Evaluation of Standing Supports for Longwall Tailgate Entry Using NIOSH Support Technology Optimization Program (STOP)

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Unplanned tailgate collapses and difficult mining conditions in U.S. longwalls have necessitated the use of innovative tailgate support systems. Severe ground movement induced by longwall loading has caused operators to utilize secondary support systems that can match yield and strength requirements with expected ground reactions. In 2020, the National Institute for Occupational Safety and Health (NIOSH) updated the Support Technology Optimization Program (STOP) in order to better evaluate these secondary support systems by providing mine operators with a simple and practical tool to make engineering decisions about the selection and placement of various secondary support systems. This update implements important changes to STOP's user interface and functionality and significantly enhances the use of ground reaction curve design criteria. The paper provides examples of using the 2020 version of STOP to evaluate a current standing support system followed by using the ground reaction curve design criteria at this case study mine.

INTRODUCTION

The Support Technology Optimization Program (STOP) (NIOSH 2020) was initially created to provide both an engineering foundation for support design as well as to examine and compare new support technologies. There are a variety of standing supports currently being utilized in underground coal mining operations in the United States to assist in providing stable mine entries. Standing support performance requirements depend on the nature of the ground deformation and consequently require a good understanding of the interaction between the support and ground to achieve an optimum roof support system. Mining operations often employ standing support strategies that are unique to their mine, therefore it is important that the design and installation of the standing support system are compatible with the mine conditions to ensure successful ground control.

Considerable research and development have been conducted by support manufacturers to develop standing support technologies for the mining industry. Researchers at NIOSH, with the cooperation of support manufacturers, have established a testing protocol that evaluates the performance characteristics of these standing support systems (Barczak 2000). Using this protocol, each of these support systems has gone through rigorous safety performance testing under controlled loading conditions in NIOSH's Mine Roof Simulator (MRS).

To facilitate the application of this research with secondary roof support technologies and to improve mine safety, STOP was developed by NIOSH to provide a comprehensive tool for evaluating the performance of available secondary support systems and designs based on support strength, yield characteristics, cost, installation time, and material handling considerations (Barczak 2000). This program provides a process to optimize roof support applications and helps ensure the protection of mine workers by preventing roof falls due to inadequate support design. STOP can provide mine operators with a practical tool to make engineering decisions about the selection and placement of these various available secondary support system technologies. In essence, the goal of the support design is to achieve the desired load density at or before the designated design convergence.

STOP outputs a detailed analysis of the support system performance and its ground control capability. The primary goal of STOP is to determine the layout configuration that is necessary to meet the specified design criteria or to allow the user to examine a chosen layout and evaluate its ground capability relative to the desired outcome.

SUPPORT EVALUATION USING STOP

Design Criteria and Support Requirements

Design criteria are used to formulate the load and convergence requirements of the support system. Design criteria are specified by two fundamental parameters: 1) a support load density (amount of support per foot of entry) required to support the roof and floor and 2) a design convergence (at which equilibrium will be achieved to preserve roof integrity). There are also two components to the convergence criteria: controlled and uncontrolled convergence. The controlled component is composed primarily of near seam roof and floor deformations (strata delamination). Some ground movement cannot be controlled by standing roof support systems. This includes deformations produced by the elastic response of the overburden and pillar deformations that work to control the overburden mechanics. This uncontrollable convergence is an important support design parameter since the support must be able to survive this displacement without losing the necessary capacity to maintain roof control. Other relevant parameters are the entry width and the entry height and the roof and floor bearing strength. The support requirement necessary to meet the design criteria is determined by the support layout (spacing and number of rows across the entry).

HYPOTHETICAL EXAMPLES OF SUPPORT EVALUATIONS

Support Design Evaluation Based on a Current Support System

Normally, establishing the design criteria based on a current support system is considered because the support application has been successful. For this example, the load density and convergence criteria are based on the performance of a current pumpable standing support system operating in a deep cover longwall tailgate in which the performance has been questionable due to frequent premature yielding of the support. The support application was two rows of a 30-inch-diameter pumpable support on a 96-inch center-to-center spacing. The convergence when the face advanced to the tailgate was measured to be approximately 5 inches. This is then used to establish the design convergence criteria.

The support performance curve is shown in Figure 1. It is seen from this curve that the support sheds load after about 3 inches of convergence. The mine also employed a yield pillar in the gateroad adjacent to the tailgate entry. This design under the deep cover loading conditions likely caused pillar yielding that impacted the tailgate entry with significant “uncontrollable convergence” that is beyond the support system’s capacity to prevent. This “uncontrollable convergence” was estimated to be 3 in for this case study.

Using a design convergence of 5 inches and an uncontrollable convergence of 3 inches, the load density for the two rows of 30-inch-diameter pumpable supports employed on a 96 in spacing was computed by the STOP as of 27.6 tons/ft (Figure 2).

