Model calibration for prediction of over-break – KB example

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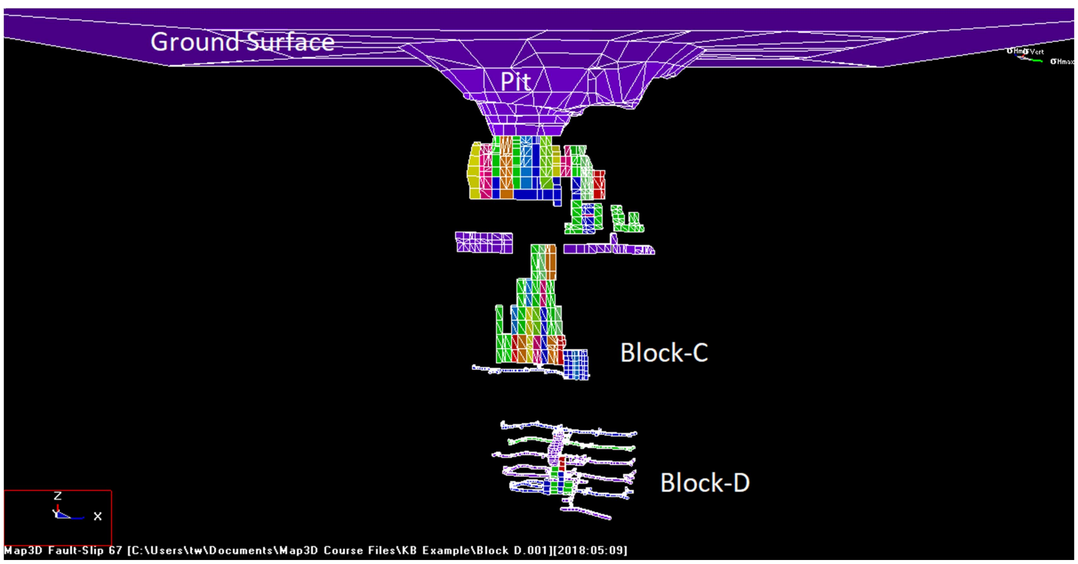
Files required:
- Block C.001 to Block C.007
- Block D.001 to Block D.009
- cp0074_all.ms

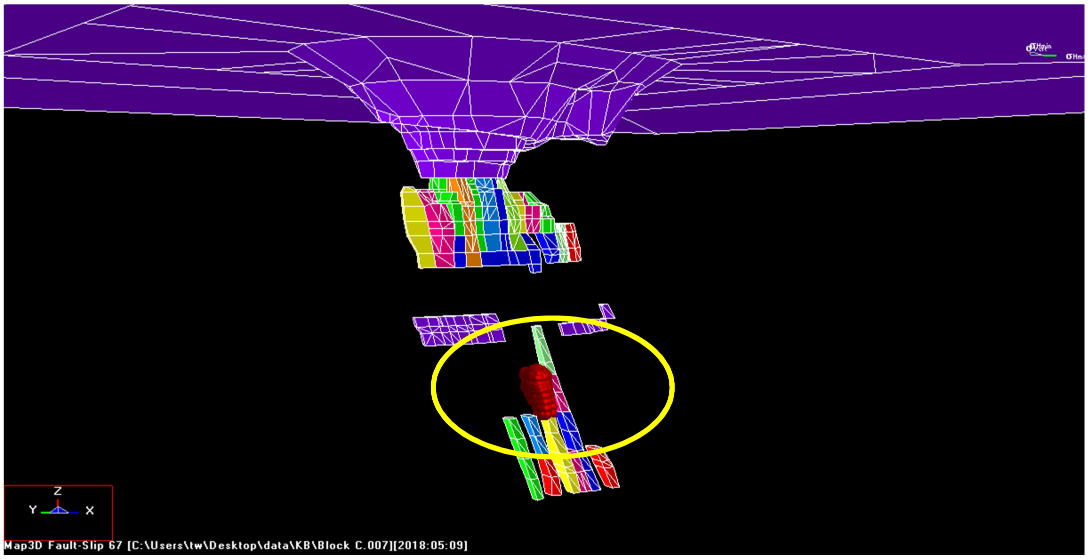
In this example, over-break at an earlier stage of the mining (Block-C) is used to calibrate a model to make predictions of expected behaviour for mining at a subsequent deeper level (Block-D). In these models, ground surface and the pit are shown in purple, various stopes are shown in different colours. The mining is considered in two stages, Block-C (base level 740m below ground surface) and Block-D (base level 1010m below ground surface).



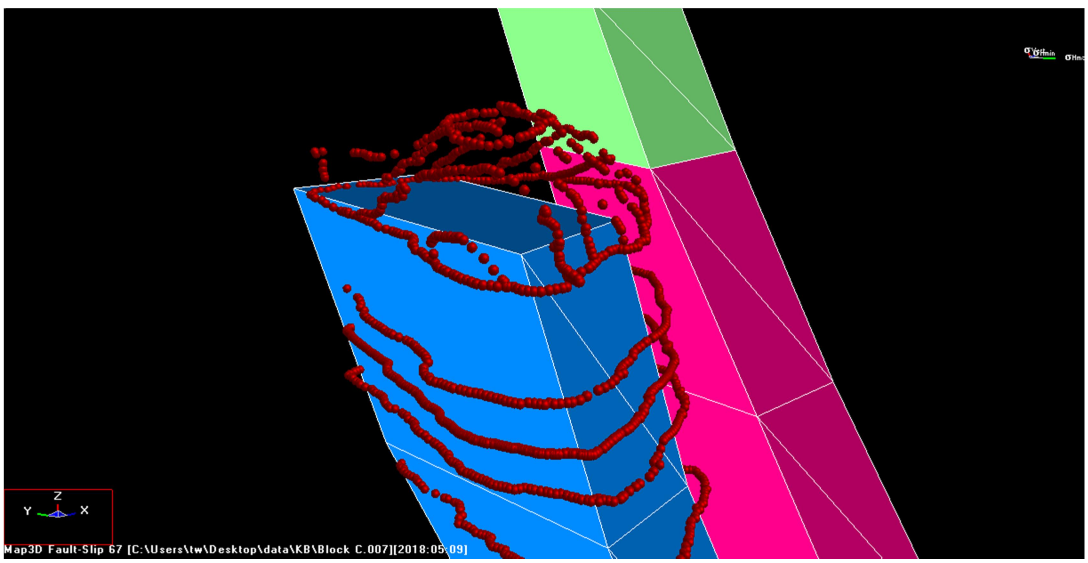
The area of interest in Block-C is located 560m below surface. This area shows some over-break which will be used to calibrate the strength parameters to make a prediction of the expected over-break for mining in Block-D. The mine had developed a Hoek-Brown failure criterion: this is compared to the predictions for the calibrated model.

Block C - Calibration

The stope was modelled according to the designed shape “Map3D > File > Results View > Block C.001”. The Block C area is highlighted with the yellow outline.

