**Appendix**

**(1) The convergence-confinement method**

The analytical convergence-confinement method (CCM), assuming rock mass as elastic-perfectly plastic Hoek-Brown material, was used to analyze the performance of a circular tunnel (radius ). Multiple PFs were considered to analyze the tunnel reliability: (i) plastic zone radius () and (ii) tunnel wall convergence (). Expressions for PFs were adapted from literature by assuming that the tunnel is unsupported without internal/support pressure and rock mass yields with zero plastic volume change (Brown, 1980).

where , are the Hoek-Brown parameters of rock mass; is deformation modulus of rock mass and is UCS of intact rock. Rock mass properties (, , ) can be obtained from intact rock properties () and GSI using the relations provided by Hoek et al. (2002) and Hoek and Diederichs (2006) given below:

The parameter is the critical pressure below which plastic zone develops around the tunnel and its mathematical expression is given below:

**(2) Cohesion Weakening Friction Strengthening (CWFS) model**

Hajiabdolmajid et al. (2002) proposed a plastic strain-dependent CWFS model modeling non-simultaneous mobilization of the friction and cohesion of rock. The fundamental assumption of the CWFS model is that the frictional component of rock strength can only be mobilized, alike granular materials, when the rock fragments can move relative to each other in shear after a significant reduction in the cohesion component. The schematic diagram in Fig. A illustrates the CWFS strength model. The CWFS model, in addition to elastic parameters and dilation angle, requires six parameters, i.e. peak cohesion (, residual cohesion (), initial friction angle (), mobilized friction angle (), plastic strain limit of cohesion (), and plastic strain limit of friction () as inputs.

Walton (2019) provided the guidelines for estimation of the above-mentioned CWFS model parameters based on the extensive literature review. These suggested guidelines were adopted in this study to estimate the required parameters from intact rock properties for the analysis as given below.

Further, the value of can be taken as (Hajiabdolmajid et al., 2002; Zhao et al., 2010; Walton, 2019). The plastic strain limits for cohesion () and friction angle () were assumed to be 0.0018 and 0.0038, respectively (Walton, 2019). These assumptions were based on the relationship provided between and UCS; and and UCS from literature values by Walton (2019).

****

**Fig. A.** Schematic diagram illustrating the CWFS strength model and involved parameters.

**(3) Supplementary data**

**Table A1.** Original sample of critical discontinuity properties for example 1.

|  |  |  |  |
| --- | --- | --- | --- |
| No. | JRC | (°) | JCS (MPa) |
| 1 | 2.15 | 32.63 | 10.66 |
| 2 | 2.87 | 27.76 | 6.29 |
| 3 | 3.58 | 37.51 | 18.05 |
| 4 | 2.15 | 31.17 | 9.10 |
| 5 | 2.87 | 30.68 | 8.63 |
| 6 | 3.58 | 32.63 | 10.66 |
| 7 | 2.15 | 29.71 | 7.77 |
| 8 | 2.87 | 35.07 | 13.87 |
| 9 | 3.58 | 32.15 | 10.11 |
| 10 | 3.32 | 32.15 | 10.11 |
| 11 | 4.42 | 32.63 | 10.66 |
| 12 | 5.53 | 32.15 | 10.11 |
| 13 | 3.32 | 31.66 | 9.59 |
| 14 | 4.42 | 33.12 | 11.24 |
| 15 | 5.53 | 32.15 | 10.11 |
| 16 | 3.32 | 32.15 | 10.11 |
| 17 | 4.42 | 32.15 | 10.11 |
| 18 | 5.53 | 32.15 | 10.11 |
| 19 | 3.32 | 27.76 | 6.29 |

**Table A2.** Original sample of rock properties for example 2.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| No. |  | UCS (MPa) |  (GPa) | GSI |
| 1 | 12.1949 | 153 | 75 | 42 |
| 2 | 10.9272 | 164 | 85 | 42 |
| 3 | 8.3032 | 59 | 85 | 42 |
| 4 | 3.6465 | 125 | 58 | 42 |
| 5 | 8.8251 | 141 | 60 | 35 |
| 6 | 16.0289 | 102 | 84 | 43 |
| 7 | 12.9051 | 68 | 82 | 35 |
| 8 | 16.8598 | 101 | 73 | 35 |
| 9 | 6.5479 | 131 | 33 | 53 |
| 10 | 15.0637 | 120 | 30 | 40 |
| 11 | 4.2672 | 92 | 74 | 55 |
| 12 | 17.3260 | 57 | 36 | 45 |
| 13 | 17.2944 | 77 | 57 | 40 |
| 14 | 14.9430 | 169 | 39 | 42 |
| 15 | 18.7750 | 140 | 97 | 40 |
| 16 | 12.6379 | 264 | 79 | 42 |
| 17 | 11.5167 | 109 | 41 | 35 |
| 18 | 10.6426 | 102 | 79 | 35 |
| 19 | 16.7689 | 126 | 61 | 31 |
| 20 | 18.9248 | 106 | 72 | 50 |
| 21 | 14.6554 | 105 | 71 | 32 |
| 22 | 12.2824 | 27 | 48 | 49 |

