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Numerical Approach to Predict the Strength of St. Peter Sandstone Pillars acted upon by Vertical Loads– A case study at Clayton, IA, USA.

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Abstract: - Estimation of pillar strength is an important part of assessing the stability of pillars used in mines. Previous studies conducted to estimate the strength of St. Peter Sandstone using empirical approach proved not adequateas a result of very little room and pillar underground development at the time. In this study, numerical models using finite difference code are used to predict the strength of St. Peter Sandstone pillars under varying overburden loads. A stable pillar case with dimension of 12.192 m × 12.192 m ×9.144 m, and room width of 10.3632 m is considered for this study.The relevant input parameters are discussed.Stress-strain behavior of the pillars acted upon by varying overburden loads are also presented. Based on the peak stress from the stress-strain plots, an empirical-based pillar strength formula is developed for St. Peter Sandstone. From this formula, a relationship has been established to define the maximum overburden depth for which a pillar will remain stable. For instance, for safety factors of 1.5 and 2, the maximum overburden covers should be no more than 80 mand 59 m respectively.The results is valid for a stable pillar case whose life is over 60 years.

I. INTRODUCTION

The United States is among the top ten largest producer of natural gas in the World. Hydraulic fracturing has been the key method of extraction of unconventional oil and gas resources in the United States. This technology employs hydraulically fractured sand (usually called frac sand) which keep the cracks open so that natural gas can flow freely into wells. Recently, demand for hydraulically fractured sand has increased as a result of ongoing and increased exploration and production of natural gas from deep shale formations in the United States. The high demand of hydraulically fractured sand by the US oil and gas industries, have prompted the development and expansion of mining industries to meet its production requirements.

Among other formations, hydraulically fractured sand is primarily produced from St. Peter Sandstone in North America. The surge of hydraulically fractured sand has led to increased production capacitiesof mining industries exploiting St. Peter Sandstone deposit. In most cases, St. Peter Sandstone is mined using open pit surface mining technologies and dredging. Nevertheless, where the cost of removing the overburden material becomes too expensive, room and pillar underground mining method has been used to extract this flat lying deposit. This formation is unique in the sense that it is friable and possess almost zero cohesion. Additionally, it has extremely high friction angle of up to 69^{o}. These unique properties make underground extraction very challenging.

Peterson's empirical pillar design method for St. Peter Sandstone was limited due to inadequate room and pillar underground developmentsat St. Paul, MN [1]. Until now, pillar design approach based on numerical methodshave never been studied on St. Peter Sandstone despites its advantages. Numerical methods considernumerous and complex geometric and geological variables which affect pillar stability.

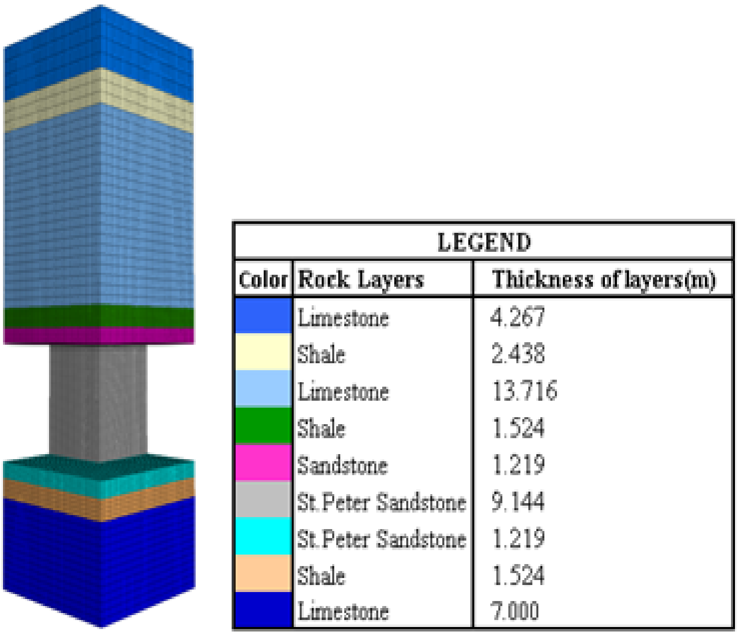
Field surveys have revealed successful stable pillar sizes used in Clayton, IA. In order to adapt any pillar size, it is important to analyze the stability of each pillar. Theoretically, pillar stability can be analyzed using its safety factor. The safety factor of pillars is defined as the pillar strength divided the pillar stress.The focus of this paper, is to develop an empirical formula to estimate the strength of St. Peter Sandstone pillars under varying overburden depths using numerical methods.Estimation of the pillar strength is an important part of assessing pillar stability as far as health and safety of workers is concerned. A stable pillar case with dimension of 12.192 m × 12.192 m ×9.144 m, and room width of 10.3632 m is considered for this study. Based on the pillar strength function, a relationship is established between the pillar stress and the pillar factor of safety. This function is then used to estimate the maximum overburden weight the pillar can carry to attain the expected factor of safety. The overburden load on the pillar is a function of the overburden depth by the unit weight of the rock. The outcomes are expected to assist in effective room and pillar mine planning at St. Peter Sandstone Mines in the United States.