Using these criteria, the layout (support spacing and number of rows) of any alternative support system can be computed to provide the same load density at the designated design convergence

The alternative supports chosen for this case study were a 9-pt, mixed hardwood crib constructed from 6x6x36-inch timbers and a 36-inch Link-N-Lock engineered timber support. Note that all support applications are two rows of standing supports. As shown

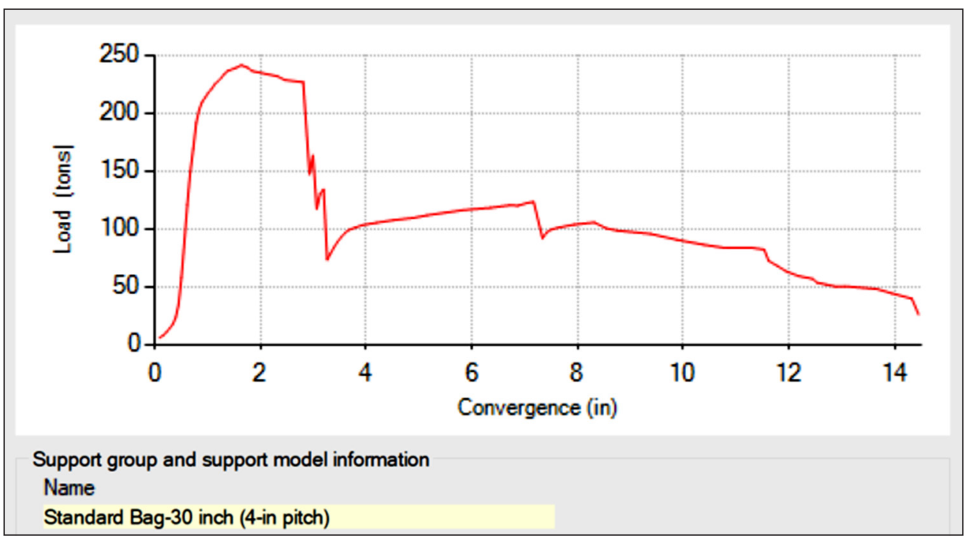

Figure 1. Full-scale performance curve for a 30-inch-diameter pumpable support from NIOSH’s STOP Version 4.0.

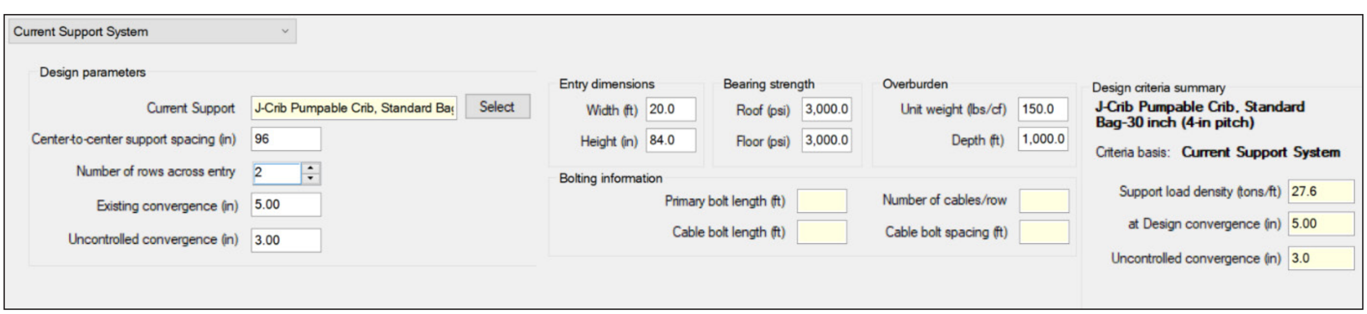

Figure 2. A window from the STOP Beta Version 4.0 showing design criteria based on the Current Support System.

