RI 9081

Bureau of Mines Report of Investigations/1987

Assessment of Longwall Roof Behavior and Support Loading by Linear Elastic Modeling of the Support Structure

By Thomas M. Barczak and W. Scott Burton

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9081

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BUREAU OF MINES
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Library of Congress Cataloging in Publication Data:

Barczak, Thomas M.
Assessment of longwall roof behavior and support loading by linear elastic modeling of the support structure.

(Bureau of Mines report of investigations; 9081)

Bibliography.

Supt. of Docs. no.: I 28.23:9081.

1. Longwall mining—Mathematical models. 2. Elastic analysis (Theory of structures). I. Burton, W. Scott. Title. III. Series: Report of investigations (United States. Bureau of Mines); 9081.

TN23.U43 [TN275] 622 s [622′.26] 86-607949

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

in	inch	s	second
pct	percent		

ASSESSMENT OF LONGWALL ROOF BEHAVIOR AND SUPPORT LOADING BY LINEAR ELASTIC MODELING OF THE SUPPORT STRUCTURE

By Thomas M. Barczak[1] and W. Scott Burton[2]

ABSTRACT

Longwall roof behavior is characterized by strata displacements in both the face-to-waste (horizontal) and roof-to-floor (vertical) directions. The roof support structure provides resistance to this motion by translation of these displacements into vertical and horizontal support loading. Observations indicate that the shield reacts with both a vertical and horizontal force to uniaxial convergence (displacement). However, there are different magnitudes depending on whether the displacement is vertical or horizontal. This makes it possible to use supports as monitors of strata activity and loading. The Bureau of Mines examined this behavior using a linear elastic model of the support structure with two degrees of freedom. Vertical and horizontal load reactions were related to associated displacement actions of the strata. This was done by determining the stiffness of the shield under controlled vertical and horizontal displacement motions in the Bureau's mine roof simulator. This report provides example predictions of strata convergence and isolation of horizontal support loading due to vertical roof convergence using the linear elastic shield model. The report also examines efforts to determine strata behavior by direct measurement of support displacement.

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INTRODUCTION

Longwall roof behavior is characterized by strata displacement in both the face-to-waste (horizontal) and roof-to-floor (vertical) directions. Tests with shield supports indicate vertical convergence produces both a vertical and horizontal load reaction as does horizontal displacement. In other words, the shield support not only reacts axial loads in the same axis as the applied displacement, but also induces off-axis load reactions as a result of the mechanics of the shield structure. Only loads resulting from strata activity need to be considered in the design of the support. Load reactions that are not in response to strata activity (i.e., loads being induced by the mechanics of the structure) are indications of inefficient designs, if such load reactions are of no benefit to strata control. To put this in perspective, tests indicate that over 75 pct of the horizontal load experienced by shield supports is the result of shield-induced load caused by setting the support against the roof.

Because uniaxial strata displacements produce biaxial (horizontal and vertical) support reactions, isolation of the source of horizontal loading and evaluation of strata activity from support reactions require an understanding of the interaction of the support with the strata. Fortunately, the behavior of the shield to vertical displacement is different from that of horizontal displacement; otherwise roof supports could not be used as monitors of strata activity to distinguish between roof-to-floor and face-to-waste displacements; or, conversely, as load monitors to distinguish between load reactions in response to strata activity and support-induced loads due to support mechanics.

This report describes the research that determined the differences in shield behavior relative to vertical and horizontal convergence and the development of a model to enable roof supports to be used as monitors of strata activity and roof loading.

LINEAR ELASTIC FORCE-DISPLACEMENT SHIELD MODEL

To resolve the issue of the source of horizontal shield loading and to develop methods whereby the supports can truly be used as monitors of strata activity, the Bureau is investigating the utilization of a linear elastic model with two degrees of freedom to model support behavior. The load-displacement relationship of the shield structure can then be described by the following mathematical relationships, which describe vertical and horizontal support reactions as a function of vertical (roof-to-floor) and horizontal (face-to-waste) displacements.

$$F_v = K_1 \delta_v + K_2 \delta_h \tag{1}$$

and

$$F_h = K_3 \delta_v + K_4 \delta_h, \tag{2}$$

where F_v = vertical support resultant load;

F_h = horizontal support resultant load,

δ_v = vertical (roof-to-floor) shield displacement,

δ_h = horizontal (face-to-waste) shield displacement,

and K_n = stiffness coefficients.

