Analysis of Floor Stability in the Illinois Basin Underground Coal Mines (AFSIL)

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The Pavilion of the city of Marion, IL

Why Study Floor Stability?

- All major coal seams in the IL Basin have weak immediate floor materials
- Required at the permitting stage
- During mining
- Subsidence after mining

Central Issues

- How do we estimate the strength or load bearing capacity of the floor?
- What is the stress state or load on the floor?
- Does the stress exceed strength?
  - Should we connect stress and strength via a stability factor? Do we use different stability factors for short-term vs. long term stability? If yes, how do we obtain those numbers?

How do we find answers?

- Several approaches
- Strength estimation can be done using complex numerical modeling tools or simple soil mechanics based bearing capacity models or large-scale in-situ tests
- Load estimation can also be made using numerical models or simple equations like the popular “tributary area” method

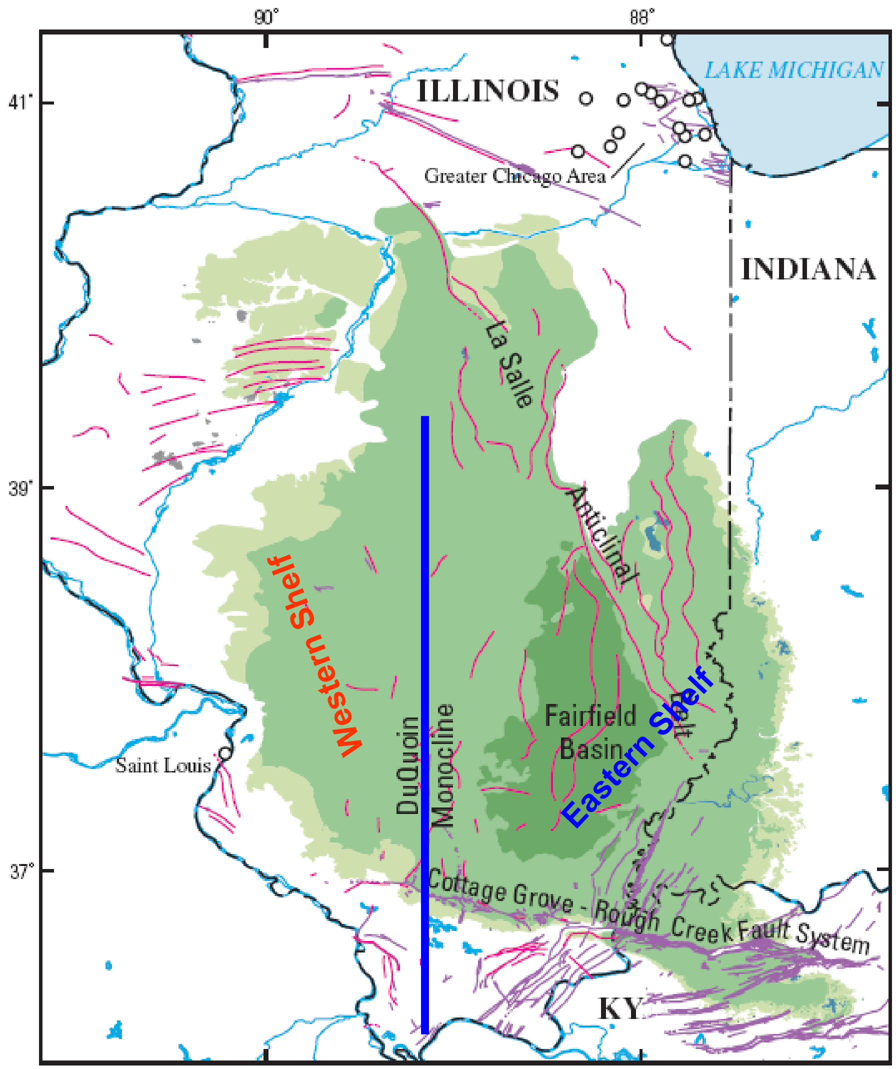
Floor Strength - Multiple Factors

- In contrast to the average stress estimation, determination of floor bearing capacity is lot more complex and several variables need to be considered:
  - geology of the underclay/claystone and rock units below
  - “nature” of the floor revealed by laboratory properties
  - In-situ plate bearing tests as a means to estimate the immediate floor cohesion
  - Strength of main floor
  - Simplified soil mechanics models
  - Back analysis against actual cases of floor instability and stability
  - Advanced numerical models when the geo-mining conditions are complex

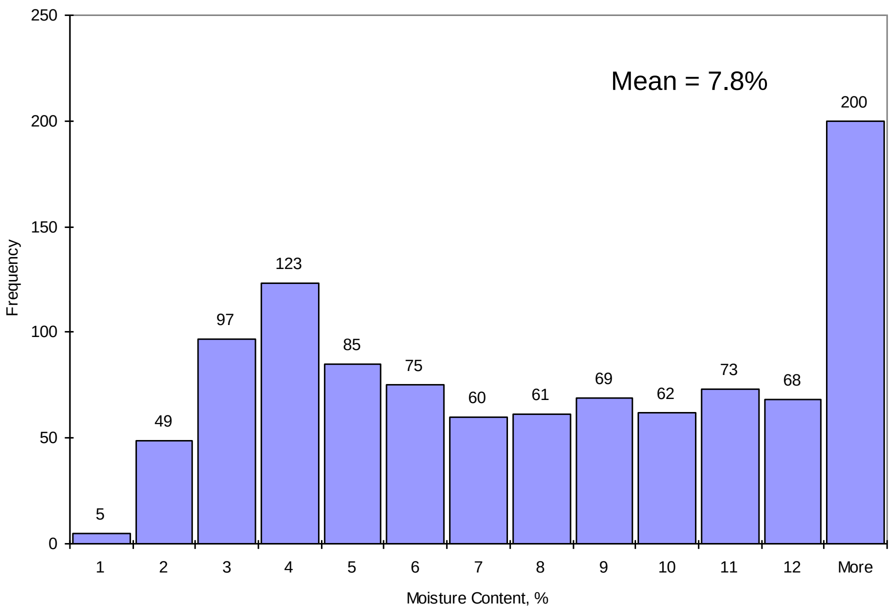
Design Methods

- Vesic-Speck method is currently popular
- AFSIL is based on large databases of laboratory and in-situ testing as well as case histories