II. NUMERICAL MODELLING

Fast Lagrangian Analysis of Continua in three dimensions (FLAC 3D) was used to simulate pillar, floor and roof rock strata. FLAC 3D software is a finite difference numerical code developed by Itasca Consulting Group. The software is capable of modelling elastic and strain softening behavior of rocks using elasto-plastic constitutive law. The model geometry, in-situ stresses, input data, and modelling procedure are described in this section.

2.1 Model Geometry and Grid Generation

The models were set up to simulate a single pillar. FLAC 3D was used to create models of St. Peter Sandstone pillars with dimensions of 12.912 m × 12.12.192 m × 9.144 m. The room width is set to be 10.3632m. These pillar and room dimensions have been used successfully in abandoned St. Peter Sandstone mine in Iowa. In the analysis, onlyone-quarter of the pillarand half of the room width were modelled to take advantage of symmetry conditions.In order to reduce computational time, only five overlying strata typical in the study area are included in the geometric models. The thickness of the various overlying strata are as shown in Figure 1.1.



LEGEND		
Color	Rock Layers	Thickness of layers(m)
🟦	Limestone	4.267
🟨	Shale	2.438
🟦	Limestone	13.716
🟩	Shale	1.524
🟪	Sandstone	1.219
⬜	St.Peter Sandstone	9.144
🟦	St.Peter Sandstone	1.219
🟧	Shale	1.524
🟦	Limestone	7.000

Figure 1.1 A FLAC 3D quarter Model and mesh used to simulate pillar, roof and floor strata.

2.2 Estimation of Input Parameters

The mechanical strength properties of the pillar, roof and floor rock were obtained from laboratory testing and literature [1]. The average uniaxial compressive strength tests of St. Peter Sandstone, sandstone, shale and limestone were conducted at Missouri University of Science and Technology rock mechanics laboratory. In the absence of field measurements, Hoek and Brown's empirical formula [2] was used to estimate the modulus of deformation of the rock masses involved in this study. Hoek and Brownrelated modulus of deformation, E_m(in GPa), to the uniaxial compressive strength, $\sigma_{c,}$ (in MPa) and the Geological Strength Index (GSI), using equation (1). Based on the quality of St. Peter Sandstone, sandstone and limestone, GSI of 42.5, 70, and 75 were assumed respectively for St. Peter Sandstone, sandstone and limestone.