Vertical and horizontal shield loading can then be determined if the shield displacements (δ_v and δ_h) are known. Inverting equations 1 and 2 enables determination of shield displacements from known resultant shield loading as described in equations 3 and 4. Both solutions require knowing the shield stiffness coefficients (K_1, K_2, K_3, K_4).

$$\delta_v = C * (K_4F_v - K_2F_h) \qquad (3)$$

and $$\delta_h = C * (-K_3F_v + K_1F_h) \qquad (4)$$

where $C = [1/(K,K_4 - K_2 K_3)]$.

Consistent with previous discussions, the model indicates that uniaxial displacements produce biaxial support reactions. It is also seen that unless the shield is stiffer in one axis than the other ($K_1 <> K_2$ and $K_3 <> K_4$), support reactions relative to vertical and horizontal strata displacements would be indistinguishable.

The shield stiffness coefficients (K_1, K_2, K_3, K_4) were determined with the aid of the Bureau's mine roof simulator (MRS). The MRS, shown in figure 1, is a massive hydraulic press capable of subjecting full-scale roof support elements to the kinds of force and displacement actions that could be encountered during underground operation. The simulator is active in both the vertical and horizontal axes and can be programmed to operate in displacement control independently in each axis, allowing a shield to be subjected to controlled vertical and horizontal displacements.

Examination of equations 1 and 2 and figures 2 and 3 reveals how the shield stiffness parameters were determined. By commanding the MRS to maintain a fixed horizontal displacement of the platen

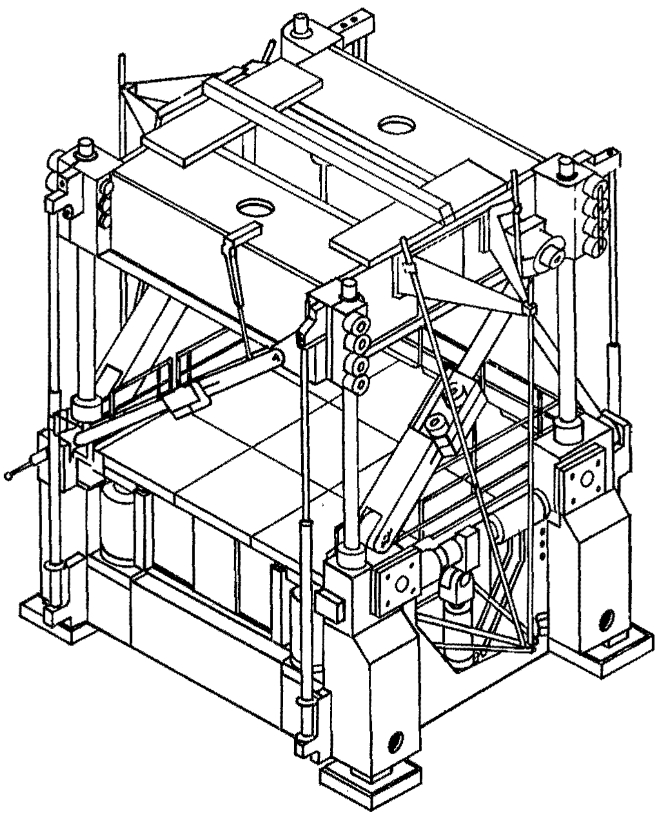
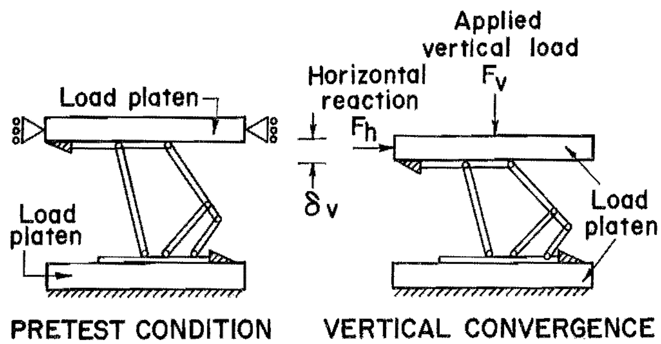
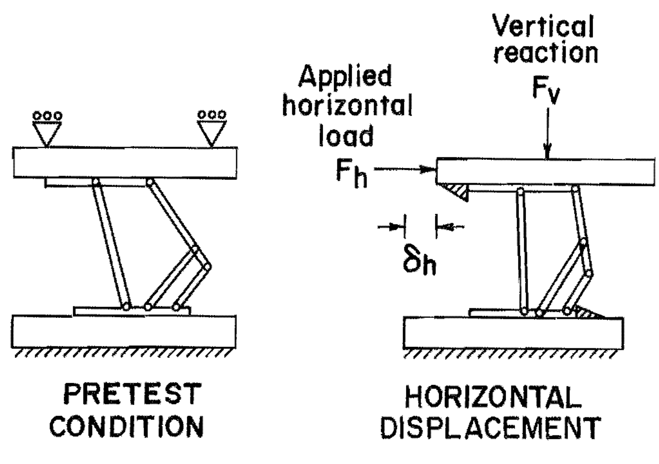