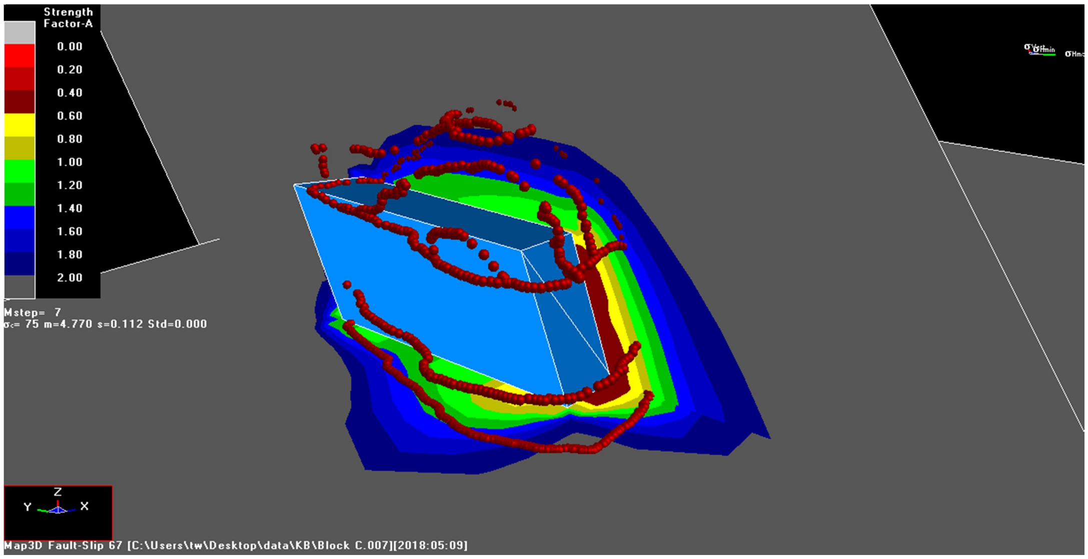


The cavity survey shown in red ("Map3D > Visualization > User File > cp0074_all.ms") illustrates the over-break at step 7. The objective here is to find a failure criterion that provides the best estimate of the over-break.



Rock Mass Failure

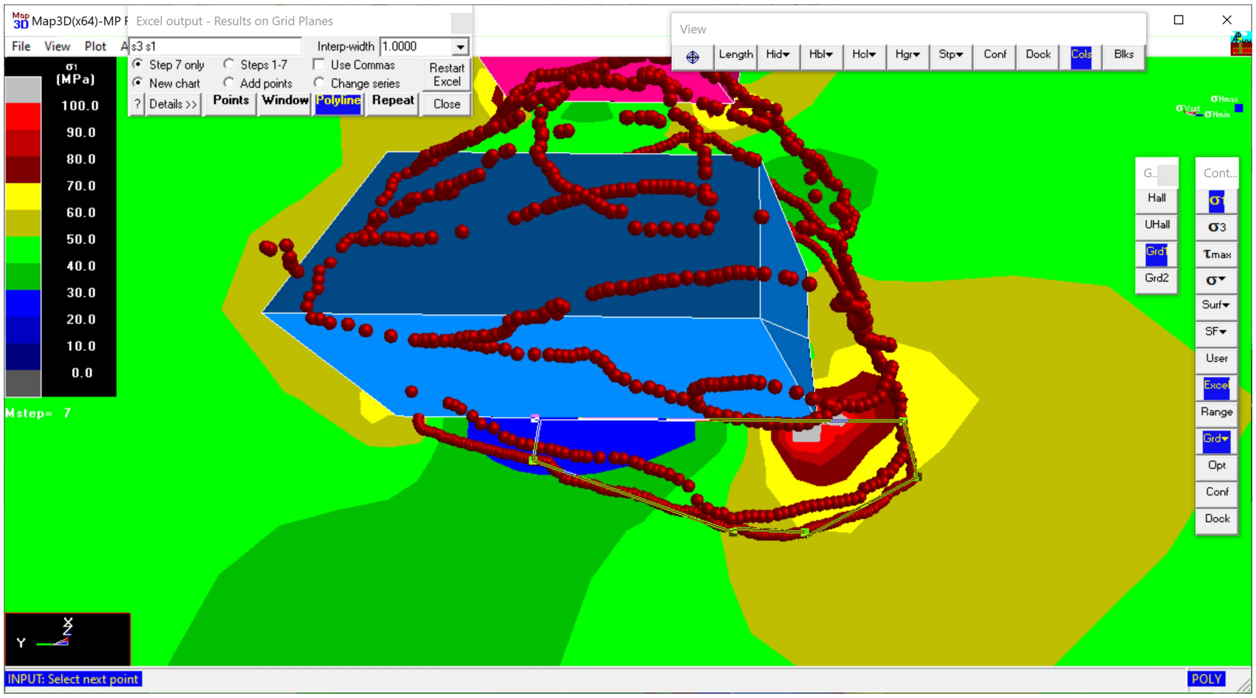
The mine had developed an Hoek-Brown failure criterion with the values σ_c^{50} = 75 MPa, *m* = 4.77, *s* = 0.112. The predicted failure zone is shown in yellow and red below. This does agree somewhat with the failure zone observed using the cavity survey, although it is clearly an under-estimate, particularly over the back.



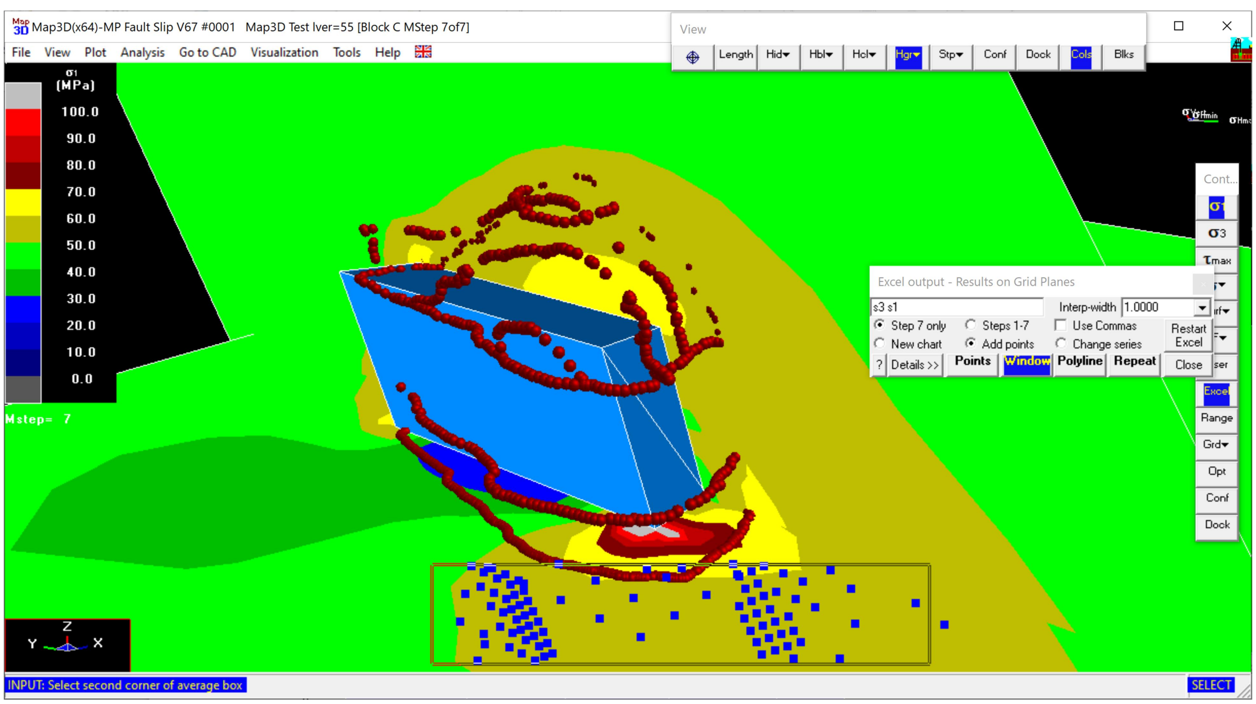
Let's now present the stresses in a useful format. Plot the major principal stress σ_1 using “Map3D > Plot > Stress > σ_1”. We must also change to step 7 using “Map3D > File > Mining Step # > Mining Step #7”.

