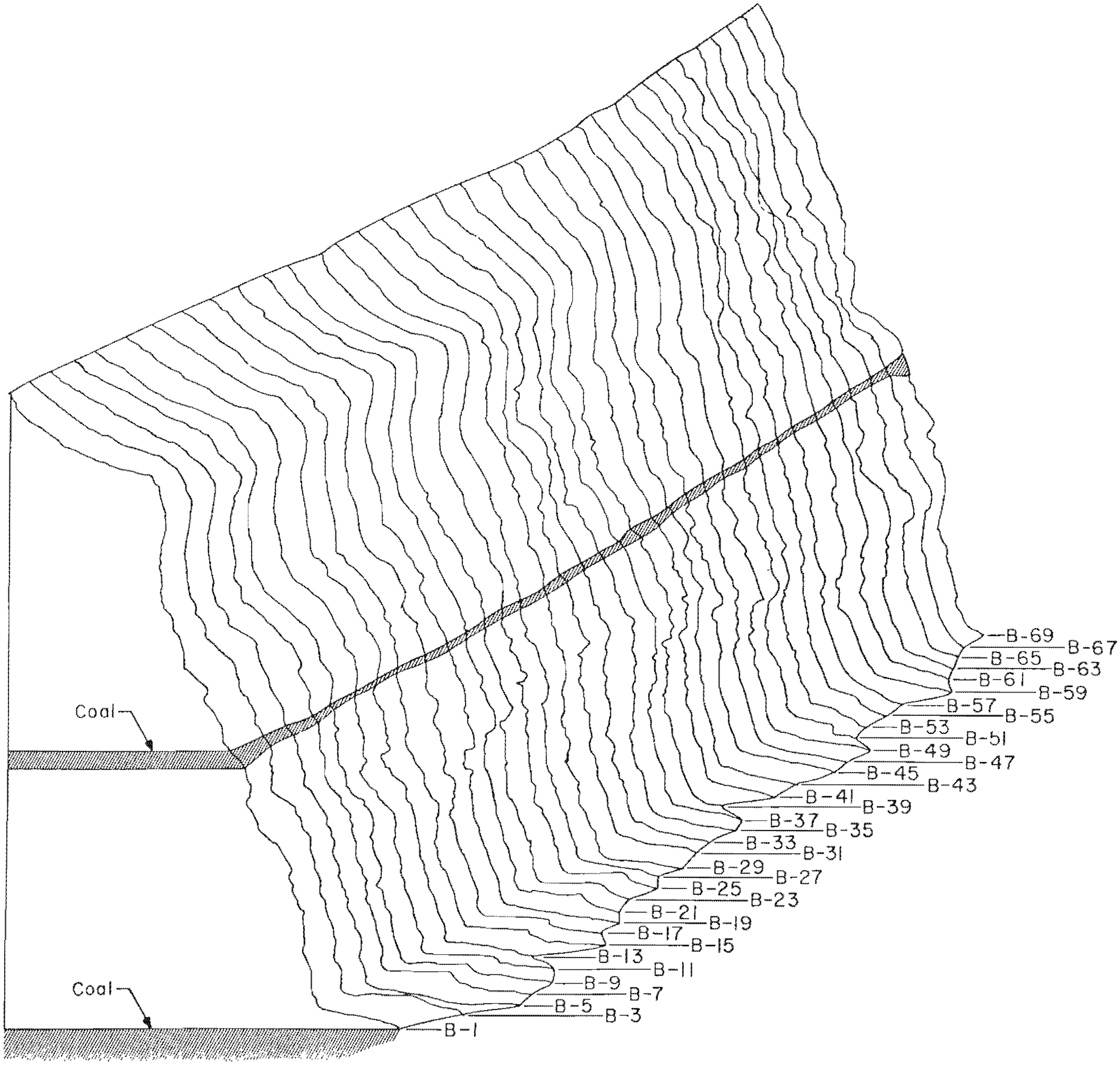

FIGURE B-2. - Test highwall profiles, 250-ms delays in highwall holes.