FIGURE 1.—Mine roof simulator (MRS).



$$F_v = K_1\delta_v + K_2\delta_h \rightarrow \delta_h = 0 \rightarrow F_v = K_1\delta_v$$
$$F_h = K_3\delta_v + K_4\delta_h \rightarrow \delta_h = 0 \rightarrow F_h = K_3\delta_v$$

FIGURE 2.—Vertical convergence tests in the MRS.



$$F_v = K_1\delta_v + K_2\delta_h \rightarrow \delta_v = 0 \qquad F_v = K_2\delta_h$$
$$F_h = K_3\delta_v + K_4\delta_h \rightarrow \delta_v = 0 \qquad F_h = K_4\delta_h$$

FIGURE 3.—Horizontal displacement tests in the MRS.

(fig. 2), the shield is subjected to pure vertical convergence. Terms $K_2\delta_h$ and $K_4\delta_h$ of equations 1 and 2, respectively, then become zero since $\delta_h=0$, leaving $F_v = K_1\delta_v$ and $F_h = K_3\delta_v$. The vertical reaction of the shield to the applied vertical displacement (δ_v) is measured by the MRS force required to produce this displacement (F_v). Horizontal support reaction is the constraining force (F_h) required to maintain fixed horizontal displacement of the platens. Therefore, knowing the vertical displacement and the associated reactive forces of the shield, the vertical stiffness parameters (K_1 and K_3) can be calculated: K_1 being equal to the ratio of resultant vertical shield load to the vertical displacement and K_3 equal to the ratio of the resultant horizontal load to the vertical displacement. Likewise, subjecting the shield to pure horizontal (face-to-waste) displacement (fig. 3) permits determination of stiffness coefficients K_2 and K_4 as terms $K_1\delta_v$ and $K_3\delta_v$ of equations 1 and 2, respectively, become zero for $\delta_v=0$.

The results of the MRS tests, for one shield configuration, are shown in figure 4, depicting reactive shield forces as a function of applied MRS displacements. The slopes of the force-displacements plots under controlled vertical and horizontal convergence determine the stiffness parameters (K_1, K_2, K_3, K_4). Table 1 presents least squares analyses determinations of the stiffness parameters at shield heights of 58 and 78 in, with and without an active canopy capsule. As can be seen from the table, the shield exhibits different responses at different shield heights because of changes in the geometry of the structure. The stiffness of the structure in both the vertical and horizontal axis, increases at reduced shield heights. This necessitates developing characteristic stiffness curves as a function of shield height, and current research efforts are devoted to this task.

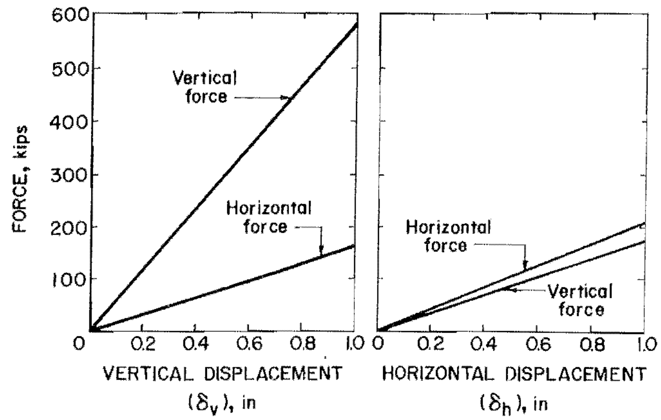


FIGURE 4.—Shield stiffness test results.