Using Excel, I now collect stresses for points inside and outside the over-break zone, as well as along the indicated depth of failure. In this case I will use “s3 s1” as the arguments for the “Map3D > Plot > Excel” function. Here “s3 s1” represent respectively σ_3 and σ_1 such that σ_3 will be the x-axis (abscissa) and σ_1 will be the y-axis (ordinate).

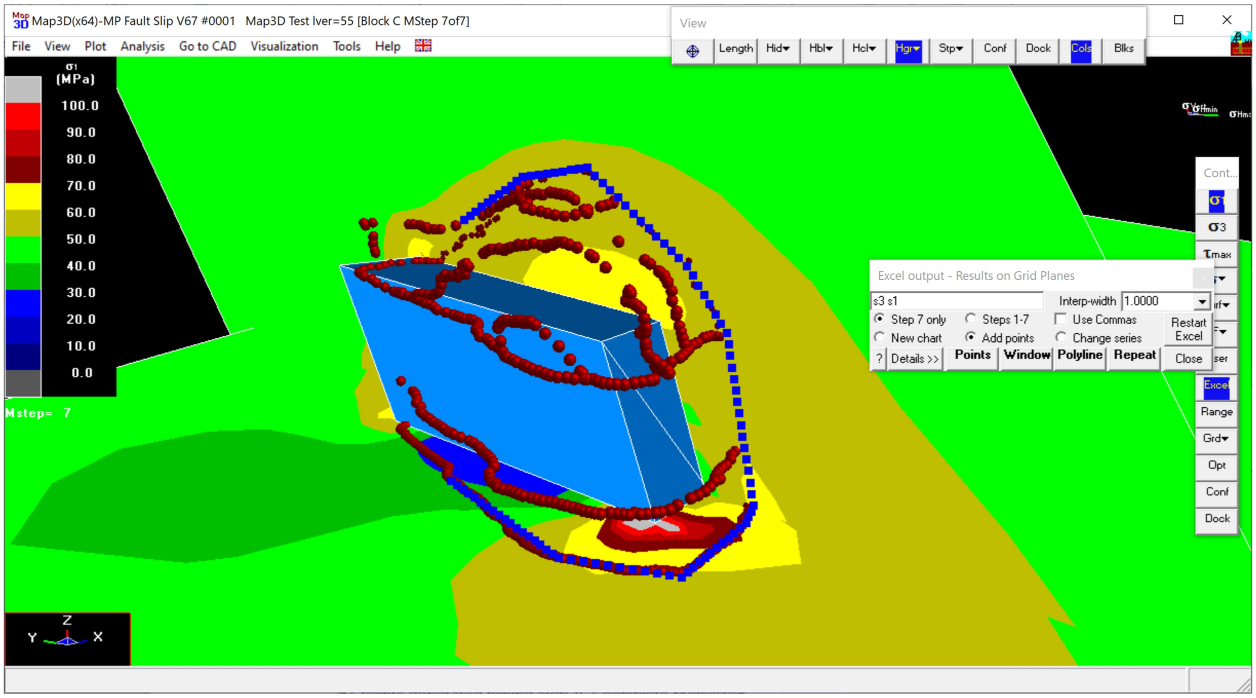
Using the “Map3D > Plot > Excel > Polyline” function, multiple sets of data inside the failed zone can be dumped to Excel by defining a closed loop as shown below. First for grid #1, then for grid #2. Be sure to hold the shift key down until the loop selection is complete.



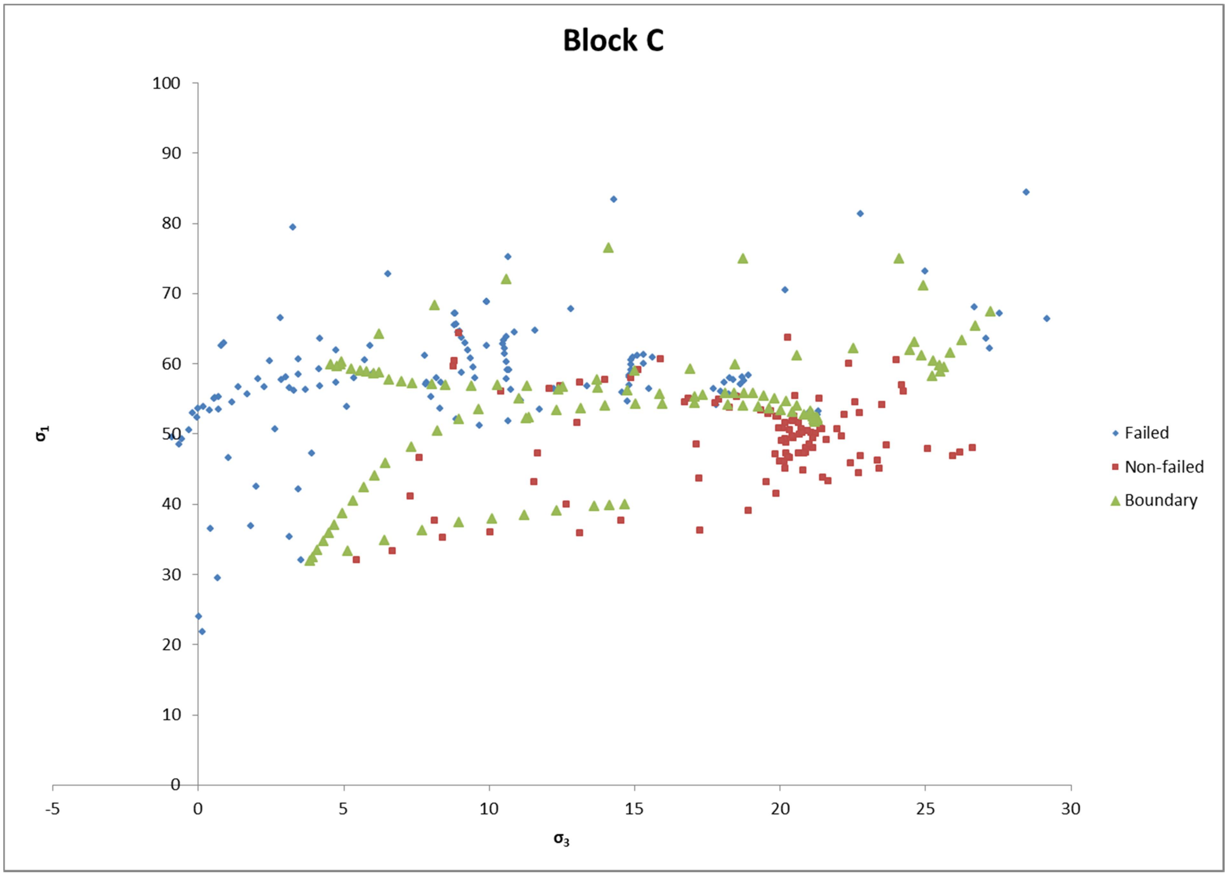
Now I will select “Map3D > Plot > Excel > Change Series” function then repeat this process for points outside the failed zone either using the “Map3D > Plot > Excel > Polyline” function or the “Map3D > Plot > Excel > Window” function, again for grid #1, then for grid #2.