The current "one-size-fits-all" approach may not be adequate

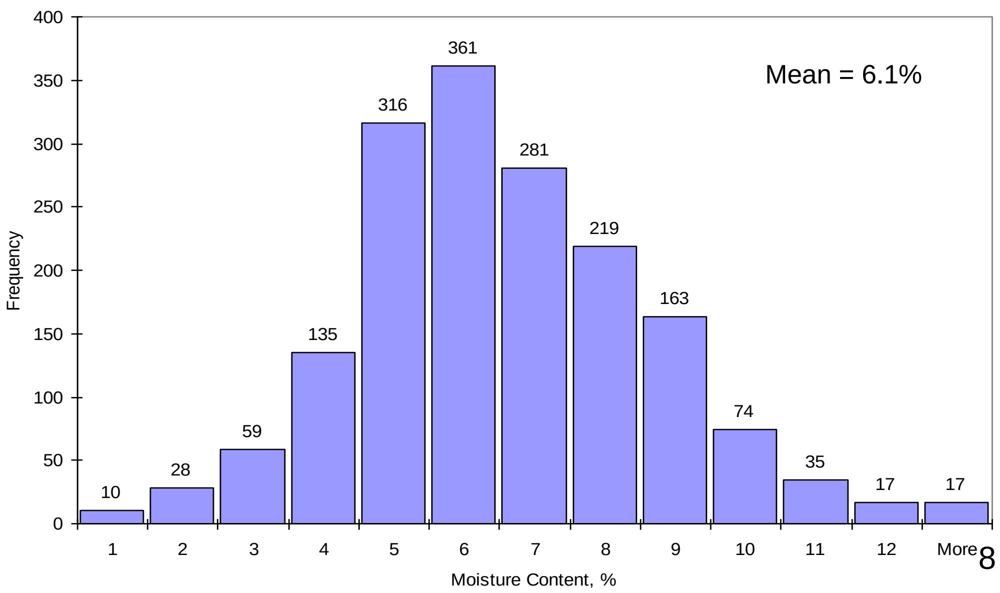


6 Seam – moisture content

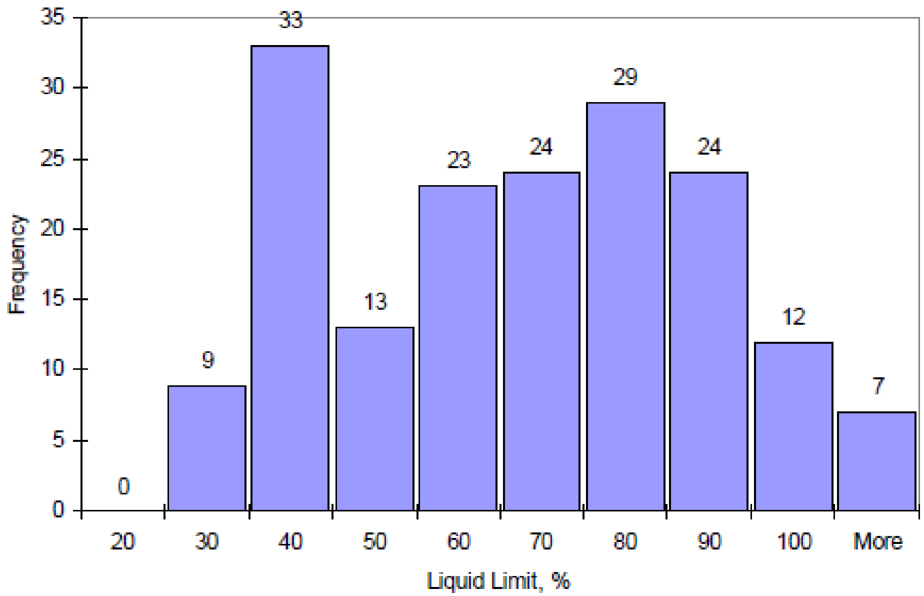


Western Shelf

Eastern Shelf

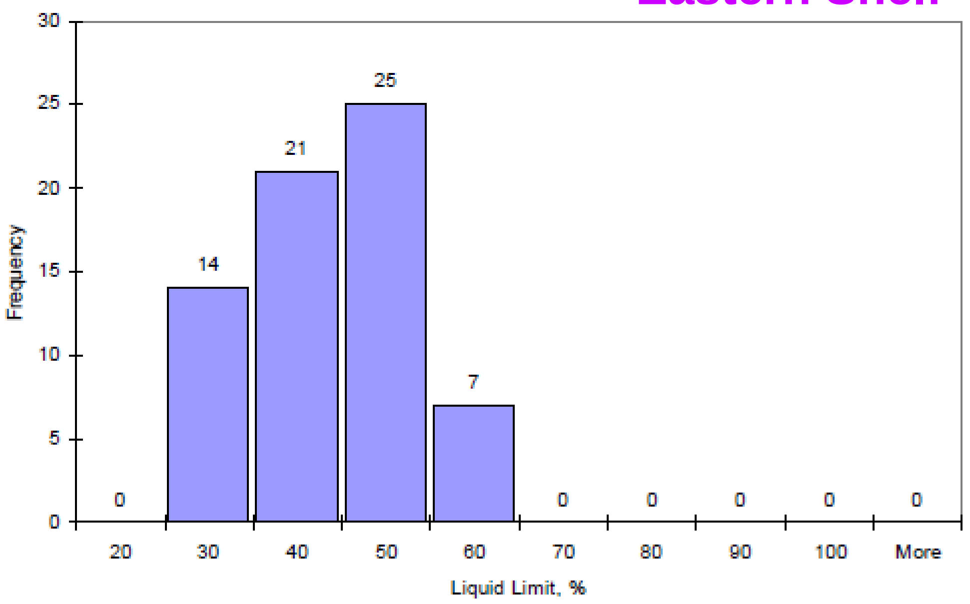


6 seam– Atterberg Limits

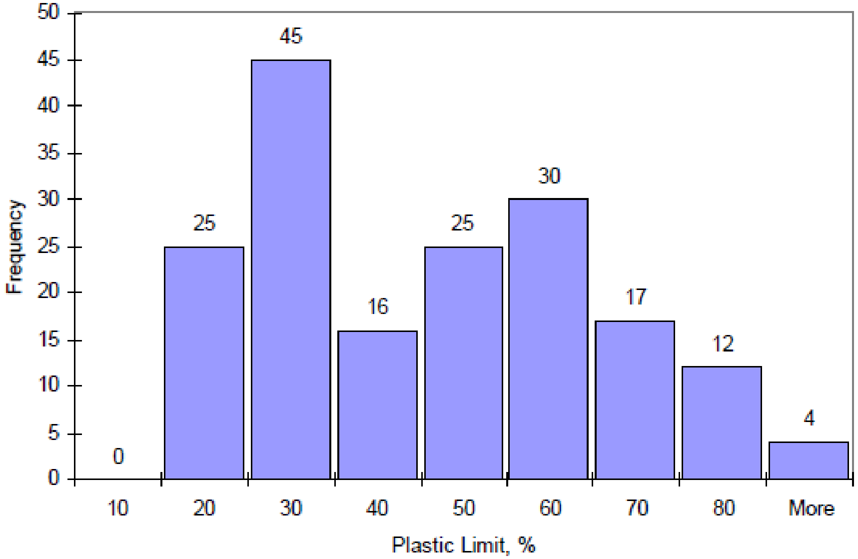


Western Shelf

Eastern Shelf

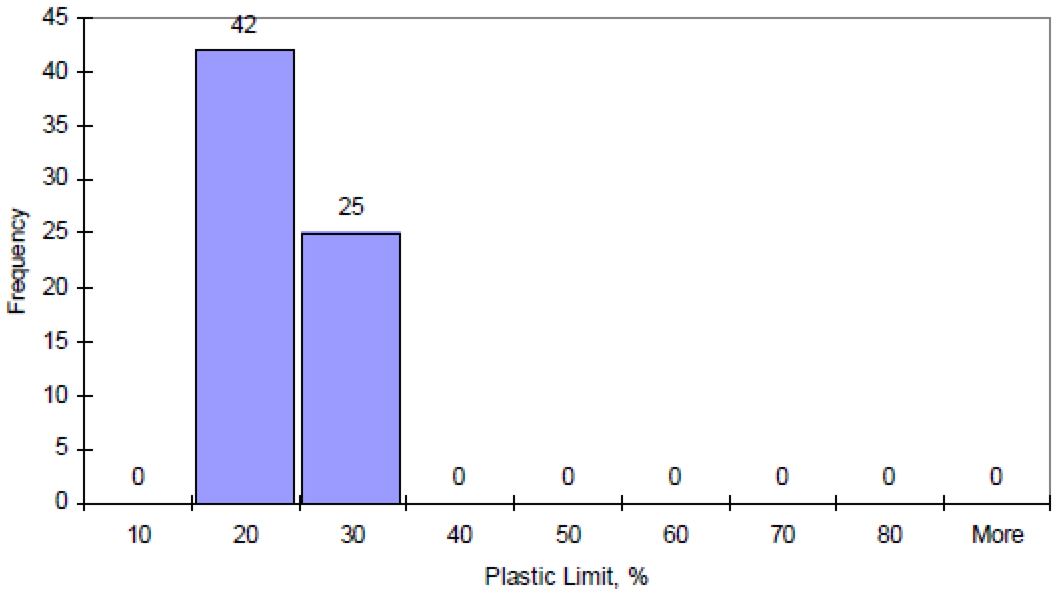