Literature reveals that St. Peter Sandstone is friable possessing almost zero cohesion and has friction angle of up to 69°[3]. A friction angle of 60° was assumed for St. Peter Sandstone. Presently, it is unknown the estimated value of cohesion for St. Peter Sandstone. The equivalent cohesion of St. Peter Sandstone was estimated using Hoek and Brown's empirical equation [4]. Equation (2)relates the uniaxial compressive strength of intact rock to the cohesion and friction angle [4]. Where, θ is the friction angle, and c, is the equivalent cohesion. The tensile strength of the rock was assumed to be one-tenth the uniaxial compressive strength of intact rock. Table 1.1 summarizes the physical and mechanical properties of the rock mass.

$$E_m = \sqrt{\frac{\sigma_c}{100}}\,10^{\frac{(GSI-10)}{40}} \qquad (1)$$

$$c = \frac{\sigma_c(1-\sin\theta)}{2\cos\theta} \qquad (2)$$

Table 1.1 Physical and Mechanical properties of rock mass

Parameter	St. Peter Sandstone	Sandstone	Limestone	Shale
UCS (MPa)	5.4	52	76	4.02
Density(Kg/m^3)	2030	2245	2563*	2100
Bulk Modulus (GPa)	0.558	11.5	24.5	0.313
Shear Modulus (GPa)	0.717	9.7	14.7	0.341
Cohesion (MPa)	0.72	-	-	-
Residual cohesion (MPa)	0.20	-	-	-
Friction angle(degrees)	60	-	-	-
Residual Friction angle (degrees)	50	-	-	-
Tensile Strength (MPa)	0.54	-	-	-

*[1]

2.3In-situ Stresses

In this study, the pillars were loaded by the weights of the overlying strata. The overall vertical stress on the pillar is the summation of the unit weights of the rocks overlying the pillar multiplied by their respective thicknesses. The average unit weight of the rocks (γ) is assumed to be 0.025 MN/m^3. Additional external vertical loadswerealso applied at the top of the pillar to take care of the weights of the overlying rocks not included in the models.The external load applied on the model is the difference between the designed stress on the pillar and the overall vertical stress on the pillar.Horizontal stresses in both x and y directionsare assumed to be same and equal to 1.5 times the vertical stress.The vertical stress and horizontal stresseswere estimated respectively using equation (3) and (4). Where σ_z isthe vertical stress in the z direction; $\sigma_x$and σ_y are the horizontal stress in the x and y direction respectively;H is the depth of the overburden materials.

$$\sigma_z = \gamma H = 0.025\, H \qquad (3)$$

$$\sigma_x = \sigma_y = 1.5\, \sigma_z \qquad (4)$$

2.4Numerical Modelling Procedure

Estimation of the strength of St. Peter Sandstone pillar can be determined in a way similar to laboratory determination of uniaxial compressive strength of intact rock.The failure criteria chosen for the pillar rock is strain softening constitutive model. Using strain softening model, the cohesion and friction angle are reduced using a user defined piecewise linear function. Elastic model was chosen for roof and floor strata. Details of the material properties for the pillar, roof and floor strata are presented in Table 1.1.

Vertical and horizontal stresses applied are as discussed in section 2.3. The model was initially stepped to equilibrium to allow the kinetic energy of the mesh to damp out and to generate in-situ stresses within the model. In order to determine the strength of the pillar (the ultimate load-bearing capacity per unit area of the pillar), the model was subjected to increasing vertical loading by applying a constant velocity on top of the model. The magnitude of the velocity is 10^{-5} m/s. The displacement of the four vertical symmetry planes of the model are restricted in the normal direction, and the bottom of the model was fixed to restrict movement in the vertical direction. The average vertical stress in all the pillar zones and the mean vertical strain in the pillar were defined and monitored using an internal programming language in FLAC 3D. The axial strain in the pillar was computed as the mean roof-to-floor displacement over the entire pillar area divided by the pillar height.