Finally, I will set the “Interp-Width” to 1 m, select “Change Series”, then start the “Map3D > Plot > Excel > Polyline” function. Note that you must hold down the shift key in order to select multiple points along the indicated depth of failure.



The stress plot appears as follows.

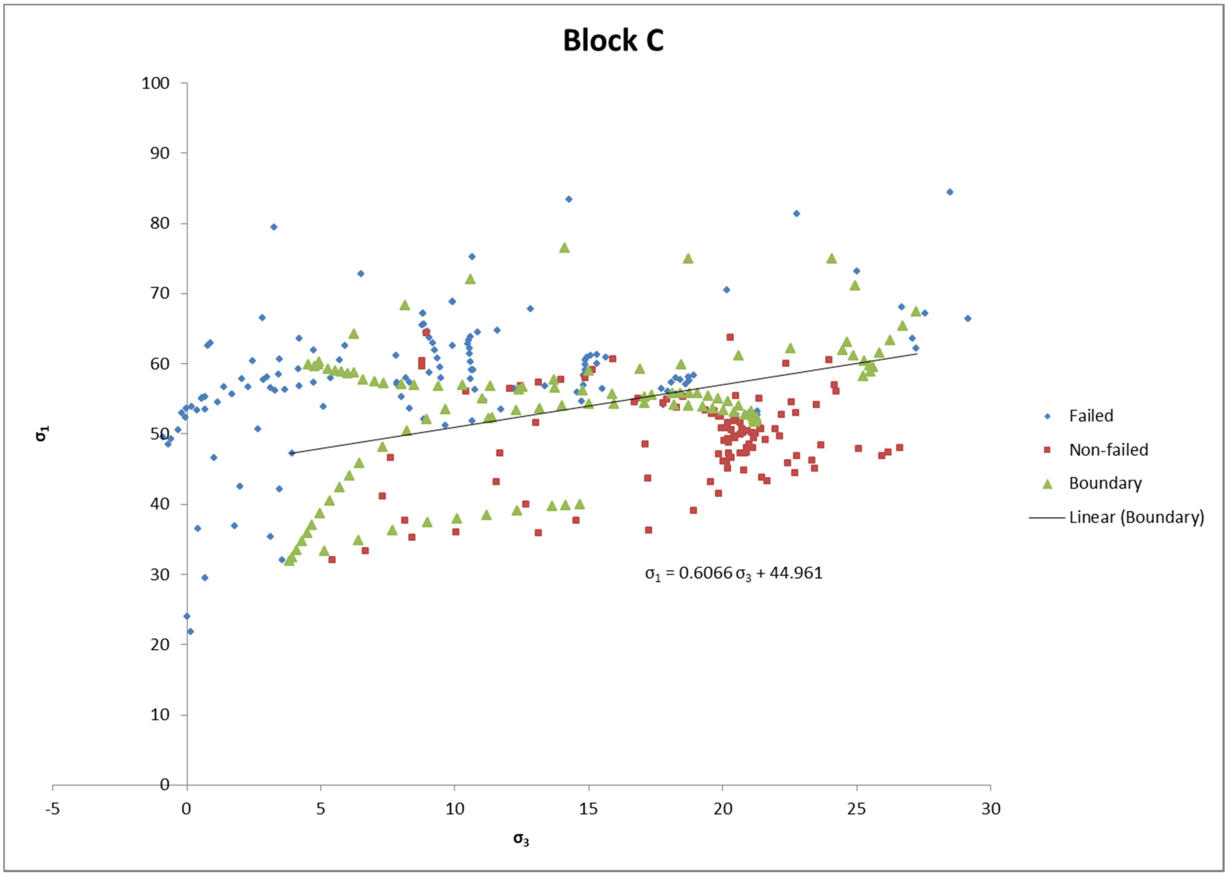


The objective is to find a failure criterion line that neatly divides the failed (blue diamonds) and non-failed (red squares) stresses, and also is centred on the points at the indicated depth of failure (green triangles).