6 seam – Atterberg Limits



Western Shelf

Eastern Shelf

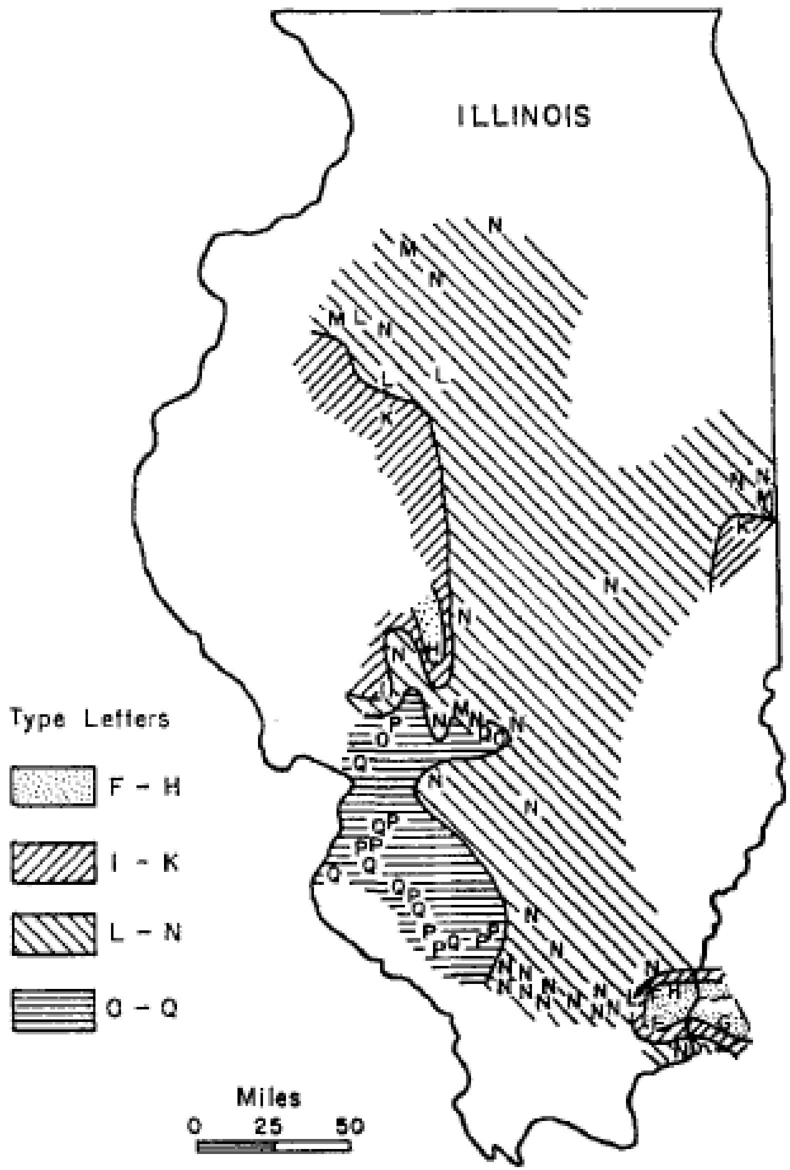


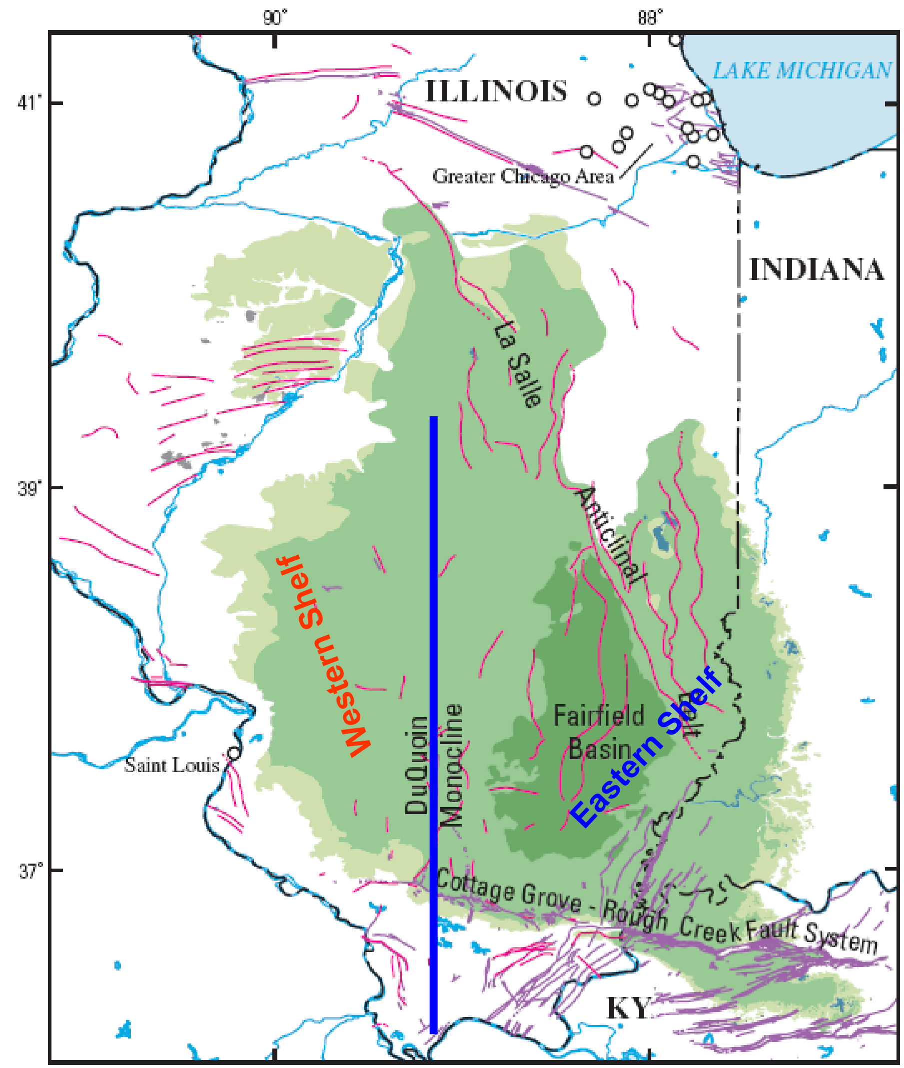
Eastern and Western Shelf Atterberg Limit Data

Location	6 Seam Average Values		
	Liquid Limit	Plastic Limit	Plasticity Index
Eastern Shelf	39	19	19
Western Shelf	63	42	22

Location	5 Seam Average Values		
	Liquid Limit	Plastic Limit	Plasticity Index