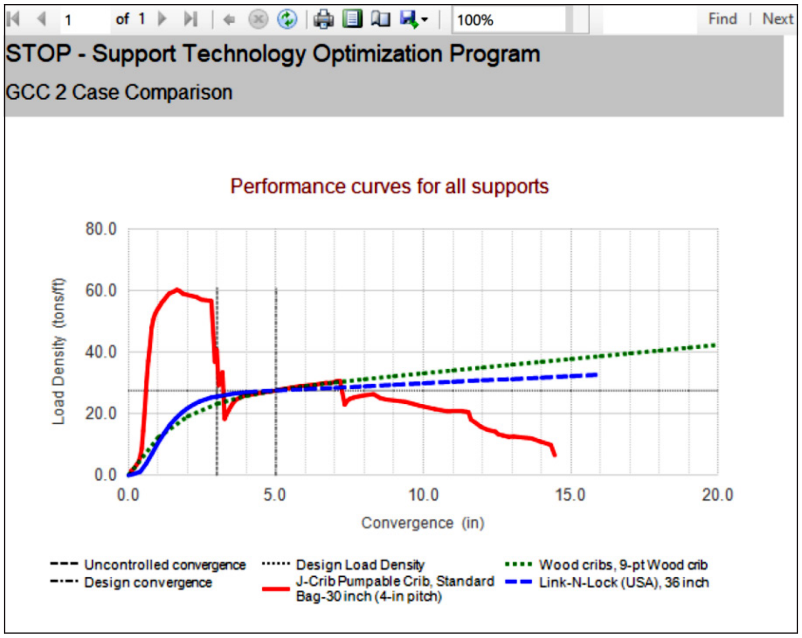

Figure 3. Load density-displacement performance plot of pumpable crib, Link-N-Lock, and wood crib from the STOP Version 4.0.

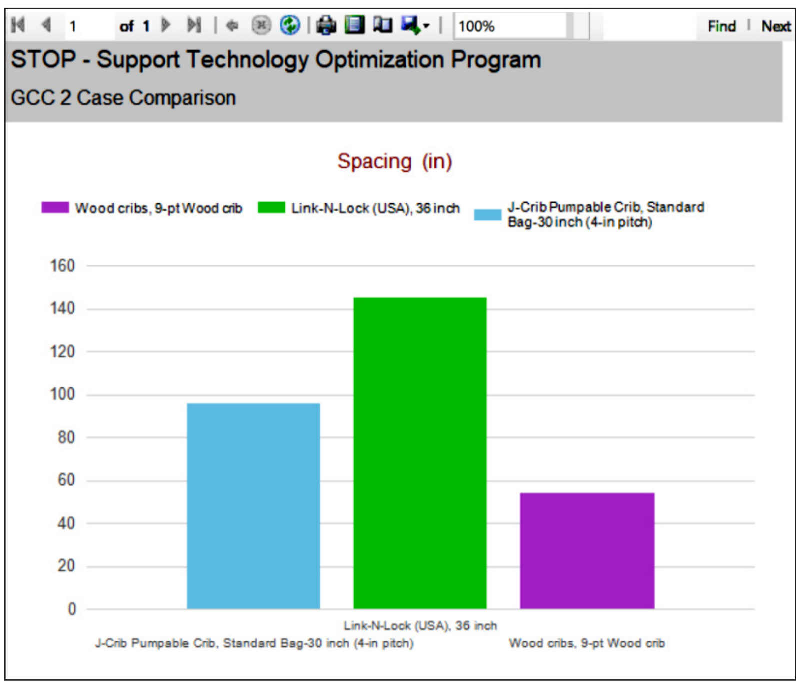

Figure 4. Spacing evaluation of Link-N-Lock and wood crib support systems as a replacement for pumpable support from the STOP Beta Version 4.0.

in the Figure 3, all three support systems can provide equivalent support, however, with varying center-to-center support spacing. Figure 4 shows the spacing for each support required to provide a design load density of 27.6 tons/ft at the design convergence of 5 inches. The Graphical Data Analysis tab of STOP plots the support performance as a function of unit support load (Figure 5) or load density (Figure 3) as a function of convergence and graphically compares the various support systems.

Figure 5 shows that a high peak load capacity of a support does not necessarily translate to a better support design, as evidenced in this case study. The impact, as was shown in this case, is that the high initial capacity of the pumpable support was not utilized in

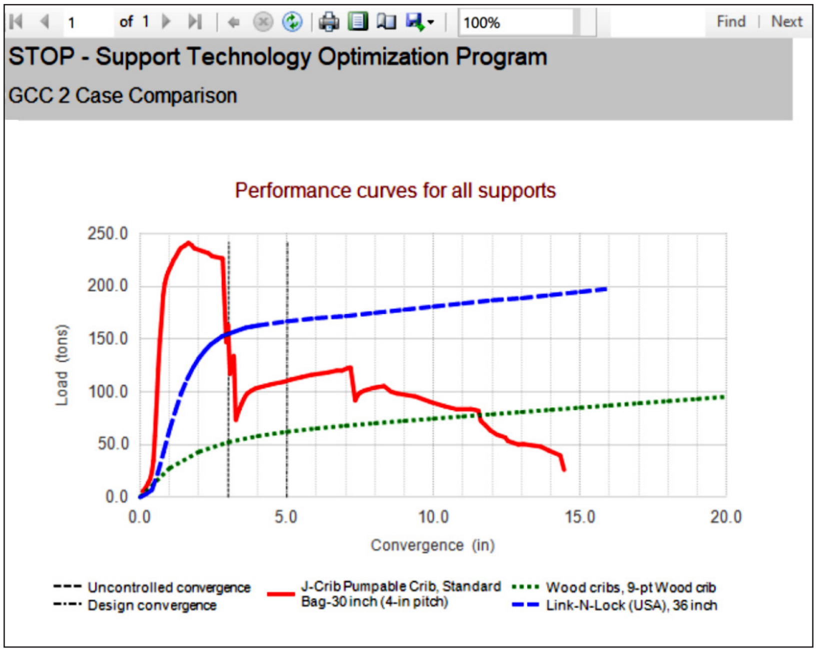

Figure 5. Load-displacement performance plot of pumpable crib, Link-N-Lock, and wood crib from the STOP Version 4.0.