**Table A3.** Jackknife statistics of sample mean, SD and AIC values of sensitive properties for example 2.

|  |  |  |
| --- | --- | --- |
| Statistic | UCS (MPa) | GSI |
| Jackknife Mean | Jackknife COV | Jackknife Mean | Jackknife COV |
| Sample Mean | 115.3636 (115.3807) | 0.0922(0.0878) | 41.1364 (41.1342) | 0.0342(0.0332) |
| Sample SD | 48.3941 (46.2002) | 0.2723(0.2303) | 6.4375 (6.2303) | 0.1544(0.1452) |
|   | 187.1366 (233.1338) | 0.0685(0.0450) | 117.1706 (145.6587) | 0.0568(0.0455) |
|   | 187.4791(233.6266) | 0.0542(0.0382) | 116.3272 (144.4154) | 0.0552(0.0446) |
|  | 186.1893(232.0401) | 0.0636(0.0411) | 119.0115 (147.8019) | 0.0525(0.0440) |
|   | 186.0320(232.1454) | 0.0503(0.0366) | 116.4767 (144.6778) | 0.0555(0.0447) |
| Note: Bootstrap statistics are listed inside the parentheses for comparisons. |

**Table A4.** Original sample of rock properties for example 3.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| No. |  | UCS (MPa) |  (GPa) | GSI |
| 1 | 21.77 | 20.81 | 16.03 | 16.25 |
| 2 | 25.45 | 34.80 | 2.47 | 50.75 |
| 3 | 6.47 | 30.74 | 2.71 | 63.25 |
| 4 | 25.79 | 82.33 | 10.10 | 57.75 |
| 5 | 15.97 | 31.16 | 6.32 | 71.25 |
| 6 | 6.11 | 13.82 | 15.22 | 29.75 |
| 7 | 8.61 | 43.65 | 10.56 | 56.25 |
| 8 | 13.80 | 30.14 | 7.94 | 66.25 |
| 9 | 27.85 | 17.46 | 8.65 | 58.25 |
| 10 | 28.21 | 58.38 | 4.32 | 63.75 |
| 11 | 6.87 | 53.26 | 16.93 | 64.25 |
| 12 | 28.49 | 70.03 | 12.68 | 8.00 |
| 13 | 27.83 | 82.01 | 4.29 | 55.75 |
| 14 | 12.42 | 92.92 | 8.35 | 62.75 |
| 15 | 21.24 | 84.99 | 9.90 | 66.25 |
| 16 | 6.66 | 103.04 | 6.84 | 23.75 |
| 17 | 11.12 | 43.36 | 12.50 | 8.50 |
| 18 | 25.90 | 84.43 | 21.10 | 21.75 |
| 19 | 20.95 | 54.73 | 12.20 | 56.25 |
| 20 | 27.94 | 136.94 | 5.36 | 64.75 |
| 21 | 16.62 | 151.17 | 3.16 | 59.25 |
| 22 | 5.39 | 119.82 | 4.53 | 56.25 |

**Table A5.** Jackknife statistics of sample mean, SD and AIC values of sensitive properties for example 3.

|  |  |  |  |
| --- | --- | --- | --- |
| Statistic |  | UCS (MPa) | GSI |
| Jackknife Mean | Jackknife COV | Jackknife Mean | Jackknife COV | Jackknife Mean | Jackknife COV |
| SampleMean | 17.7936(17.8132) | 0.1068(0.1025) | 65.4541(65.5466) | 0.1296(0.1216) | 49.1364(49.1599) | 0.0909(0.0868) |
| SampleSD | 8.7066(8.4903) | 0.0781(0.0799) | 38.7694(37.6074) | 0.1487(0.1380) | 20.4241(19.8301) | 0.1445(0.1402) |
|  | 127.7827(159.3626) | 0.0257(0.0227) | 179.7242(224.5450) | 0.0359(0.0278) | 157.4053(196.1248) | 0.03960.0364 |
|  | 129.4613(161.3350) | 0.0340(0.0294) | 177.2287(221.4748) | 0.0381(0.0309) | 168.2413(209.1056) | 0.0313(0.0323) |
|  | 126.6316(157.7985) | 0.0239(0.0222) | 176.4868(220.6996) | 0.0331(0.0262) | 158.4897(196.9119) | 0.0458(0.0412) |
|  | 127.9611(159.6053) | 0.0275(0.0240) | 176.4478(220.5863) | 0.0348(0.0278) | 163.4663(203.5655) | 0.0294(0.0290) |
| Note: Bootstrap statistics are listed inside parentheses for comparisons. |