Eastern Shelf	31	17	14
Western Shelf	30	17	13

The two shelves of the Basin



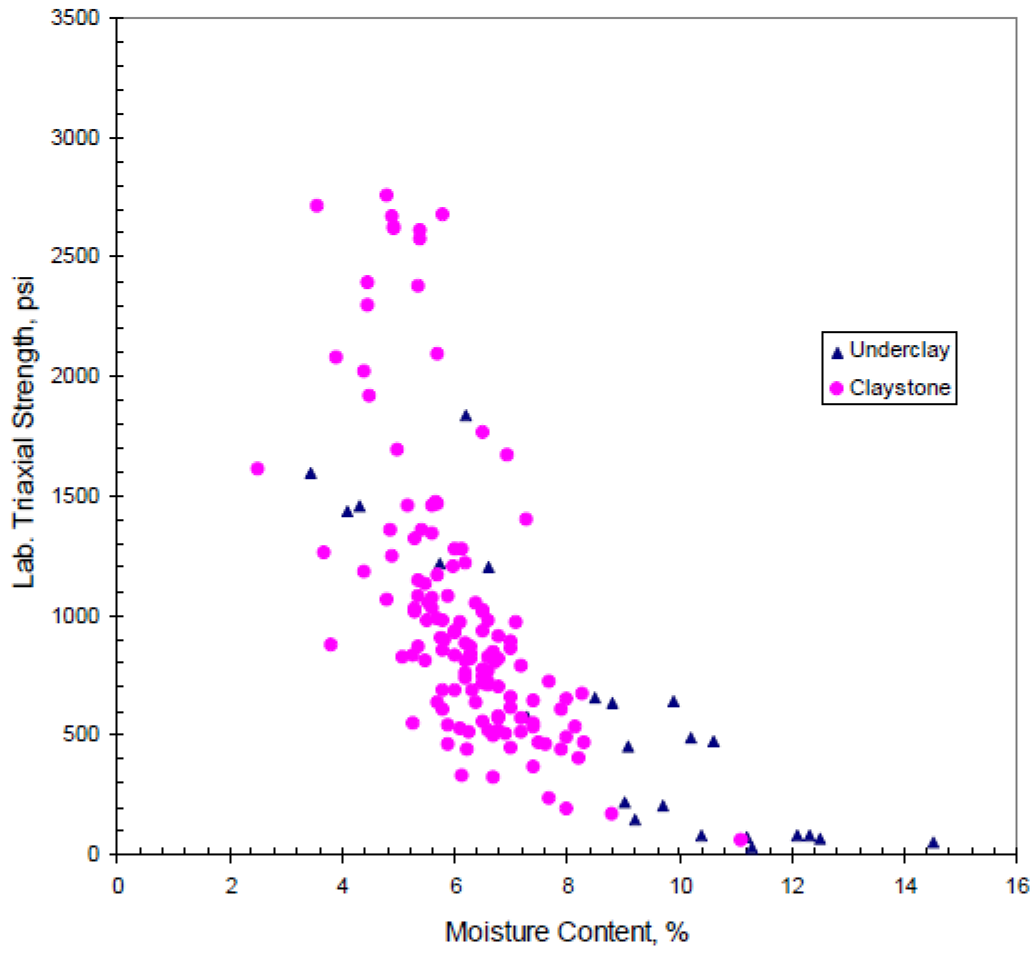


US 51 in IL can be used to delineate the two shelves

Speck's Equation

- Based on laboratory triaxial strength tests
- 23 tests on "underclay" done at 300 psi confining pressure
- Data doesn't shown any significant difference between "underclay" and "claystone"