determining the support spacing due to load shedding in the elastic deformation (uncontrolled convergence) region prior to reaching the required design convergence. If a support reaches its peak load capacity before the equilibrium ground conditions are met and it is unable to sustain the required capacity to achieve equilibrium, then failure of the rock mass (mine roof) is a possible result. Also observed from Figure 3, the difference is small between the support load at the design convergence (5 inches) and the maximum support capacity after the design convergence for all supports, but especially for the pumpable support system. This "safety factor" provides an assessment of how much additional capacity is available if the support system conditions change and additional support capacity is required.

Support Design Evaluation Based on Using Ground Reaction Curve (GRC)

As was seen in the previous example, uncontrollable convergence can be very influential in determining if a support system will be compatible with the mine loading conditions and provide successful ground control. And qualitatively approximating the degree of "uncontrollable convergence" is difficult without significant ground control experience at the study site. The ground reaction curve provides a means to quantitatively evaluate this design parameter.

It has long been recognized that the ground reaction curve can be utilized for establishing support design criteria for underground excavations (Brady and Brown, 1985). The ground reaction curve provides a correlation between the amount of support used and the associated entry convergence.

Figure 6 provides a conceptual illustration of the ground reaction curve according to Esterhuizen et al. (2020) which plots the ground response and the development of deadweight loading with increasing convergence. Generally, the ground reaction curve has a negative slope indicating that a decrease in the support load density would result in increasing roof-to-floor convergence; that is, a high-capacity support system is required to limit convergence, whereas a lower-capacity support system would result in greater convergence. The actual shape of the ground reaction curve is dependent on many factors (roof and floor geology, entry geometry, overburden and mining-induced loading, and roof bolt application) and must be determined for a specific site. Ground reaction curves can be created by using numerical models and semi-calibrated with in-mine instrumentation. A given curve may not be applicable to other mines or even to other areas of the same mine unless they experience similar conditions.

There are three important regions in the curve, shown in Figure 6:

- Elastic (overburden) deformation (blue)—This region primarily represents the convergence associated with elastic deformation of the strata and pillar response that is too powerful to be controlled by any practical support system. This behavior is also referred to as the "uncontrollable convergence" region.
- Strata deformation region (green) represents the onset of inelastic deformation associated with initial fracturing and delamination of the roof strata (yellow). This region is where support capacities can influence the strata behavior.
- Detached block region (red)—Beyond this point, the roof fracturing and failure extends above the bolting system creating the potential for a detached block (dead weight) roof loading condition, which should be avoided in the support design strategy.

Numerical Model of Ground Reaction Curve

Barczak et al. (2008) demonstrated the methodology to estimate the GRC for the longwall tailgate indirectly by using the field measurements and calibrated numerical models. Esterhuizen et al. (2010) explains the difficulty in fully measuring the ground reaction

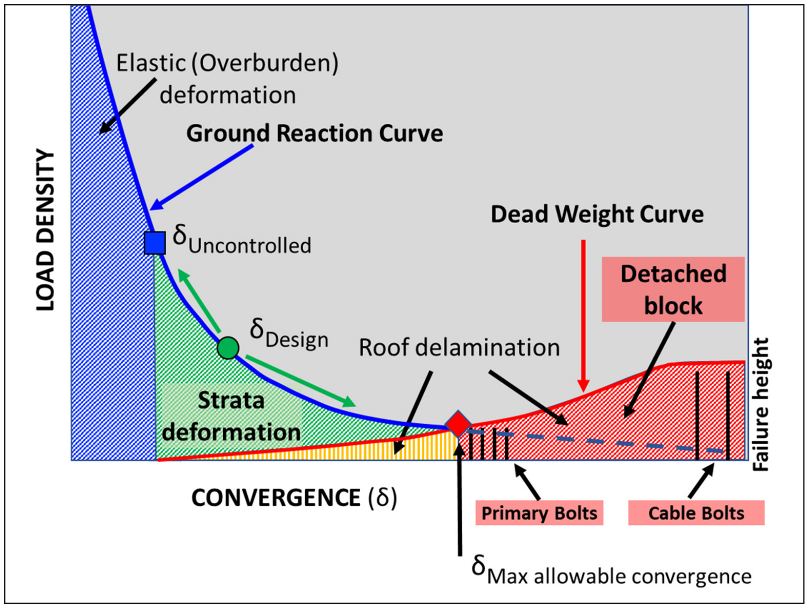

Figure 6. Example ground reaction curve used in STOP.

curve in the field due to the significant loads that would have to be applied to balance the deformation of the roof and floor. The basis of the GRC modeling methodology, to estimate entry scale geology-dependent ground reaction curves, used in this study was developed by Esterhuizen et al. (2006, 2017, 2020), Barczak et al. (2008) and Tulu and Esterhuizen (2016).