2.5Modelling Results

Figures 1.2 and 1.3 show average stress strain behavior of a single pillar acted upon by varying overburden depths. The peak vertical stress on the stress-strain plots represent the pillar strength.The average pillar stress was computed using tributary area theory (equation (5)) [5]. Where w, is the pillar width; l is the room width; H, is the depth of cover. The pillar strength can be estimated using equation (6)). Equation (6) was developed based on the best fit graph of pillar strength and pillar stress as shown in Figure 1.4. Safety factor (Equation (7)), of the pillar is defined as the pillar strength divided by the pillar stress. A function is also defined to relate the factor of safety to the pillar stress by the best-fit graph shown in Figure 1.5. Table 1.2 summarizes the results of the numerical model, pillar stress and safety factor based on the depth of the overburden cover.

$$\text{Pillar Stress} = \sigma_p = 0.025\text{H}\frac{(\text{w}+\text{l})^2}{\text{w}^2} \qquad (5)$$

$$\text{Pillar Strength} = 9.1746\,\sigma_p{}^{0.0456}\,(6)$$

$$\text{Safety Factor} = \text{F} = \frac{\text{Pillar Strength}}{\text{Pillar Stress}} = 9.1746\sigma_p{}^{-0.954} \qquad (7)$$

Table 1.2Summary of Model Results.

Depth of Cover (m)	Pillar Stress (MPa)	Pillar Strength (MPa)	Factor of Safety
22.86	1.96	9.55	4.88
30.48	2.61	9.67	3.71
45.72	3.91	9.58	2.45
56.39	4.82	9.75	2.02
60.96	5.22	9.62	1.84
76.20	6.52	9.93	1.52
91.44	7.82	10.39	1.33
106.68	9.13	10.53	1.15
121.92	10.43	10.19	0.98
137.16	11.74	10.48	0.89
152.40	13.04	9.90	0.76

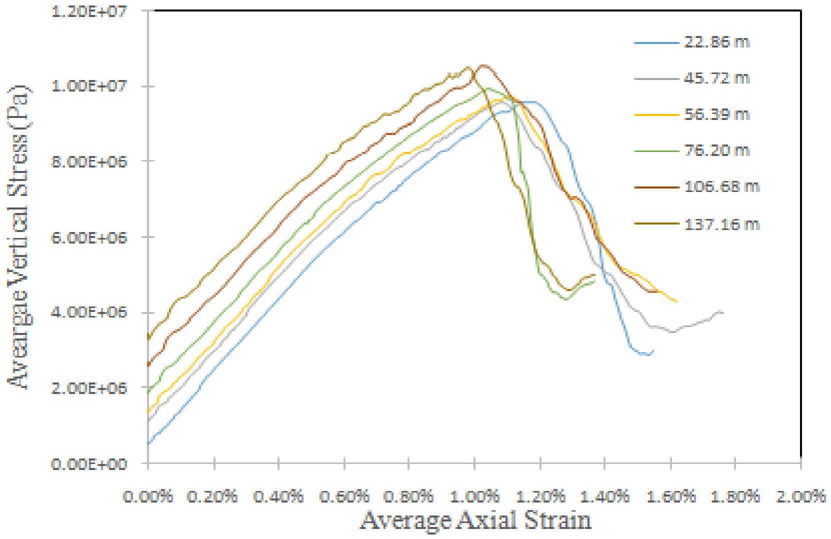


Figure 1.2. Stress-strain behavior of St. Peter Sandstone pillars for overburden depthsof 22.86 m, 45.72 m, 56.39 m, 76.20 m, 106.68 m and 137.16 m