Original Speck's Data



Speck's Equation

- From the laboratory triaxial strength tests

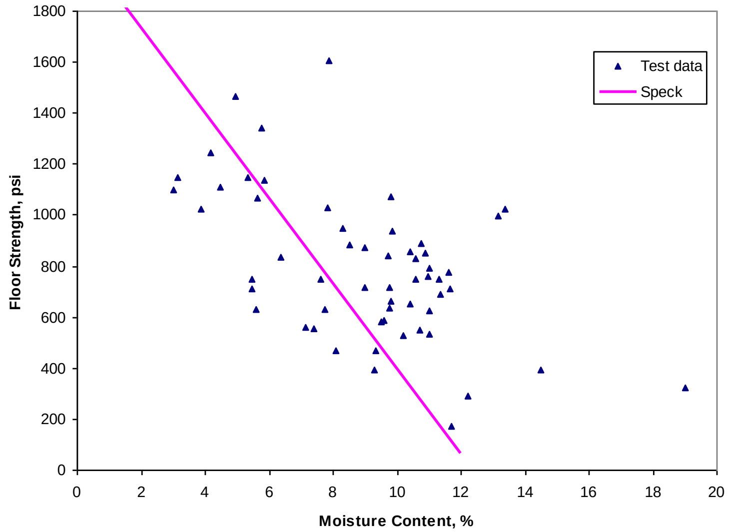
  $$q = 2070 - 167\ MC$$

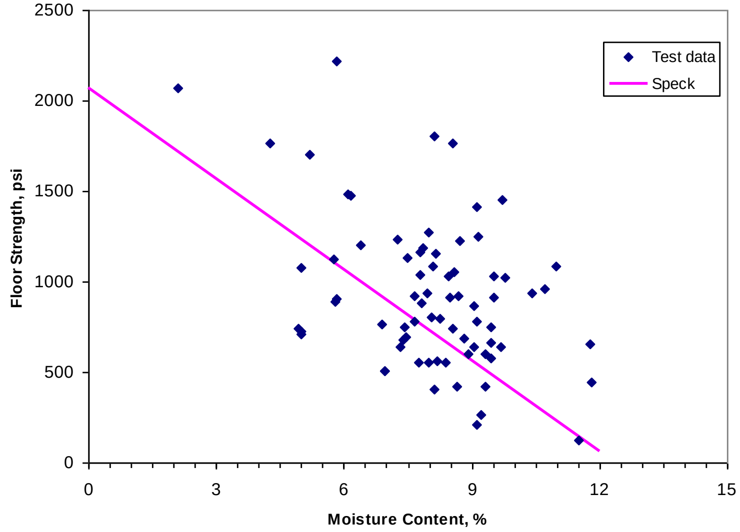
- To compute the weak bed cohesion, a correction factor of 0.15 was recommended based on a handful of plate tests at two Zeigler mines around Decatur, IL
- Speck's equation does not give cohesion, strictly speaking
- Recommended a constant 248 psi value for strong bed cohesion

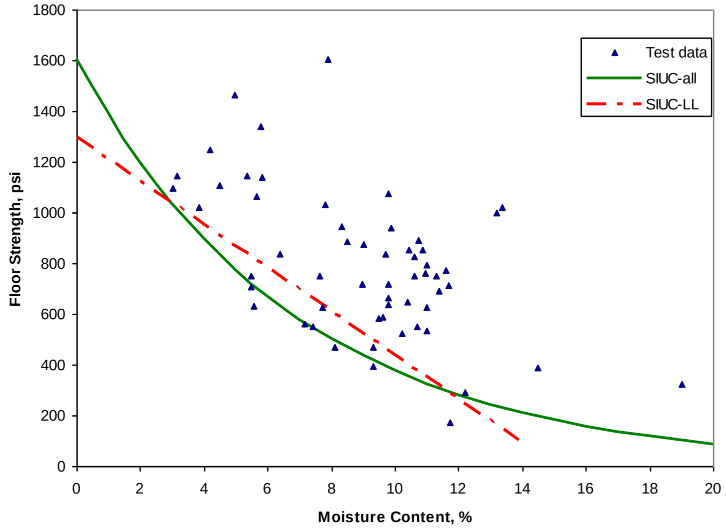
In-situ Plate Test Database

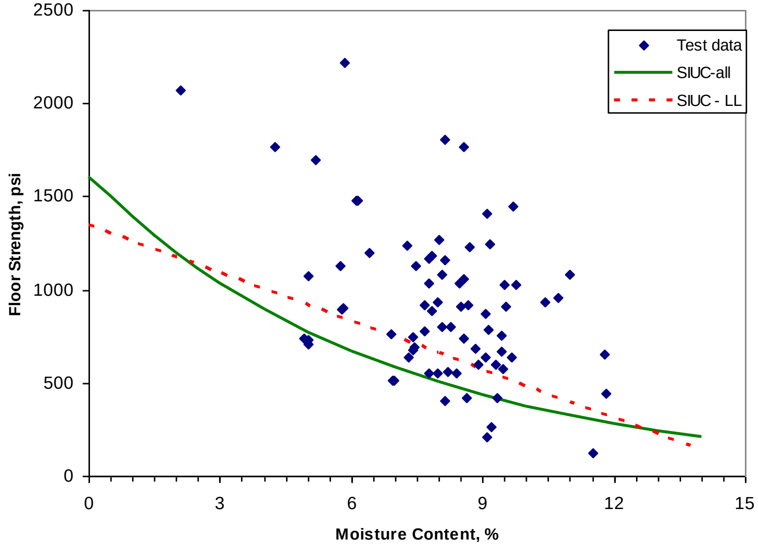
- Largest database of plate tests
- 132 individual tests from 17 coal mines
- Collected all the published data and personal communications in addition to over 40 new tests at five mines