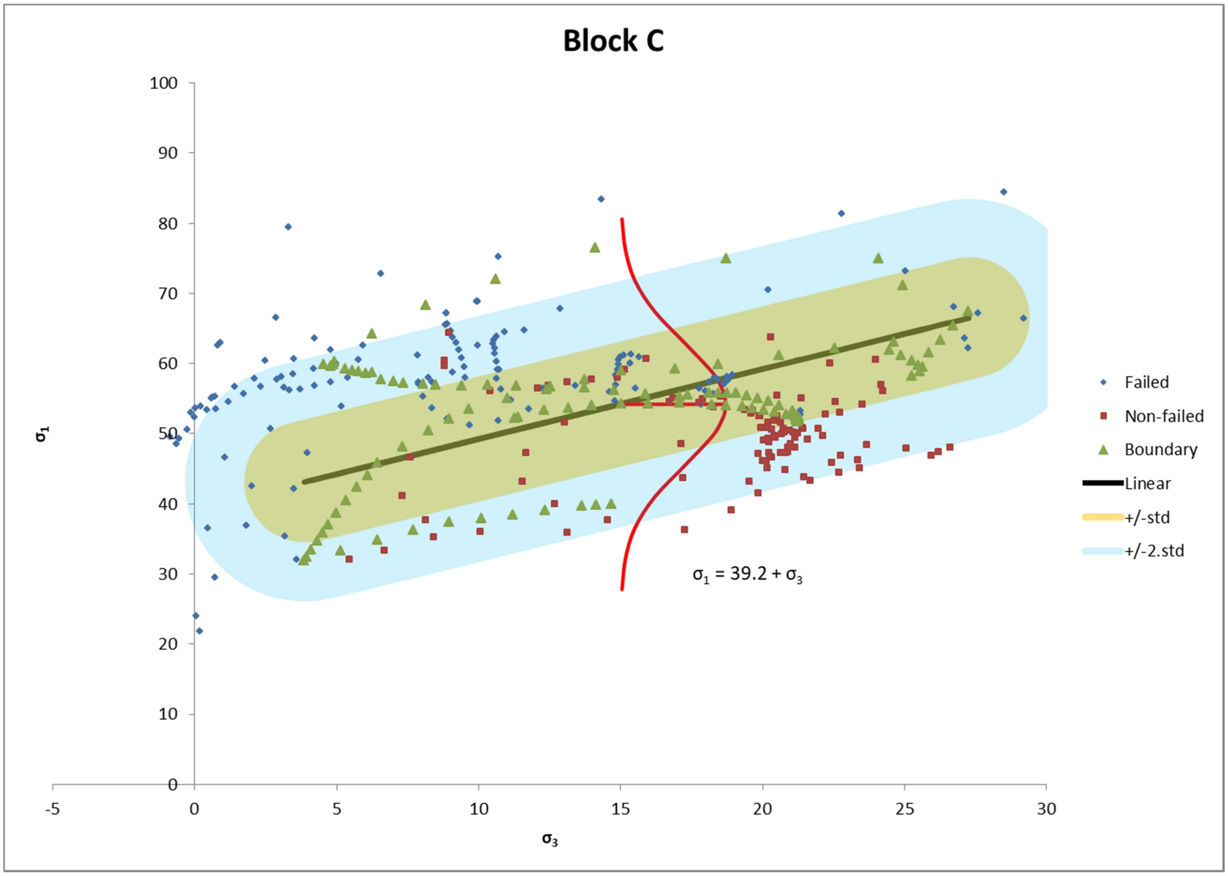
1) $\sigma_1 = UCS + q \times \sigma_3$

Let's try $\sigma_1 = UCS + q \times \sigma_3$ where *UCS* and *q* represent respectively the intercept and slope of the failure criterion on a σ_1 versus σ_3 plot.

The best fit straight line is one that intercepts the σ_1-axis at around *UCS* = 45.0 MPa and has a slope *q* = 0.61 as shown below (the best fit line though the green triangles). In spite of this being a best-fit line, the slope must be at least +1 or larger. This is because the slope *q* can be related to friction angle as $q = \{1 + sin(\varphi)\}/\{1 - sin(\varphi)\}$ where φ represents the friction angle. Values of $q < +1$ would imply negative friction, clearly impossible.



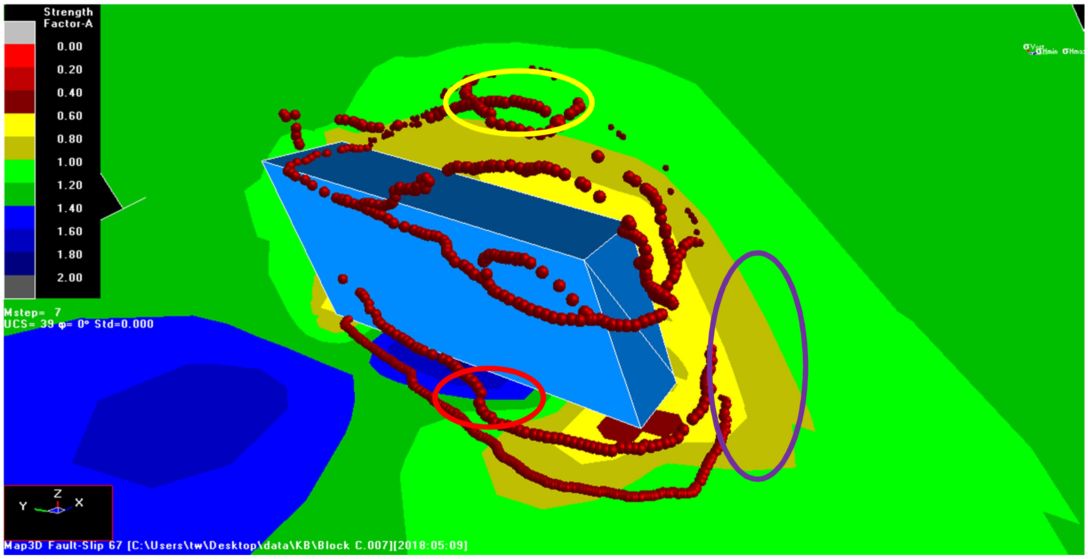
Let's now find the best fit straight line for the case where $q = 1$ (i.e. $\varphi = 0$). This line will pass through the mean value of σ_1 and σ_3 for the green triangles. These are calculated respectively as 53.8 MPa and 14.5 MPa. The intercept, *UCS*, for this line can be calculated from 53.8 = *UCS* + *q* 14.5 with *q* = 1 and gives *UCS* = 39.2 MPa.



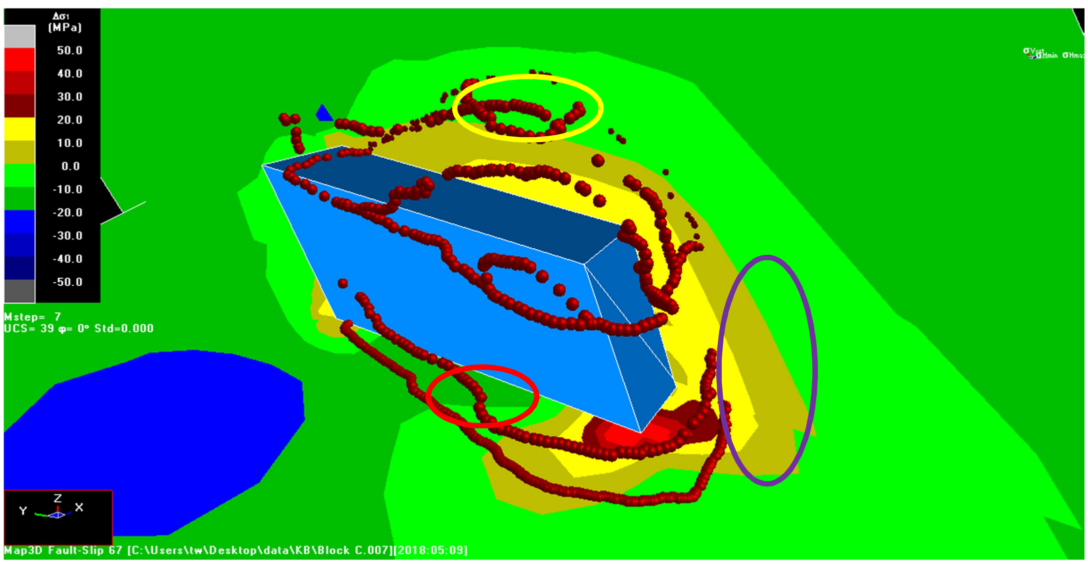
The scatter around the best fit line with the q = 1, can be determined as the standard deviation calculated using the σ_1 difference between the line and the boundary points (the green triangles) as ±8.8 MPa. The normal distribution is shown in red. Now, dividing this by the average value of σ_1 (the average of σ_1 values for the green triangles), the coefficient of variation can be determined as ±16.4%, not as small as desirable, but an acceptable fit.

It can be observed that most of the failed points (blue diamonds) fall above this line, and most of the non-failed points (red squares) fall below this line, which is good.

This failure criterion can now be presented in Map3D by substituting the values for the best fit line (UCS = 39.2 MPa and q = 1.0). Below this is presented as strength factor defined as ($UCS + q \times \sigma_3$) / σ_1. In this case the predicted failed zone is shown in yellow and red.