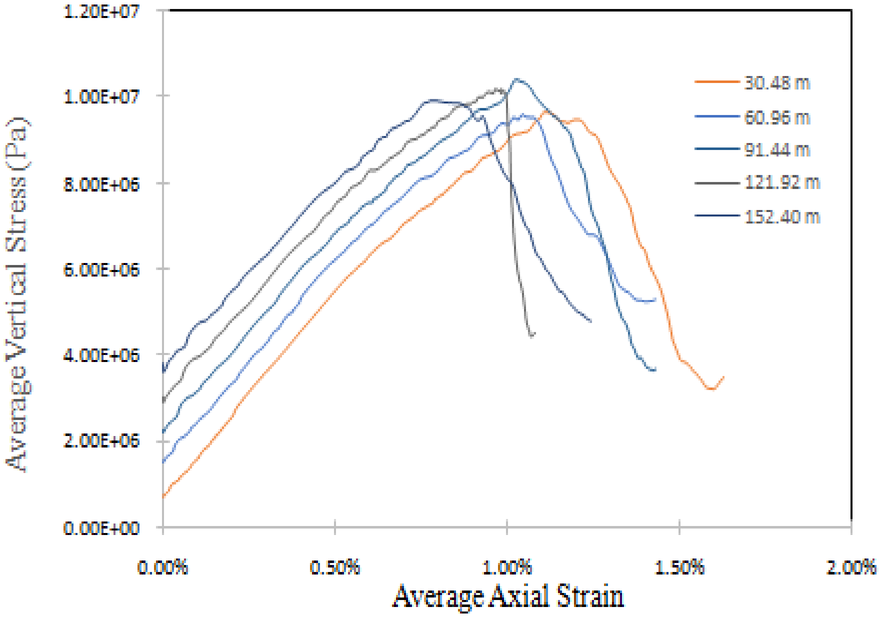


Figure 1.3.Stress-strain behavior of St. Peter Sandstone pillars for overburden depth: 30.48 m, 60.96 m, 91.44 m, 121.92 m, and 152.40 m.