The model includes the 2D slice of a cross-section along the gateroad entry. The 2D model employs actual immediate roof stratigraphy, using all the geological layers as thin as 4 in. The overburden layers are modeled as a strain-softening ubiquitous joint material, which simulates the bedding weaknesses in strongly bedded strata. Interface elements are used to model the interfaces between the geological layers in the overburden. The coefficient of friction of interfaces was set to 0.25. Joint shear stiffness was set according to recommendations in FLAC3D theory and background manual (Itasca, 2017). Primary and secondary bolts were simulated explicitly with the pile structural elements option in the FLAC3D, and bolt properties were assigned as shown by Tulu et al. (2012) and Esterhuizen and Tulu (2016). Different Longwall gateroad loading stages were simulated implicitly by the application of the stress boundary conditions at the top boundary of the model. The procedure demonstrated by Barczak et al. (2008) can be used to develop the ground response curves for each loading stage.

Procedures to determine the design criteria

The following procedures are followed to calculate each of the design parameters. The methodology proposed in this project can rationally quantify the mobilization of the dead weight with respect to GRC and estimate the uncontrolled convergence and maximum allowable convergence.

Ground Reaction Curve

The blue curve in Figure 7 represents the GRC derived for a Pocahontas No.3 geology and stress-state by applying internal pressure within the modeled entry and reducing this internal pressure gradually. The primary and secondary bolts were kept inside the excavation during the gradual reduction of the internal pressure. During the pressure reduction, convergence of the entry at a specific location, depending on the installation of standing supports, is computed.

Dead Weight Curve

The red curve in Figure 7 represents the dead weight of the detached roof. Mobilization of the dead weight during the deformation of the immediate roof strata was calculated from the height of the detached roof strata. Esterhuizen et al. (2020) estimated the height of the detached roof from the analysis of the extensometer data, and they indicated that a 1 in or larger separation within the immediate roof strata implies the detachment of the roof layers, and mobilization of the dead weight. During the development of the GRC, separation of the immediate roof strata is monitored up to 20 ft from the roof line. In Figure 8, point "R2" represents a grid point on the roof line and point "R1" represents a grid point 20 ft from the roof line. Separation of each layer can be calculated by computing the displacement of all the grid points on the line "R1R2" relative to point "R1." Height of the detached roof can be visualized as the distance from the roof line (grid point R2) to contour line representing 1-in layer separation of the strata. Dead weight of the detached strata was calculated by multiplying the specific weight of the rockmass with the volume of detached strata.

Uncontrollable Convergence

Barczak (2020) indicated that initially the slope of the ground response curve is linear (the blue section of the GRC in Figure 6). Deformations in this initial stage of the GRC are the result of the elastic response of the immediate roof, and pillar deformation that control overburden response. He also pointed out that no support systems can control this deformation, and he referred to this region of the GRC as "uncontrollable convergence." There isn't any direct way to measure uncontrollable convergence in the field. Therefore, immediate roof/floor deformation and pillar stress measurements are the best sources to interpret the uncontrollable convergence of an entry indirectly with the help of numerical analysis. The