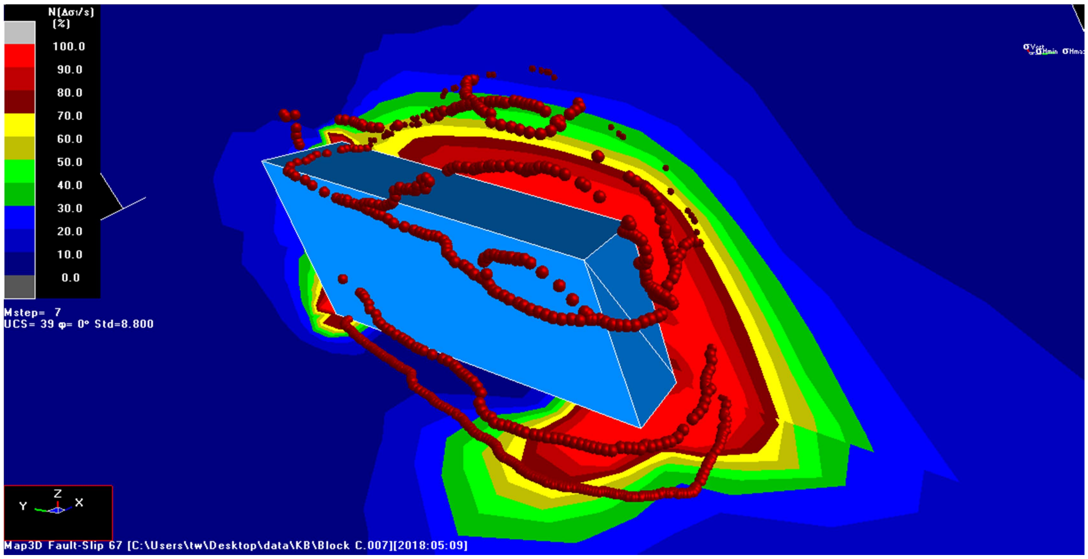


This can also be presented as excess stress defined as $\Delta\sigma_1 = \sigma_1 - (UCS + q \times \sigma_3)$. Again, the predicted failed zone is shown in yellow and red.

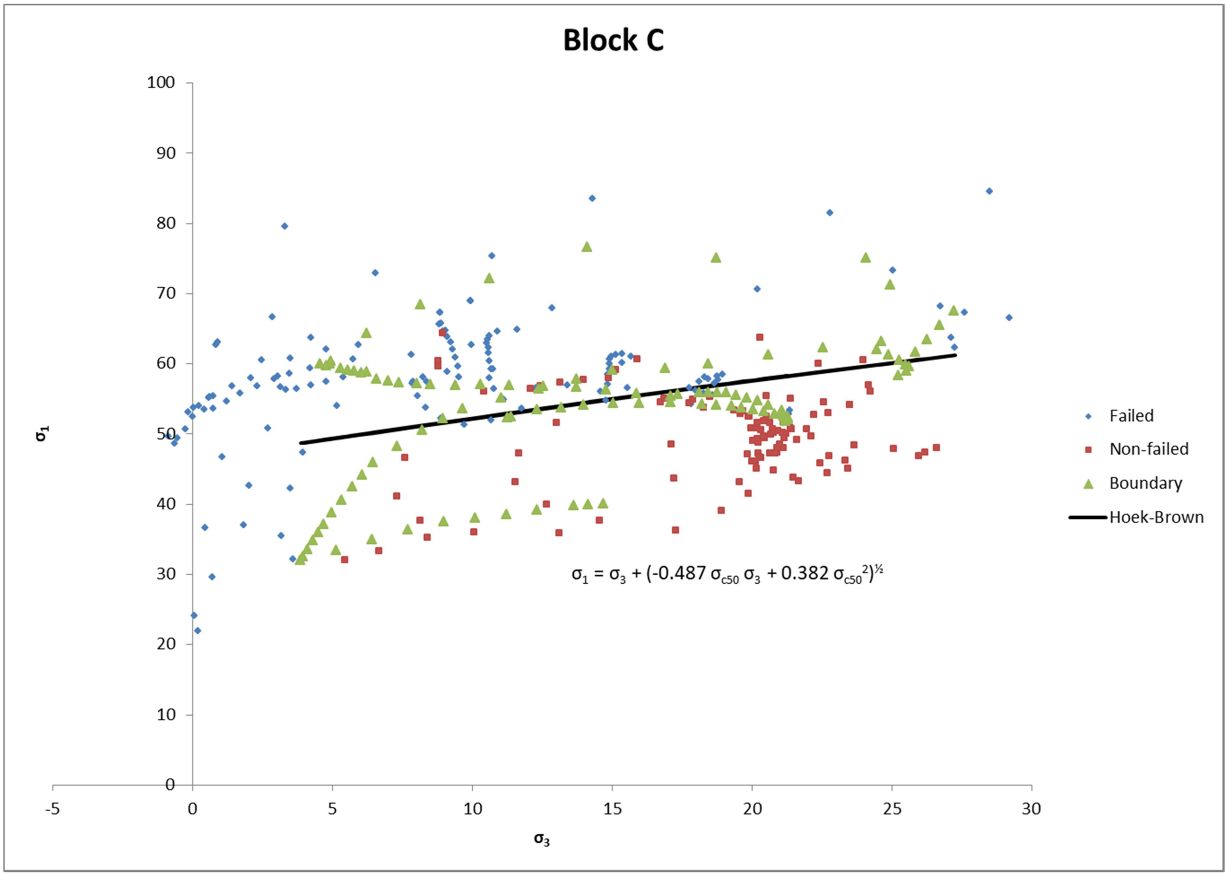


It can be observed that this failure criterion has underestimated the extent of the failed zone above the stope (yellow outline) and along the side of the stope (red outline), and overestimated the extent in the hanging wall (purple outline).

Finally, the uncertainty in this prediction can be presented as probability of failure defined as $N(\Delta\sigma_1 / std)$ where the function N represents the normal distribution and the symbol *std* represents the standard deviation for the scatter around the best fit line found as ±8.8 MPa above. Here, the zone of uncertainty is shown as the variation between dark blue and bright red. This zone represents the scatter of the stresses around the best fit line (green triangles in the σ_1 versus σ_3 plot above).