In-situ strength equations



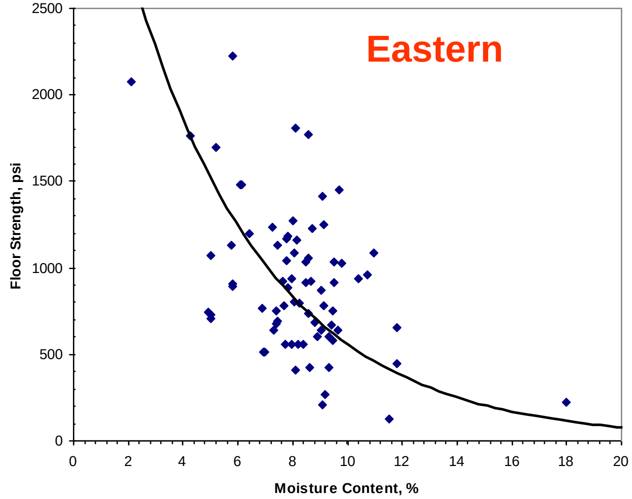




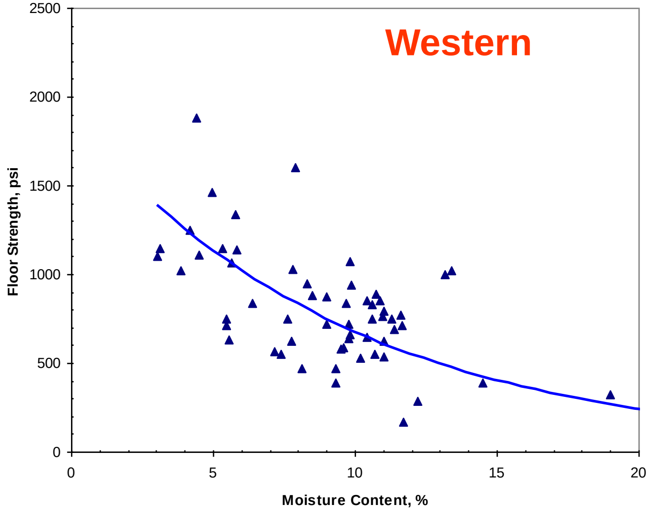


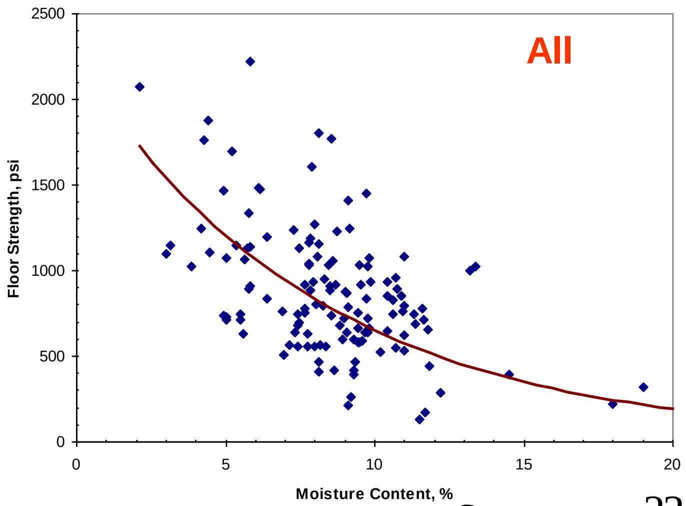
Gadde’s Plate Strength equations

$$q_{Gadde-Eastern} = 4164\ e^{-0.2MC}$$



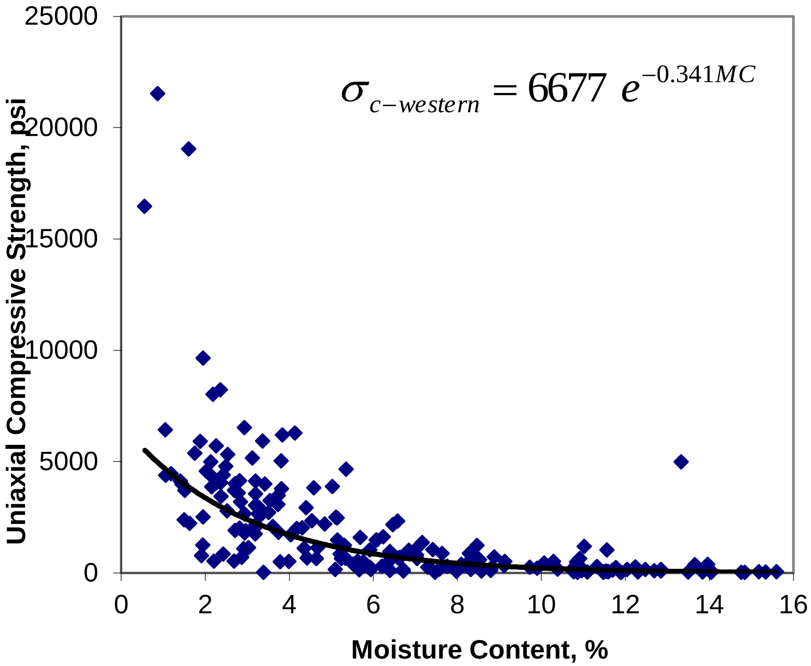
$$q_{Gadde-Western} = 1905\ e^{-0.1MC}$$



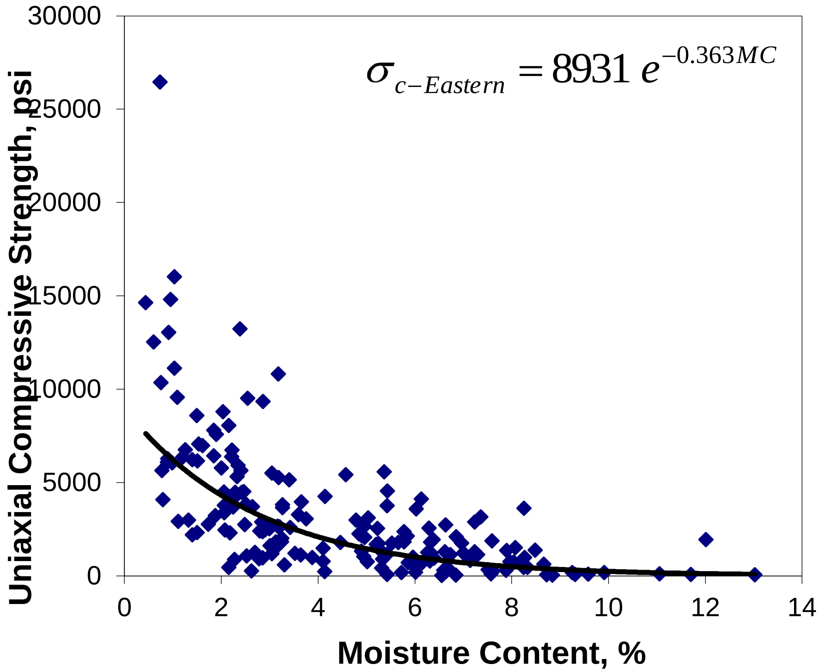


$$q_{Gadde-All} = 2240\ e^{-0.12MC}$$

Gadde's Main Floor Unconfined Compressive Strength Equations for Claystone



Western shelf

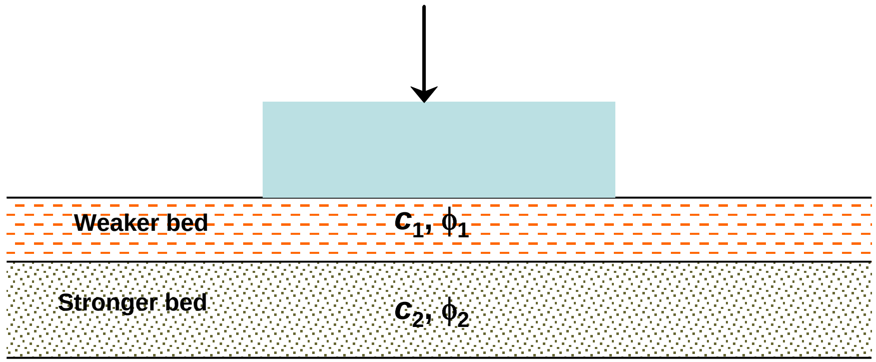


Eastern Shelf

Computation of Bearing Capacity

- The current approach used in the Basin is to treat the floor underneath a pillar as a two-layer material and use a soil mechanics based bearing capacity model developed by Vesic
- No details known
- Has been used for over two decades

Vesic's Model



$$q_{floor} = c_1 N_m$$

$$N_m = \frac{K N_c^* (N_c^* + \beta - 1)\left[(K+1) N_c^{*2} + (1 + K\beta) N_c^* + \beta - 1\right]}{\left\{\left[K(K+1) N_c^* + K + \beta - 1\right]\left[(N_c^* + \beta) N_c^* + \beta - 1\right]\right\} - \left[K N_c^* + \beta - 1\right](N_c^* + 1)}$$

where,

K = ratio of undrained shear strength of the lower stronger layer (c_2) to the upper weaker layer (c_1),

$N_c^* = s_c N_c$; $N_c^* = 6.17$ *for* $\phi = 0$ *and for a square pillar*

β = punching index given by $\dfrac{BL}{[2(B+L)H]}$

with B = width; L = length of the footing; and H = thickness of the upper weaker layer.

