**Appendix**

In displacement-based FE analysis, the traditional Mohr-Coulomb yield function presents a number of computational difficulties due to the gradient discontinuities which occur at the tip of the yield surface and the edges of the hexagonal yield surface pyramid. To avoid these computational difficulties, a number of methods have been proposed to remove the associated gradient singularities. In the present paper, the method proposed by Abbo and Sloan (1995) has been adopted, and this is briefly described below.

A hyperbolic approximation in the meridional plane is used to eliminate the tip singularity. In (,) space, the hyperbolic approximation to the Mohr-Coulomb yield criterion is shown in Fig. A1



Fig. A1 Hyperbolic approximation to Mohr-Coulomb yield criterion [after Abbo (1997)].

The equation of the hyperbola in Fig.A1 can be mathematically described by:

 (A1)

in which,

 (A2)

 (A3)

 (A4)

 (A5)

 (A6)

We have used Eq.(A1) to model the Mohr-Coulomb yield function. Apparently in Fig.A1, *a* is the distance of the Mohr-Coulomb yield surface tip and the hyperbola tip, and a smaller value of *a* represents a closer approximation of the Mohr-Coulomb yield surface. The hyperbolic yield surface with various *a* values is displayed in Fig. A2.



Fig. A2 Hyperbolic approximation to Mohr-Coulomb meridional section [after Abbo (1997)].

More details of the hyperbolic yield surface can be found in Abbo (1997) and He et al. (2019).