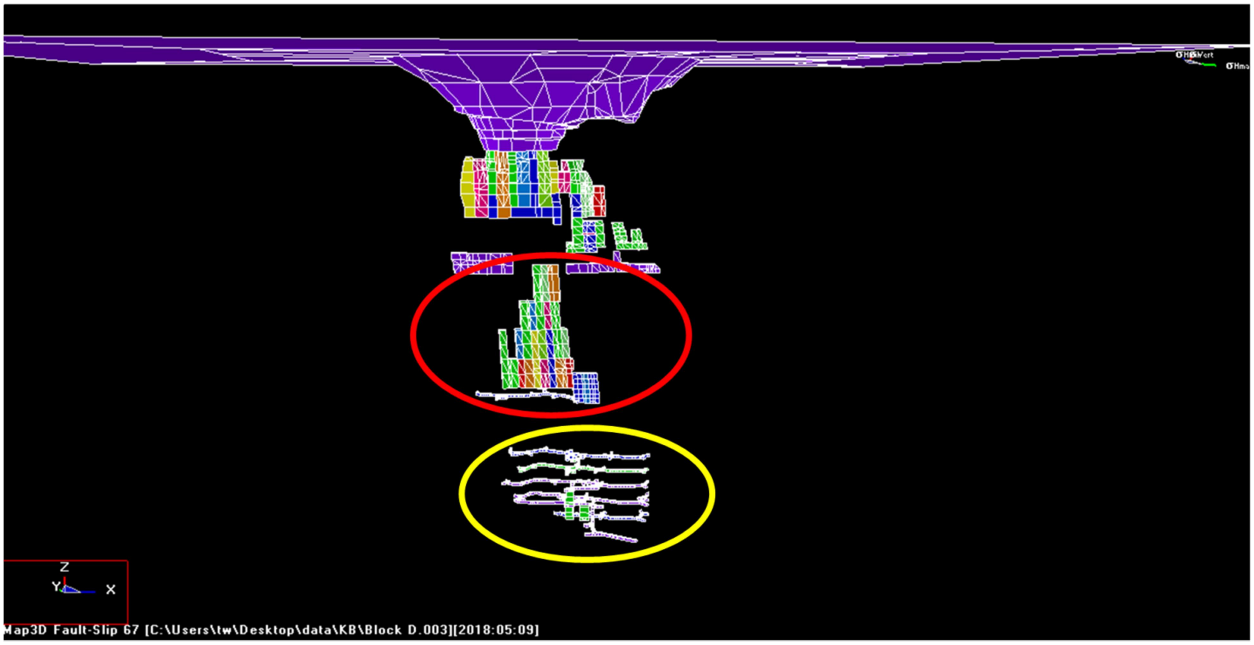
For completeness, let's now find the best fit Hoek-Brown line $\sigma_1 = \sigma_3 + (m \times \sigma_{c50} \times \sigma_3 + s \times \sigma_{c50}^2)^{½}$. To do this I rearrange the Hoek-Brown criterion into a linear form as $(\sigma_1 - \sigma_3)^2 = m \times \sigma_{c50} \times \sigma_3 + s \times \sigma_{c50}^2$. Noting that σ_{c50} = 75 MPa, and using linear regression, it can be found that the best fit values are m = -0.487 and s = 0.382. Although this result can be plotted as shown below, it must be noted that this criterion is not valid since by definition $m \geq 0$. This follows for the same negative friction reasoning discussed above for the best fit straight line.



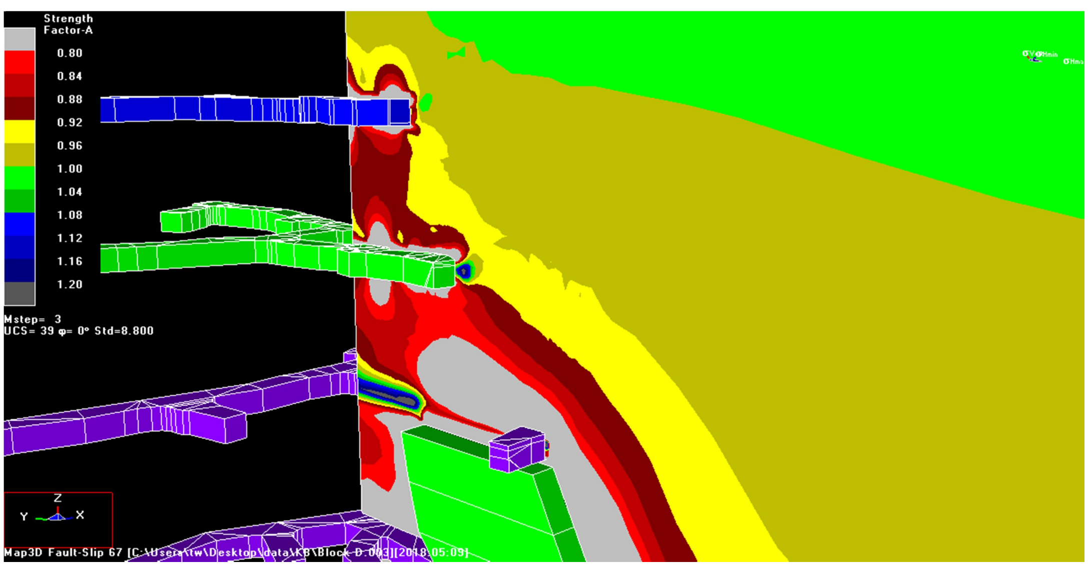
Note that if we set *m* = 0 and solve for the best fit criterion the result is simply a straight line with a slope of one, the same result found previously above.

Block D prediction

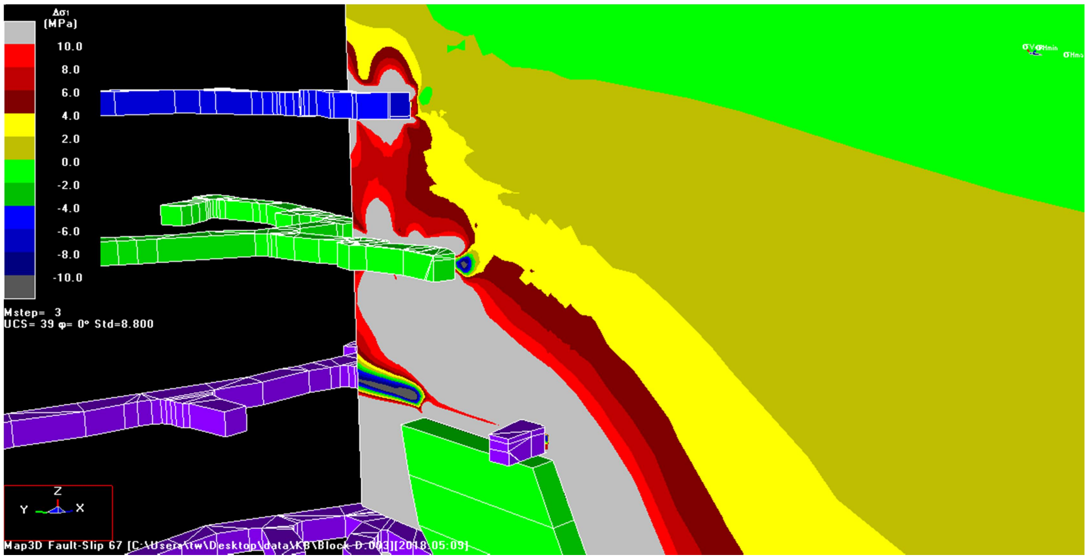
Now that we have a failure criterion, this can be used to predict the expected behaviour for Block D. Block D (yellow outline) is laid out in a similar manner to Block C (red outline) except it is 460 m deeper.



The failure criterion derived above can now be presented in Map3D by substituting the values for the best fit line (*UCS* = 39.2 MPa and q = 1.0). Of particular interest is the prediction for mining step #3. This can be selected using "Map3D > File > Mining Step # > Mining Step 3. Below this is presented as strength factor defined as $(UCS + q \times \sigma_3) / \sigma_1$. In this case the predicted failed zone is shown in yellow, red and light grey.