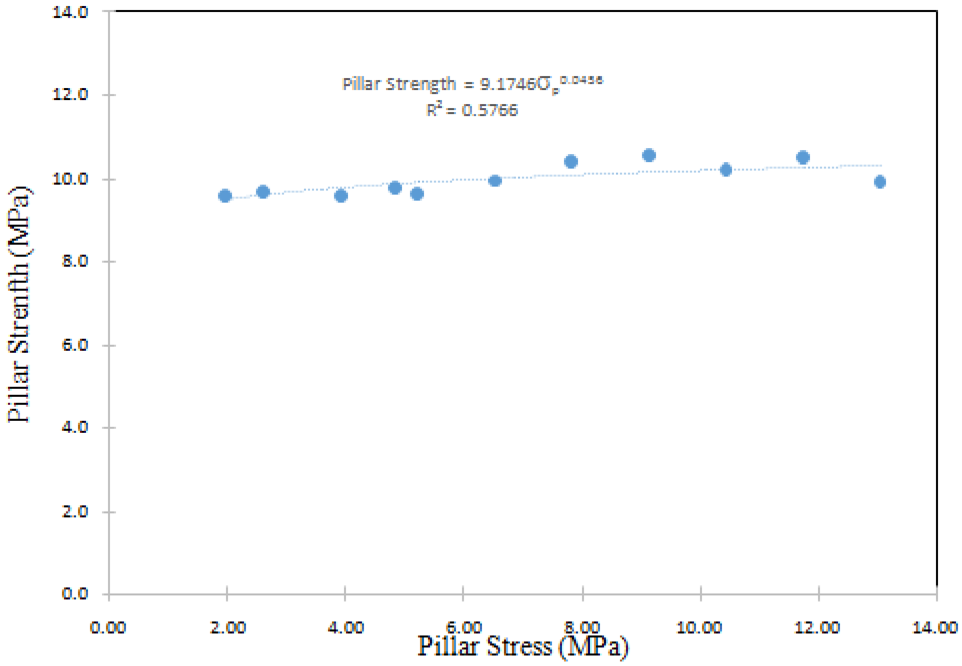


Figure 1.4Correlation between pillar strength and pillar stress

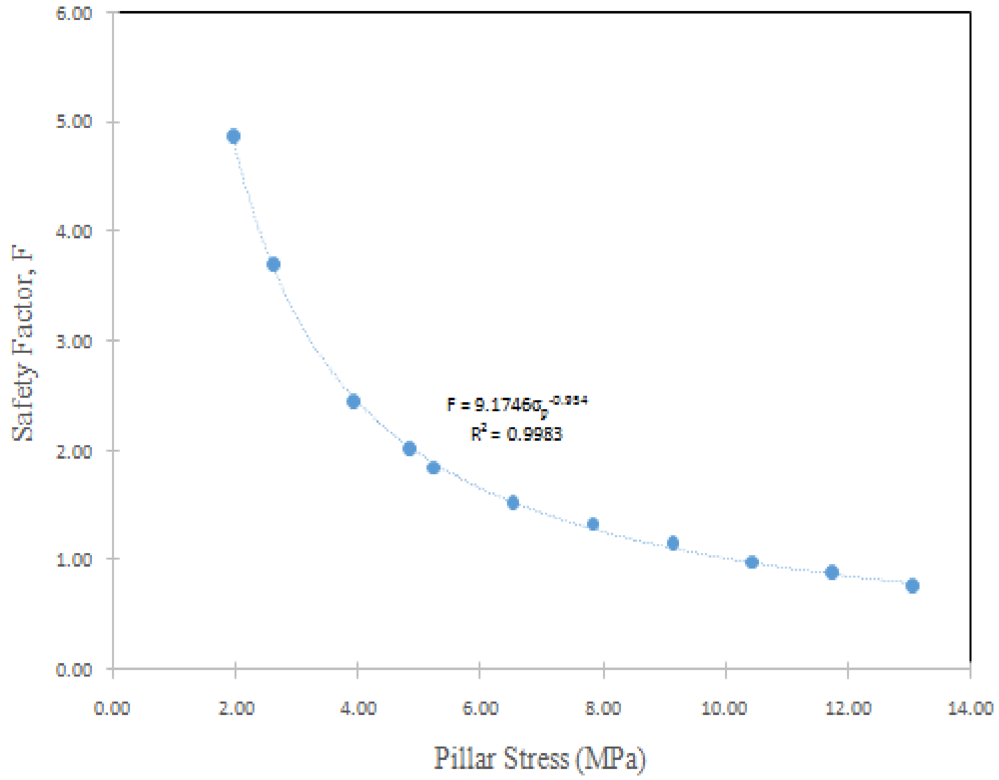


Figure 1.5Correlation between Safety factor and pillar stress

Figure 1.6A 12.192 square meter pillar size and 9.144 m high; room width of 10.36 m; pillar life is over 60 years; overburden depth is 57 m.

III. DISCUSSIONS AND CONCLUSIONS

Using numerical models, the average peak stress which represent the pillar strength can be obtain from stress-strain behavior of pillars. Stress strain behavior of pillars can be used to assess the stability of pillars. From the stress-strain curves shown in Figure 1.2 and 1.3, it is evident that the pillar shows signs of instability when the overburden depth is greater than 106.68m. Above this depth, the safety factor of the pillar falls below 1.0. A safety factor less than unity means that the average stress imposed on the pillar exceeds the pillar strength, hence pillar failure. For example, in Figure 1.3, where the overburden was 121.92 m (i.e. > 106.68 m), a sudden pillar failure occurred because the safety was less than 1 (F = 0.98). The results of the model has been used to develop an empirical formula to estimate the pillar strength presented in equation (6).

Also, from this study, an empirical formula (equation (7)) has been developed to relate the safety factor to the pillar stress. Based on this equation (7), a maximum overburden depth can be predicted for an expected safety factor necessary for pillar stability. The overburden depth relates the pillar stress as given in equation (5). For instance, if the pillar and room dimensions considered in this investigation is expected to have a safety factor of 1.5, 2, 2.5 and 3, then the maximum overburden cover should be no more than 80 m, 59 m, 47 m, and 38 m respectively.

A stable pillar case with room and pillar dimensionssimilar to that of Figure 1.6 (pillar life >60 years)has been analyzed. From the analysis, the pillar has a safety factor of 2.02, which justifies the pillar’s stable condition after 60 years.

Numerical models can be used to estimate pillar strength. However, the accuracy of numerical models depend on the accuracy of the input parameters. In this study, a number of input parameters have been assumed. The results of this study is limited to these assumptions. For realistic numerical models, field measurements in the pillar, roof and floor strata are necessary.

IV. ACKNOWLEDGEMENTS

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