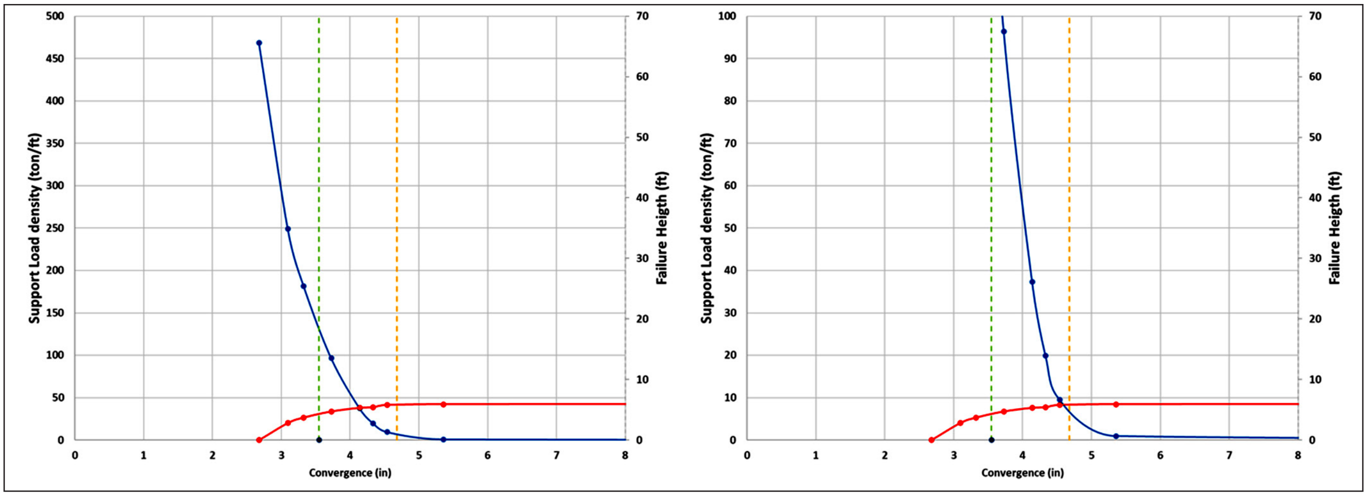

Figure 7. The ground reaction curve and dead weight curve for the Pocahontas No.3 seam based on a configuration of 2,000 ft of overburden and a 9.0-ft coal seam height.

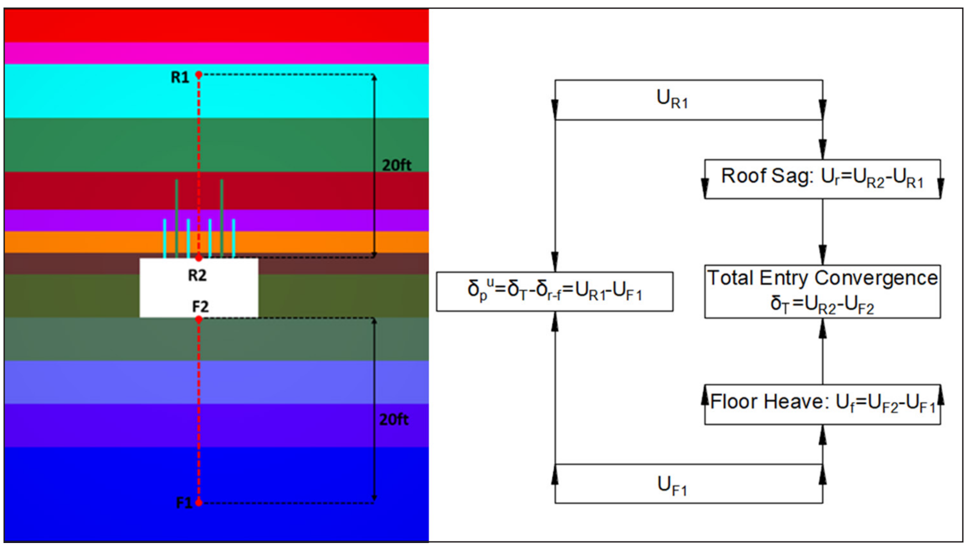

Figure 8. Entry scale model and deformation computations.

following procedures are used calculate the magnitude of the *uncontrollable convergence* (δ_u).

Roof deformation (u_r) will be calculated using Equation 1.

$$u_r = u_{R2} - u_{R1} \quad (1)$$

where; "u_{R1}" and "u_{R2}" are the vertical displacements of the points *"R1"* and *"R2"* in Figure 8. Similarly, floor heave "u_f" will be calculated using Equation 2.

$$u_f = u_{F2} - u_{F1} \quad (2)$$

where; "u_{F1}" and "u_{F2}" are the vertical displacements of the points *"F1"* and *"F2"* in Figure 8. Total convergence of the entry "δ_T" was calculated using Equation 3. Total convergence in Equation 3 includes the influences of the roof, floor and pillar deformations and includes both controllable and uncontrollable convergence. Convergence of the entry only due to the roof and floor deformations (δ_{r-f}) can be calculated using Equation 4.

$$\delta_T = u_{R2} - u_{F2} \quad (3)$$

$$\delta_{r-f} = u_r - u_f \quad (4)$$

Uncontrollable convergence due to the pillar deformation (δ_p^u) was calculated using Equation 5.

$$\delta_p^u = \delta_T - \delta_{r-f} \quad (5)$$

There isn't a simple equation for computing the contribution of elastic deformation of roof and floor strata to measured roof sag and floor heave. Therefore, uncontrollable convergence due to the elastic responses of the immediate roof and floor (δ_{r-f}^u) was estimated indirectly by querying the bedding plane separation (joint-tensile plastic strain) and slip (joint-shear plastic strain) of the model zones. Finally, the magnitude of the total *uncontrollable convergence* (δ^u) can be calculated using Equation 6.

$$\delta^u = \delta_p^u + \delta_{r-f}^u \quad (6)$$

Maximum Allowable Convergence

This parameter can be calculated analytically by finding the intersection of the ground response curve (blue curve in Figure 7) and the dead weight curve (red curve in Figure 7). After this point, the "Detached Block" design option of the STOP can be used to estimate the required support density to support the dead weight of the detached roof strata.