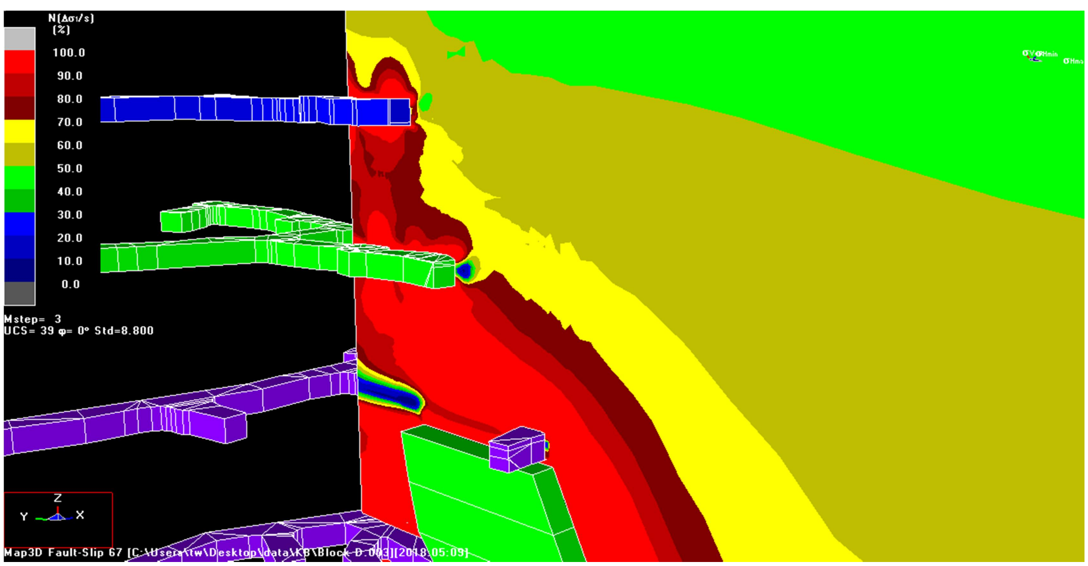


This can also be presented as excess stress defined as $\Delta\sigma_1 = \sigma_1 - (UCS + q \times \sigma_3)$. Again, the predicted failed zone is shown in yellow, red and light grey.

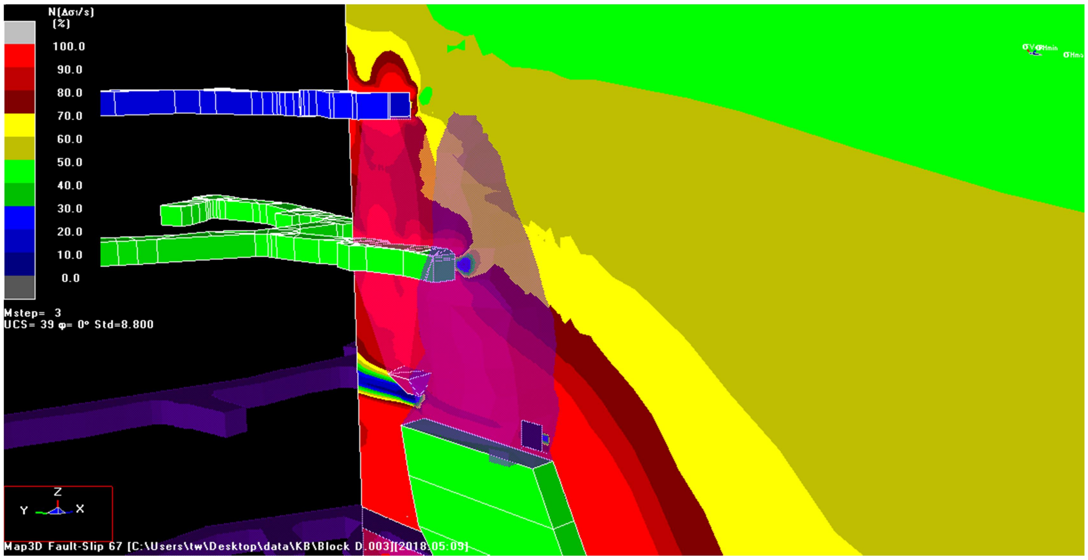


It can be observed that this failure criterion predicts a large amount of failure at this point in the mining sequence, clearly illustrating where the worst of the failure is expected to be concentrated (shown in red and light grey).

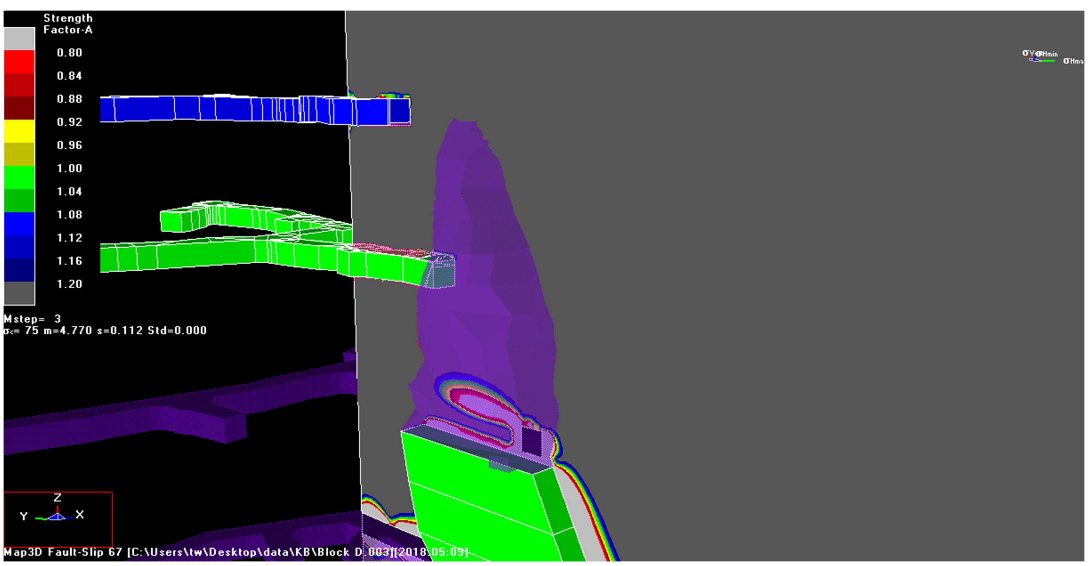
Finally, the uncertainty in this prediction can be presented as probability of failure defined as $N(\Delta\sigma_1 / std)$ where the function *N* represents the normal distribution and the symbol *std* represents the standard deviation for the scatter around the best fit line found as ±8.8 MPa above. Here, the zone of uncertainty is shown as the variation between dark blue and bright red. This zone represents the scatter of the stresses around the best fit line (green triangles in the σ_1 versus σ_3 plot above.



The above plot clearly illustrates where the worst of the failure is expected to be concentrated (shown in red). The actual observed behaviour is shown in the figure below. Here the over-break is shown as a purple silhouette. This failure occurred as an uncontrolled chimneying process which proved very difficult to arrest. The prediction appears to be biased to the footwall side compared to the observed failure, but then this failure did occur progressively which could have created this bias. It is also possible that there are some geological influence causing this bias. This should be investigated more thoroughly.



Using the Hoek-Brown failure criterion developed by the mine with the values σ_c^{50} = 75 MPa, *m* = 4.77, *s* = 0.112, the predicted failure zone is shown in yellow, red and light grey below. The over-break is shown as a purple silhouette below. This is clearly a severe under-estimate of the observed failure. This led the mine operators to believe that there were no significant stability issued to be expected.



By contrast, the failure criterion calibrated on the Block C observations suggest that severe instability should have been expected during the mining of Block D. While further verification of this criterion should be undertaken, it would appear that a useful predictor has been found.