Verification of Vesic’s Model

- Modeling showed:
  - Vesic’s model underestimates the floor bearing capacity
  - The effect of B/H, C_2/C_1 ratios is not as simple as portrayed by Vesic’s model
  - Up to B/H ratio of about 10, the error is not significant. At higher B/H values, the underestimation can be substantial

If plate test data is available

$$q_{floor} = c_1 \, N_m$$

$$N_m = \frac{K N_c^* \left(N_c^* + \beta - 1 \right) \left[\left(K + 1 \right) N_c^{*2} + \left(1 + K\beta \right) N_c^* + \beta - 1 \right]}{\left\{ \left[K \left(K + 1 \right) N_c^* + K + \beta - 1 \right] \left[\left(N_c^* + \beta \right) N_c^* + \beta - 1 \right] \right\} - \left[\left(K N_c^* + \beta - 1 \right) \left(N_c^* + 1 \right) \right.}$$

$$c_1 = \frac{q_{plate}}{6.17} \qquad c_2 = \frac{main\ floor UCS}{2} \qquad K = \frac{c_2}{c_1}$$

Vesic-Speck Model

$$q_{Vesci-Speck} = 0.15\,(2070 - 167\,MC)\,N_m \qquad (q_{floor} = c_1\,N_m)$$

$$N_m = \frac{KN_c^*\left(N_c^* + \beta - 1\right)\left[\left(K+1\right)N_c^{*2} + \left(1 + K\beta\right)N_c^* + \beta - 1\right]}{\left[K\left(K+1\right)N_c^* + K + \beta - 1\right]\left[\left(N_c^* + \beta\right)N_c^* + \beta - 1\right] - \left[\left(KN_c^* + \beta - 1\right)\left(N_c^* + 1\right)\right]}$$

$$K = \frac{248}{0.15\,(2070 - 167\,MC)}$$

where MC is the natural moisture content of the underclay or claystone

Vesic-Gadde Model

$$q_{Vesic-Gadde} = c_1 \, N_{m-Gadde}$$

$$N_{m-Gadde} = \frac{K N_c^* \left(N_c^* + \beta - 1\right)\left[\left(K+1\right) N_c^{*2} + \left(1 + K\beta\right) N_c^* + \beta - 1\right]}{\left\{\left[K\left(K+1\right) N_c^* + K + \beta - 1\right]\left[\left(N_c^* + \beta\right)\left(N_c^* + \beta - 1\right)\right]\right\} - \left[\left(K N_c^* + \beta - 1\right)\left(N_c^* + 1\right)\right]}$$

$$c_1 = \frac{4164\, e^{(-0.2\, MC)}}{6.17}, \qquad c_2 = \frac{8931\, e^{-0.363 MC}}{2}$$

for the Eastern shelf mines, and

$$c_1 = \frac{1905\, e^{(-0.1\, MC)}}{6.17} \qquad c_2 = \frac{6677\, e^{-0.341 MC}}{2}$$

for the Western shelf mines.

where MC is the natural moisture content of the underclay or claystone

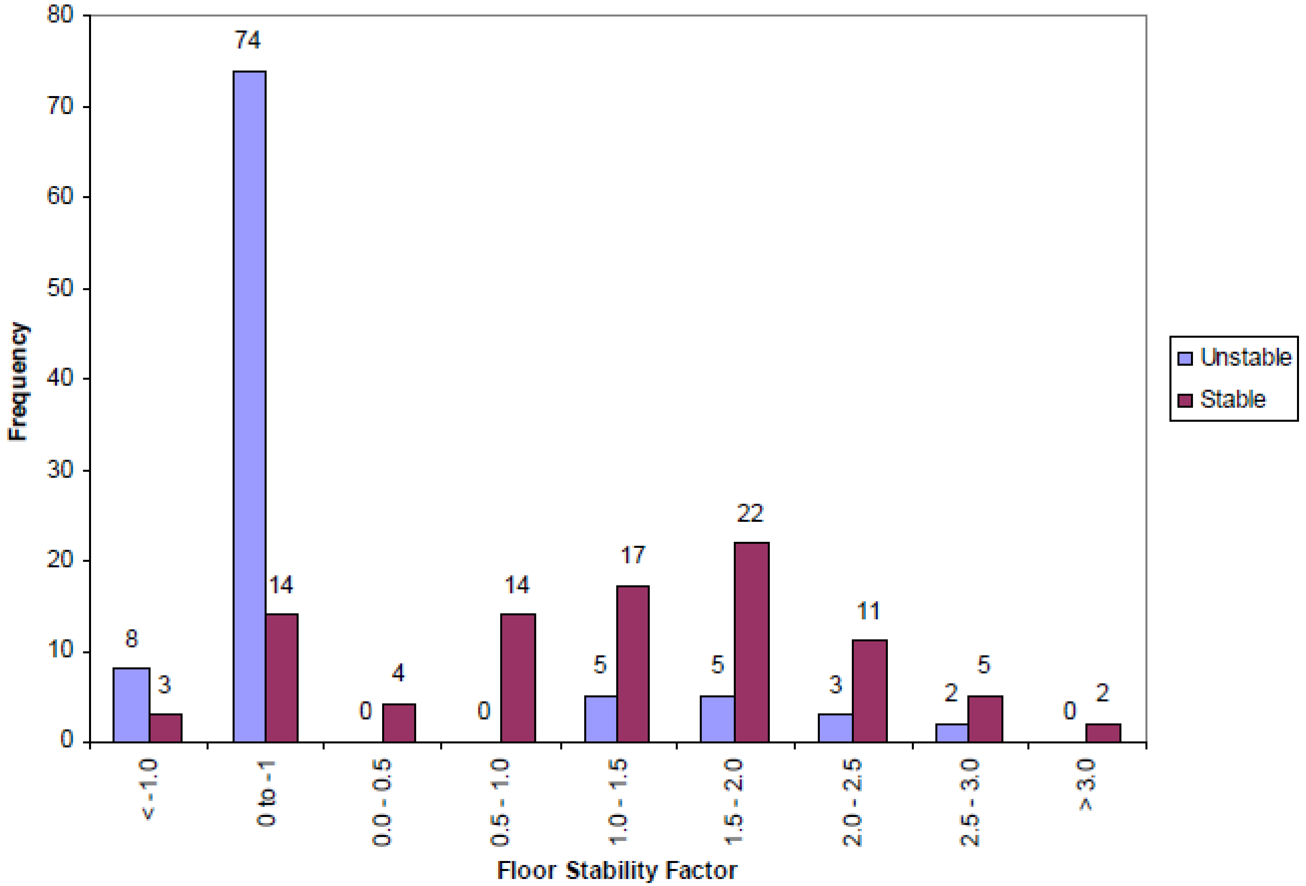
The Best Judge

- Comparison against actual cases of unstable and stable floor cases is the best way to judge a model's validity
- Despite the long history, no credible back analysis of Vesic-Speck approach was done in the past