TABLE 1. - Linear model stiffness parameters, kips per inch

Shield configuration	K_1	K_2	K_3	K_4
78-in height:				
Active canopy capsule...........	585	174	157	203
Inactive canopy capsule...........	633	268	228	229
58-in height:				
Active canopy capsule...........	666	505	328	505
Inactive canopy capsule...........	715	517	430	378

LINEAR MODEL CONVERGENCE PREDICTIONS FROM RESULTANT SHIELD LOADING

Using numerical values for the stiffness parameters (table 1), the inverted linear elastic model equations 3 and 4 can be used to determine shield displacements, which are indicative of strata activity, from measured resultant shield loading. The ability of the model to predict displacements from known vertical and horizontal shield reactions is illustrated in figure 4, which compares displacements predicted from the linear elastic model to MRS measured displacements, utilizing MRS measured vertical and horizontal shield loading as inputs to the model. As can be seen from the figure, both the vertical and horizontal convergence can be predicted with reasonable accuracy if the resultant shield loading is accurately known.

To utilize the linear elastic model to determine convergence measurements on active underground supports, some means of determining resultant shield loading other than the MRS must be available. The Bureau has developed a technique utilizing two- and three-dimensional static rigid-body modeling of shield structures to determine resultant shield load by measurement of leg, canopy capsule, and lemniscate link forces (1).[3] Tests in the MRS have demonstrated that this technique can successfully predict vertical shield loading to within 5 pct and horizontal loading to within 25 pct. This level of accuracy is suitable for semi-quantitative assessment of shield loading, but is less than desirable for predictions of shield (strata) convergence using the linear elastic model.

Examination of displacement equations 3 and 4 reveals that the errors in vertical and horizontal force determinations are cumulative with the largest error caused by overprediction of one parameter and underprediction of the other. The impact of such an error can be seen by comparison of figures 5 and 6, where resultant shield loading as determined by the two-dimensional rigid-body shield analyses were used as inputs to the linear elastic model equations 3 and 4 to predict shield displacements. Tests indicate the error in the rigid-body model force predictions is somewhat systematic, indicating the possibility of mathematically "calibrating" the error out of the system. A better approach would be to develop a more direct technique of resolving forces in the shield structure. One possibility to be examined is the utilization of load sensing pins at the canopy-caving shield hinge.

In summary, the linear elastic model presented in the previous section is adequate to predict shield displacements (strata convergence) if shield reactions are accurately known. Current methods of determining resultant shield loading from leg, canopy capsule, and lemniscate link forces through rigid-body analyses are inadequate for use in conjunction with the linear elastic model, and other more direct means are being investigated.

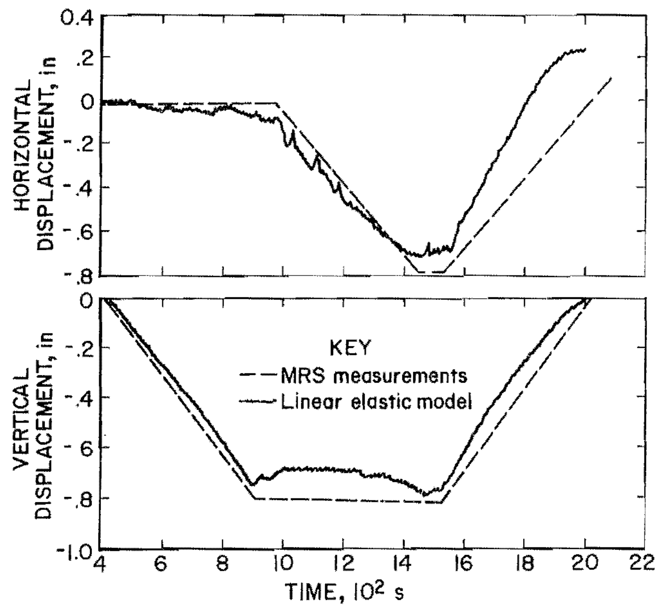


FIGURE 5.—Comparison of linear elastic model displacement predictions.

