International Journal of Rock Mechanics & Mining Sciences 76 (2015) 55–67

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Influence of backfill on coal pillar strength and floor bearing capacity in weak floor conditions in the Illinois Basin

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ARTICLE INFO

Article history:
Received 6 April 2014
Received in revised form
22 November 2014
Accepted 28 November 2014
Available online 18 March 2015

Keywords:
Coal
Room and pillar
Backfill
Fireclay
Underclay

ABSTRACT

This paper discusses the current theoretical design equations associated with foundation design in the Illinois Basin, as well as the benefits of utilizing high density backfill in a numerical model, to improve pillar and floor stability. Based upon the results, Vesic's bearing capacity solution for a two layered soil tends to underestimate the true bearing capacity of a foundation, especially at higher friction angles and when footings are placed in close proximity. Minimizing the distance between adjacent foundations has shown an improvement in the ultimate bearing capacity of a foundation; however, placing the foundations in too close proximity has shown the foundations may behave as a single foundation and undergo appreciable settlement. A 10–40% increase in pillar strength and ultimate bearing capacity can be expected when a cohesive fill is used between 25 and 75% fill of the mined height, respectively. The non-cohesive nature of the simulated backfill showed little influence on increased pillar strength, even at higher fill ratios. It was determined, that as the shearing resistance, tensile strength and stiffness of the backfill are reduced, increases in coal pillar strength is due more to the confinement aspect of an underground mine rather than the strength properties of the material itself. A methodology for analyzing the plastic flow characteristics of a coal pillar and a footing using FLAC^{3D} has also been presented herein.

1. Introduction

This paper directly relates to the numerical investigation of an immediate weak floor, a coal pillar and the support consisting of backfill represented as a confining material. In particular, this study will focus on the Illinois Basin which consists of Illinois, Indiana and Western Kentucky. The Illinois Basin is major coal producer in the U.S. where nearly one hundred thousand short tons of underground coal were produced in 2013 [1]. This research was conducted mainly because of the ever-restrictive legislation posed on coal mines in the United States by the Environmental Protection Agency (EPA). More specifically, the EPA have proposed new legislation which is predicted to increase the conventional surface disposal cost for coal mines in the future [2]. Additionally, public opposition to surface waste disposal hinders the ability to obtain surface disposal permits in a timely fashion. Surface disposal is the primary means of coal waste disposal in the United States, therefore the most practical, but not yet cost effective option for the future, will probably be underground disposal of waste as the form of high density (paste) backfill [3]. In this case, coal waste can constitute either washing plant tailings or combustion by-products such as fly or bottom ash. Currently use of high density backfill is not a routine operation for underground coal mines in the U.S. but has been used quite regularly in longwall coal mines in Germany and Poland for several decades [3].

Further, this paper considers backfill disposal in underground coal mines located primarily in the Illinois Basin of the United States. Total mineable reserves for the Illinois Basin are estimated at nearly 14.4 billion tons [4]. More importantly, the majority of underground coal mines in the major mineable coal seams in the Illinois Basin are associated with a weak immediate floor termed underclay, fireclay or clay-stone which is very friable and variable in nature. Generally underclay has been studied and analyzed from the basis of soil mechanics because of its behavior to that of a clayey soil. Most importantly, underclay can cause serious instability issues in the short-term including pillar punching, loss of entry, pillar sloughing and roof problems and subsidence in the long-term [5]. This issue is typically mitigated via oversized pillars, which significantly results in reduced extraction in room and pillar mines.

Since no theoretical methods exist, to the authors' knowledge, regarding the design of such a scenario concerning the pillar, backfill

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http://dx.doi.org/10.1016/j.ijrmms.2014.11.011
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and immediate floor interaction, and deriving such a relationship would be impractical or rigorous at best; a heuristic approach with numerical modeling was deemed most appropriate to observe this problem. This paper will discuss the shortcomings of current and theoretical design equations associated with foundation design in the Illinois Basin and the potential benefits of utilizing backfill as a confining agent to coal pillars in a numerical model. The results are presented in a pragmatic and useable manner for future design.

2. Theoretical background

Classical foundations engineering credo is concerned with the satisfaction of two criteria: designing against shear failure in the soil and minimizing excessive displacements or settlement of the foundation. Shear failure is associated with the term of *ultimate bearing capacity*, which is the load per unit area of a foundation at which shear failure in the soil occurs [6].

Foundation design as a whole has been largely geared and implemented more in civil engineering practice than any of the other engineering sciences, and for good reason. However, situations arise in underground mining where the classical foundations principles and those same theoretical relationships are necessary for the design of underground foundations. This situation occurs in the Illinois Basin, where underground coal mines in the major mineable coal seams (i.e. Herrin, Danville and Springfield Seams) are underlain by a weak immediate fireclay floor.