**Table A6.** Original sample of rock properties for example 4.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| No. |  | UCS (MPa) |  (GPa) | GSI |
| 1 | 5.67 | 87.64 | 26.5 | 94 |
| 2 | 12.00 | 77.33 | 45 | 92 |
| 3 | 19.12 | 171.00 | 37 | 88 |
| 4 | 12.67 | 76.00 | 53.4 | 90 |
| 5 | 8.83 | 147.26 | 38 | 87 |
| 6 | 9.45 | 92.00 | 32 | 89 |
| 7 | 8.02 | 94.50 | 39 | 90 |
| 8 | 11.78 | 82.33 | 42 | 87 |
| 9 | 9.45 | 98.37 | 33 | 94 |
| 10 | 11.34 | 145.91 | 30 | 90 |
| 11 | 24.01 | 106.88 | 44 | 94 |
| 12 | 18.25 | 120.42 | 25 | 90 |
| 13 | 10.01 | 114.33 | 52 | 92 |
| 14 | 11.00 | 103.65 | 40 | 94 |
| 15 | 12.03 | 119.87 | 37 | 92 |
| 16 | 6.91 | 109.55 | 35 | 91 |
| 17 | 7.60 | 114.50 | 40 | 90 |
| 18 | 11.17 | 89.00 | 27 | 77 |
| 19 | 11.81 | 133.56 | 39 | 90 |
| 20 | 12.14 | 139.77 | 37 | 98 |
| 21 | 17.00 | 127.22 | 40 | 88 |
| 22 | 20.02 | 97.44 | 38 | 90 |
| 23 | 14.05 | 131.32 | 42 | 97 |

**Table A7**. Jackknife statistics of sample mean, SD and AIC values of sensitive properties for example 4.

|  |  |  |
| --- | --- | --- |
| Statistic | UCS (MPa) |  (GPa) |
| Jackknife Mean | Jackknife COV | Jackknife Mean | Jackknife COV |
| Sample Mean | 112.1674(112.2209) | 0.0472(0.0453) | 37.9087(37.9525) | 0.0402(0.0382) |
| Sample SD | 24.7746(24.0306) | 0.1506(0.1385) | 7.1249(6.9105) | 0.1678(0.1571) |
|   | 172.3768(214.1386) | 0.0401(0.0302) | 126.7141(156.4705) | 0.0598(0.0479) |
|   | 171.1706(212.7665) | 0.0367(0.0293) | 126.9900(156.9989) | 0.0550(0.0444) |
|  | 173.3615(215.1851) | 0.0418(0.0301) | 127.6928(157.5137) | 0.0590(0.0501) |
|   | 171.3460(213.0658) | 0.0372(0.0289) | 126.6737(156.6882) | 0.0561(0.0457) |
| Note: Bootstrap statistics are listed inside the parentheses for comparisons. |

**Reference**

Brown, E.T., 1980. Underground excavations in rock. CRC Press.

Hoek, E., Carranza, C., Corkum, B., 2002. Hoek-brown failure criterion – 2002 edition. Proceedings of NARMS-Tac 1(1),267-273.

Hoek, E., Diederichs, M.S., 2006. Empirical estimation of rock mass modulus. Int. J. Rock Mech. Min. Sci. 43(2), 203–215.

Hajiabdolmajid, V., Kaiser, P.K., Martin, C.D., 2002. Modelling brittle failure of rock. Int. J. Rock Mech. Min. Sci. 39(6), 731–741.

Walton, G., 2019. Initial guidelines for the selection of input parameters for cohesion-weakening-friction-strengthening (CWFS) analysis of excavations in brittle rock. Tunn. Undergr. Sp. Technol. 84, 189–200.

Zhao, X., Cai, M., Cai, M., 2010. Considerations of rock dilation on modeling failure and deformation of hard rocks—a case study of the mine-by test tunnel in Canada. J. Rock Mech. Geotech. Eng. 2(4), 338–349.