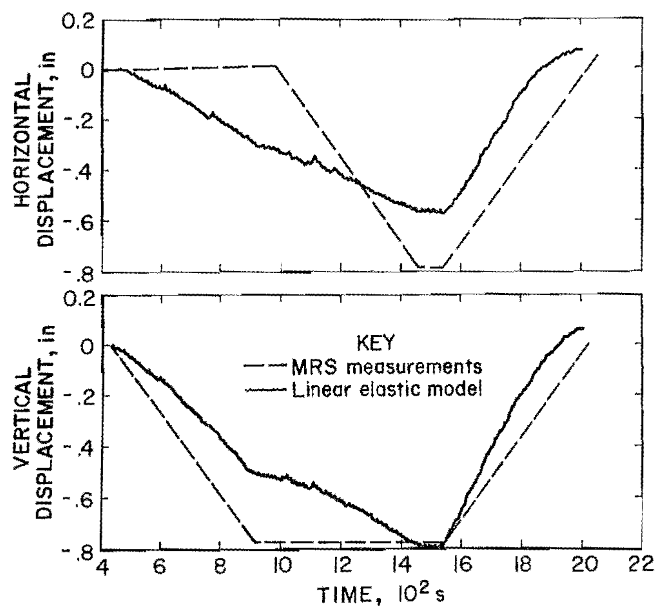


FIGURE 6.—Two-dimensional force model displacement predictions.

[3]Barczak, T. M., and R. C. Garson. Technique To Measure Resultant Loading on Shield Supports. Paper in Rock Mechanics in Productivity and Protection (Proc. 25th U.S. Symp. Rock Mech., Evanston, IL, June 25-27, 1984). Soc. Min. Eng. AIME, 1984, pp. 667-669.

LINEAR MODEL RESULTANT SHIELD LOAD PREDICTIONS FROM SHIELD DISPLACEMENTS

Equations 1 and 2 of the linear elastic model enable prediction of vertical and horizontal shield reactions from measured shield displacements. Measurements of the motion of the shield canopy relative to the base structure can be achieved numerous ways by the proper employment of displacement and inclination transducers to observe changes in shield geometry. In an effort to minimize underground instrumentation, tests were conducted in the MRS to evaluate determining shield displacements by monitoring behavior of the leg cylinders. Leg pressure was found to provide a good correlation to leg closure, and by measuring the angle of the leg cylinder relative to the canopy with a tilt transducer, it was demonstrated that shield displacement could be accurately determined from leg behavior.

Utilizing displacement measurements deduced from leg behavior in the linear elastic model equations 1 and 2, it is shown from controlled MRS tests (fig. 7), that the resultant vertical and horizontal shield forces can be quantitatively determined.

ISOLATION OF HORIZONTAL SHIELD LOADING

The advantage of the shield support over its predecessor chock-type support is its ability to withstand horizontal (face-to-waste) loading, but the necessity for high (25-30 pct of vertical load capacity) horizontal load bearing capacity is still under debate. As previously indicated, horizontal load is produced by both vertical roof convergence and horizontal strata displacement. Only the horizontal loads produced by horizontal strata displacements need to be considered in the design of a structure for application in longwall mining. Thus, it is possible that the shield is an inefficient design.

The linear elastic model provides a means to distinguish between shield-generated horizontal load caused by vertical roof convergence and strata-generated horizontal load caused by face-to-waste strata activity.

Strata-induced horizontal load = $K_4 \delta_h$ and shield-induced horizontal load = $K_3 \delta_v$. Therefore, if the vertical (δ_v) and horizontal (δ_h) displacements are known, either by deduction from resultant shield loading or by direct measurements, the sources of horizontal loading can be resolved.

It is also known from tests in the MRS, that the ratio of horizontal to vertical forces is different, as illustrated in figure 8, for vertical displacement loading than for horizontal displacement loading because of differences in vertical and horizontal shield stiffness. This difference in load ratio behavior provides another method whereby strata-induced horiztonal load activity might be isolated, but the magnitude of the support reactions would not be determined by the ratio.