Case Histories

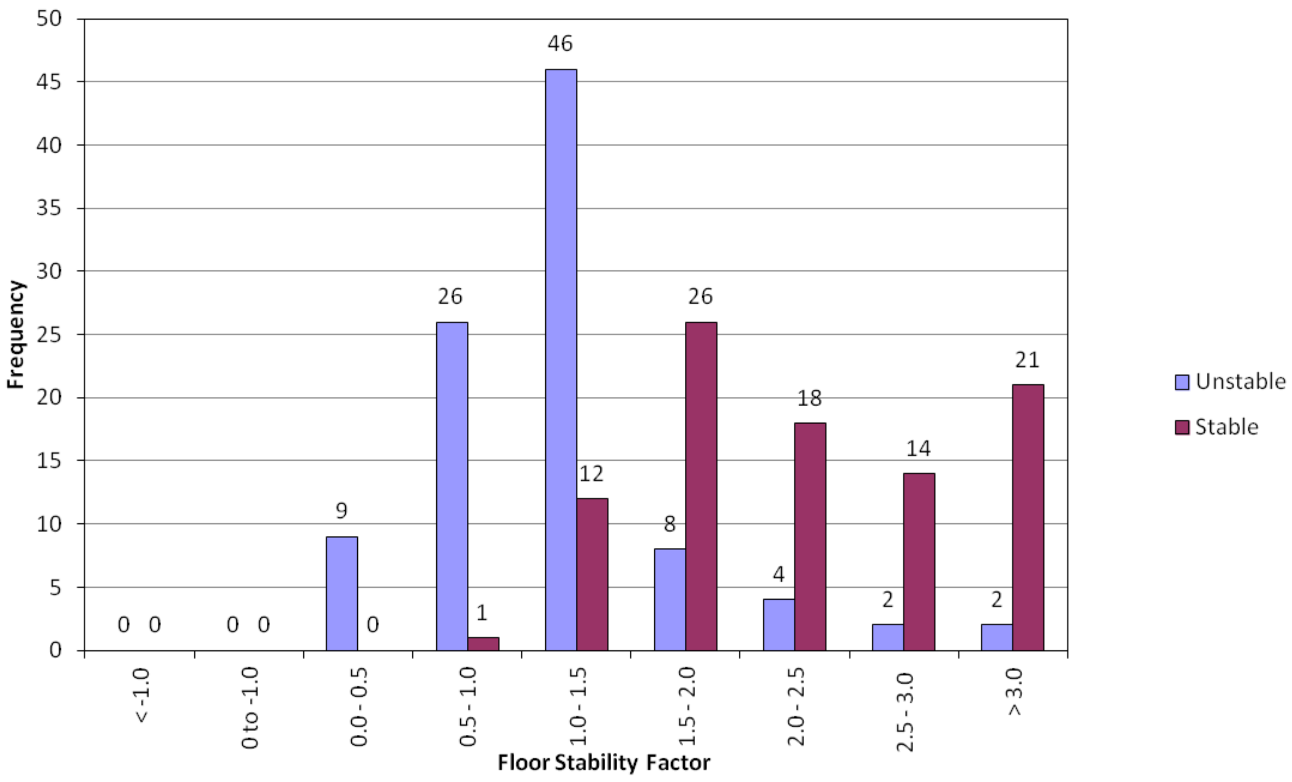
- Several stable and unstable floor cases collected from published and unpublished sources
- 17 long-term stable and unstable cases
- Only cases where the critical input data was available from a reasonably nearby test holes were selected

Vesic-Speck



- Negative stability factors
- While FSF=1.5 explains about 90% of unstable floors, 84% of all pillars had negative FSF.
- 57% of stable floors had FSF below 1.5.

Vesic-Gadde



•No negative stability factors

•FSF=1.5 explains 83% of unstable floors.

• 86% of stable floors had FSF greater than 1.5.


Design Floor Stability Factors

Stability Factors

- Vesic-Gadde performs better than Vesic-Speck as seen by the comparison against case histories
- Because of the way Speck's equation was derived, it predicts negative and physically meaningless strength at high moistures such as those seen in several Western shelf mines
- Based on the case history analysis, for long-term stability, a floor stability factor of 1.5 is recommended with Vesic-Gadde method
- For short-term stability, a stability factor around 1.0 is sufficient for room-and-pillar mining. For longwall applications, given the very short term and localized effects of abutment loading, stable gateroad floor might be seen even with SF values below 1.0. At this point, no analysis of longwall gateroads is available

Stability Factors

- Because of the several ultra low and negative stability factors, it is hard to find a meaningful discriminating floor stability factor for Vesic-Speck. Experience, however, indicates stability factors in the range of 1.3 to 1.5 might work with Vesic-Speck
- The maximum depth of unstable cases in the database was 250ft. Therefore, the recommended stability factors are strictly valid only up to this depth. However, a few stable cases had depths between 250ft and 300ft. Hence, the 1.5 stability factor may be used in this range of depth as well. At depths in excess of 300ft, perhaps such high stability factor may not be necessary. At this point, a tentative recommendation is made to use stability factors between 1.3 and 1.5 for depths greater than 300ft.

Stability Factors

- If enough local history is available at a mine, then the design stability factors should be based on the site-specific back analysis. Local experience always supersedes the "general" basin wide databases
- While the 1.5 stability factor is adequate for almost all "normal" situations, for high sensitivity surface structures (e.g. hospitals, shopping malls, churches, historic buildings etc), consideration may be given to use a stability factor of 2.0 with Vesic-Gadde. Perhaps even better alternative is to use numerical modeling based methods to study the effect of all possible variables on floor stability and its potential for inducing surface subsidence
- Efforts are being made to collect more case histories to refine the recommended stability factors

Conclusions

- Evidence shows the two-shelf model is more appropriate for floor stability analysis
- The largest plate-test database shows the conservative nature of Speck's equation
- Case history data shows Vesic-Gadde method provides the best performance
- AFSIL methodology incorporates two-shelf division of the Basin and appropriate equations to compute immediate and main floor strengths for use with Vesic's bearing capacity equation
- When the geo-mining conditions are not amenable to use simple soil mechanics based approaches, numerical modeling is recommended

- **Nothing supersedes local experience**