To date, limited research has been conducted regarding the influence of the weak immediate floor in Illinois Basin Mines. This is surprising considering the influence weak floor has on pillar stability. The most recent work was presented by Gadde [5] in 2009, where he provided a comprehensive study of the underclay floor in the Illinois basin. Within his study he developed the Vesic–Gadde equation for use in design of Illinois Basin Mines and presented the most detailed, and practically useful, numerical modeling to date. The difference between this body of work and Gadde's work is that no research regarding backfill and its influence to pillar and floor strength was conducted. Multiple other researchers presented studies [7–14], but the majority of work all occurred prior to 1991. Although all of these studies collectively contain the majority of field and theoretical studies, Gadde's work in 2009 takes advantage of the advances in numerical modeling that have occurred since the earlier research. Gadde's work is therefore referenced multiple times throughout this paper and often compared. This is primarily for calibration purposes within the numerical modeling itself, as well as to present a second look at how results of similar models may differ when different users try to simulate the same problem.

2.1. Prandtl's semi-infinite homogenous bearing capacity approximation

Of the numerous theoretical approximations for foundation design, one of the earliest approximations is the Prandtl's approximation for a continuous foundation resting on a weightless semi-infinite homogenous soil. This can be expressed by:

$$q_{c-strip} = cN_C \tag{1}$$

where c is the soil cohesion and N_c is the normalized bearing capacity factor for cohesion which is based on the effective friction angle of the soil. As stated by Gadde [5], these factors, excluding the shape correction factor for cohesion (s_c), are either negligible for a real coal mine scenario, in the Illinois Basin, or are often difficult to obtain, and are often times not considered in calculations. This is because these factors only cause an under-estimation of the bearing capacity of as little as 10% and, for example, the inclination factors play little role in the bearing capacity as most coal seams in the U.S. are relatively flat lying. In contrast to Prandtl's approximation for a strip footing shown in Eq. (1), underground foundations are generally square or rectangular and a more applicable design equation is the shape-corrected Prandtl solution shown in Eq. (2). The approximation for the bearing capacity of a footing with length and width resting on a semi-infinite soil can be approximated as:

$$q_{floor} = cN_C s_c \tag{2}$$

where s_c represents the shape-correction factor dependent on the footing dimensions, N_q and N_c.

2.2. Vesic's non-homogenous bearing capacity approximation

One of the disadvantages of Prandtl's solution is that actual mining pillar foundations are not semi-infinite and homogenous in extent. There exists some non-homogeneity of the floor underlying a coal pillar (i.e. multiple layers). Vesic's [15] approximation for a non-homogenous soil is therefore more appropriate for design purposes, and is expressed by:

$$q_{floor} = c_1 N_m \tag{3}$$

For the most part, Vesic's approximation has been the most popular methodology for pillar design in the Illinois Basin for years and is used as the method for governing approval purposes. This may not be the best approach; bearing in mind this approximation is only valid when [5]: no adjacent footings/pillars exist, angle of internal friction of both layers is zero, does not consider c-phi soils (cohesive and frictional soils), both soil layers are homogenous, does not consider different aspect ratios of the footing (square, rectangular and strip), does not consider two layered soils, is only valid for failure criteria of the Mohr–Coulomb model and when no volume change/dilation occurs in the post-failure state.

2.3. Effect of adjacent footings

The majority of fundamental theoretical approximations for bearing capacity don't consider the influence of an adjacent footing on the calculated bearing capacity. This has been widely researched in foundations engineering with the pioneering research being conducted by Stuart [16]. Within his study he considered two continuous rough footings within close proximity on granular soils. He determined that a reduction in spacing of adjacent footings may not only increase the ultimate bearing capacity of the footing but can also negatively cause an increase to the settlement in that region, if spaced too closely together. He further defined an interference coefficient that showed an increase at close spacing and a decrease with increasing distance. Multiple other studies formed similar conclusions [17–24].

2.4. Gadde's research

To better represent a realistic coal mine scenario, Gadde [5] developed an adaption to Vesic's approximation, known as the Vesic–Gadde approximation. Gadde's work is fairly new to the industry; but it is gaining popularity as it is geared for foundation and pillar design where a weak immediate floor is present, and was developed based off numerous field studies conducted in the Illinois Basin. Ultimately, Gadde's work found that the Vesic–Gadde approximation was a much better predictor for floor bearing capacity conditions in the Illinois Basin than any of the *de facto* approximations, including Vesic's. The Vesic–Gadde solution is expressed in the similar form as Eq. (3); however, the cohesion of the immediate and