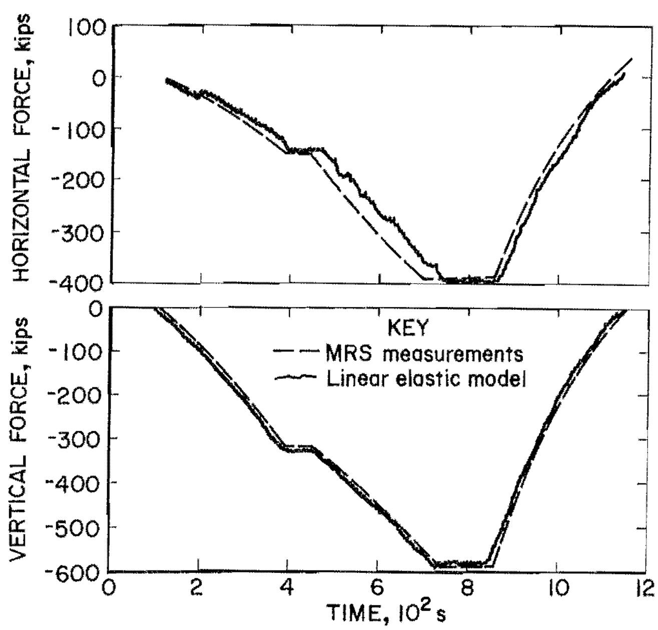


FIGURE 7.—Linear elastic model force predictions.

CONCLUSIONS

The research described in this paper provides a foundation from which a correlation between shield behavior and strata activity can be defined. Utilizing roof support specimens as instruments to monitor strata activity requires fundamental knowledge of the interaction of the roof support system with the surrounding strata. Assessment of strata activity will provide rationale for more effective roof support designs and support capacity requirements prior to mining. The conclusions and salient parts of this research follow.

o Longwall face support is thought to operate under displacement control characterized by strata displacements in both the face-to-waste (horizontal) and roof-to-floor (vertical) directions.

o The shield reacts both a vertical and horizontal load to uniaxial convergence, but with different magnitudes depending on whether the displacement is vertical or horizontal, making it possible to use supports as monitors of strata activity and loading.

o The load-displacement behavior of the shield support can be effectively modeled by a linear elastic model with two degrees of freedom.

o Shield stiffness parameters have been determined from compliance studies of the shield support in the MRS, enabling the prediction of either shield (strata) displacement or resultant shield loading if one of the two parameters is accurately known.

o Prediction of shield (strata) displacement from resultant shield loading utilizing the linear elastic force-displacement model suffers from inaccuracies in current methods of determining resultant loading from rigid-body static analyses of measured leg, canopy capsule, and lemniscate link forces.

o Prediction of resultant shield loading from shield displacements deduced from leg pressure and leg cylinder orientation appears feasible.

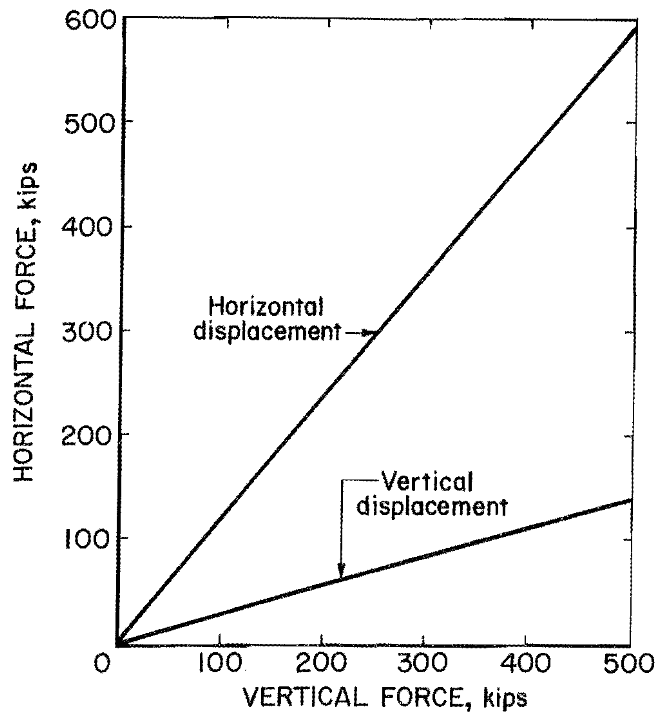


FIGURE 8.—Ratio of horizontal to vertical force as a function of vertical and horizontal shield convergence.

U.S. GOVERNMENT PRINTING OFFICE: 1987 - 605-017/60030

INT.-BU.OF MINES,PGH.,PA. 28448