Analysis Using STOP's Ground Reaction Curve as a Design Criterion

For this example, we are using a ground reaction curve that is based on a numerical model of an isolated (inby the face) tailgate entry for the Pocahontas No. 3 Seam (Figure 7). The model used the lithology shown in Table 1. Note that this lithology has a sandstone member in relatively close proximity to the mine roof. This provides good anchorage for the bolts (cable bolts in particular) and in this case limits the roof failure height to just above the primary bolts. Higher depths of cover will also impact the results. The depth of cover used in the analysis was 2,000 ft.

Table 1. Geological profile simulated in the numerical model

Roof Lithology (ft)		
Layer	**Thickness**	**Material**
1	16.04	Sandstone-Strong
2	5.614	Laminated Sandstone
3	3.208	Dark Grey Shale
4	3.208	Dark Grey Shale
5	3.208	Dark Grey Shale
Roof Lithology (ft)		
Layer	**Thickness**	**Material**
1	6.416	Shale Gray
2	6.416	Shale Gray
3	16.04	Shale Gray
4	32.08	Sandstone - Strong

Using the ground reaction curve in Figure 7 and Eq.1 through Eq.6 to define the design criteria, the uncontrollable convergence of 3.55 in is computed from the roof sag, floor heave and entry convergence values queried from the model at the isolated tailgate entry. The uncontrollable convergence is attributed to elastic response of the overburden caused by the excessive deformation of the yield pillar in this deep mine. Uncontrollable convergence is displayed as the initial linear portion of the ground reaction curve and it occurs at a load density of greater than approximately 130 tons/ft. The maximum allowable convergence of 4.68 inches is computed from the intersection of the ground reaction curve and dead weight curve and represents the onset of detached block loading equating to a dead weight failure of approximately 6 ft.

The goal of the support design is to prevent a dead weight condition from occurring. A support load density then needs to be defined to derive the support strategy. The range of acceptable load densities is limited by the uncontrollable and maximum allowable convergences (as shown by the dashed green and gold lines in Figure 7). For this example, a conservative design load density of 36.4 tons/ft at 4.15 inches of convergence is selected for analysis, which falls near the middle of the range of acceptable load densities.

Using a double row of 30-in diameter pumpable support (Figure 1) for the analysis, a center-to-center spacing of 62.0 in will meet the design criteria of 36.4 tons/ft load density (Figure 9). While the

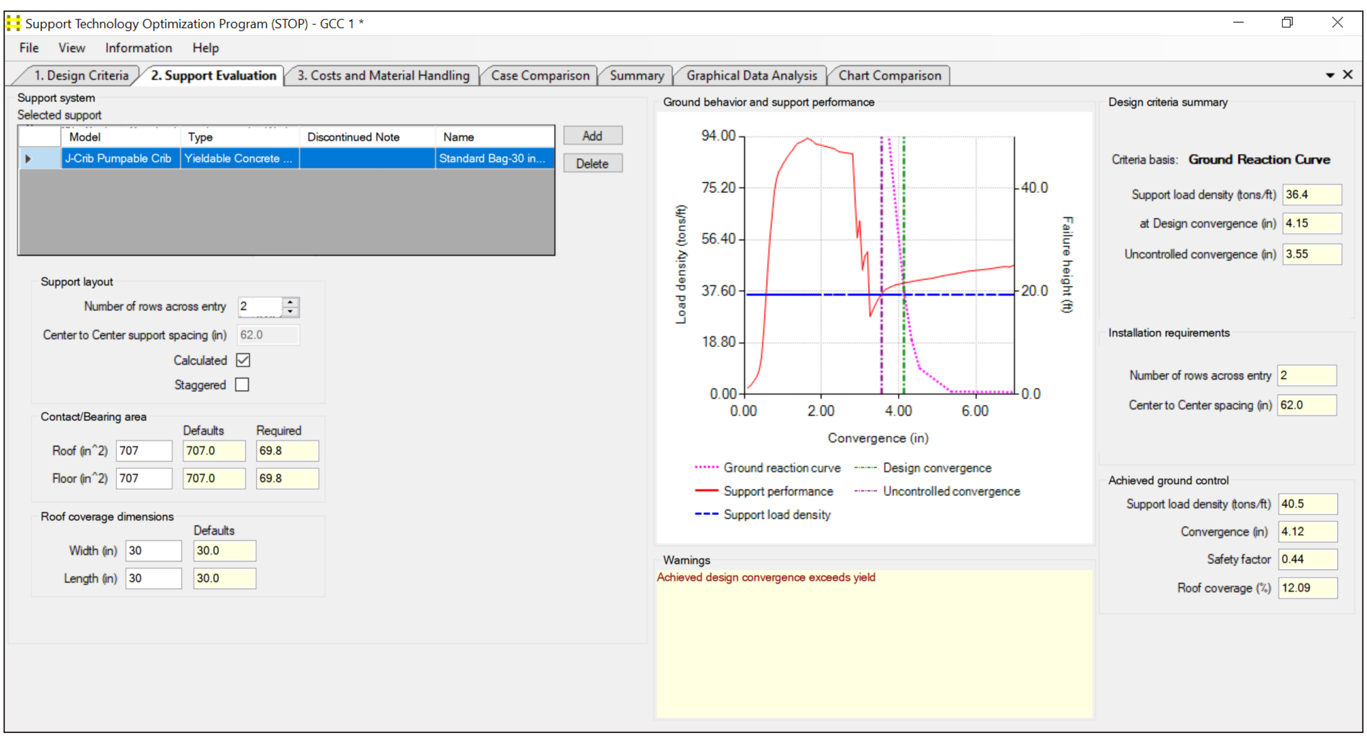

Figure 9. A pumpable crib provides the design criteria of 36.4 tons/ft established from the ground reaction curve.

center-to-center spacing of 62.0 in will meet the design criteria, notice that there is very little surplus support capacity, and with the nature of pumpable supports being inconsistent, this design would not be highly recommended and should be pursued with caution.

CONCLUSION

Advancements in roof support technology have been made over the years providing a multitude of new and improved roof support products. However, there will never be one widely used standard roof support that will be effective in all circumstances. The goal remains to match the support performance characteristics with the ground response. Evaluating several parameters such as stiffness, yield and peak load capacity, and residual load characteristics need to be examined when selecting a standing support system.

The STOP Version 4.0 is designed to analyze support designs to provide roof stability. STOP is a powerful tool for optimizing the standing support applications and providing a margin of safety in achieving roof stability. Since support characteristics are different for each support type, ground control engineers need to understand how the support performs and what degree of control it can provide to achieve roof stability. The upgraded STOP works to achieve that goal more efficiently and effectively.

As shown in the one analysis, the support system analyzed can provide a solution. The design criteria (36.4 tons/ft) used in this analysis is conservative. Additional analysis could be done at a less conservative design criteria (i.e. 25 tons/ft), but the recommendations in terms of support benefits are likely to be similar since the uncontrollable convergence is the primary driving factor here. Uncontrollable convergence is often an overlooked aspect of support design.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

Barczak, T.M. (2000). "Optimizing Secondary Roof Support Technology Optimization Program (STOP)" In: Proceedings of the 19th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 74–84.

Barczak, T.M. (2000). "NIOSH Safety Performance Testing Protocols for Standing Roof Supports and Longwall Shields" In: New technology for coal mine roof support. Mark C, Dolinar DR, Tuchman RJ, Barczak TM, Signer SP, Wopat PF, eds. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151; (IC 9453), 2000 Oct; :207–221.

Barczak, T.M., Esterhuizen, G.S., Ellenberger, J.L., Zhang, P. (2008)," A first step in developing standing roof support design criteria based on ground reaction data for Pittsburgh Seam longwall tailgate support." In: Proceedings of the 27th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp.349–359.

Brown, E.T., J.W. Bray, B. Ladanyi, and E. Hoek (1983). Ground response curves for rock tunnels. J. Geotech. Eng. 109, 15–39.

Dolinar, D., Gurley, H. (2009) "Evaluation of Tailgate Ground and Support Interaction in the Illinois Basin for the Development of a Ground Reaction Curve Based on Standing Support Design." In: Proceedings of the 28th International conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 30–37.

Esterhuizen, G.S., Barczak, T.M., (2006). Development of Ground Response Curves for Longwall Tailgate Support Design. In: Proceedings of the 41st U.S. Rock Mechanics Symposium. Golden, Colorado. ARMA's Golden Rocks 2006—50 Years of Rock Mechanics.

Esterhuizen, G.S., Gearhart, D.F., Tulu, I.B., (2017) "Analysis of monitored ground support and rock mass response in a longwall tailgate entry." In: Proceedings of the 36th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp.349–359.

Esterhuizen, G.S., Tulu, I.B., Barczak, T.M. and Dougherty, H., 2020, September. Ground Response and Support Interaction in Coal Mine Longwall Gateroads Subject to Changing Stress. In *54th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association. NIOSH (2020). STOP—Support Technology Optimization Program. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/mining/works/coversheet1819.html.

Esterhuizen, G. S., Tulu, I. B., and T. S. Bajpayee. "Application of a Brittle Failure Model to Assess Roof Stability in Coal Mine Entries." Paper presented at the 51st U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, California, USA, June 2017.

Tulu, I. B., and G. S. Esterhuizen. "Roof Collapse Modeling with FLAC3D." Paper presented at the 50th U.S. Rock Mechanics/Geomechanics Symposium, Houston, Texas, June 2016.