VII Brazilian Symposium on Rock Mechanics – SBMR 2016
Rock Mechanics and Rock Engineering for Innovation and Development
ISRM Specialized Conference 19-22 October, Belo Horizonte, Minas Gerais, Brazil

Elasto-Plastic Analysis Of Stresses In The Pillar Zone Of Twin Interacting Horse Shoe Tunnels

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SUMMARY: In Indian subcontinent single horse shoe tunnel section has been generally used in the hydroelectric power projects as well as in railways and highways projects. But with increasing demand multiple horse shoe tunnels are also a feasible option. Therefore the need arises for a detailed interaction analysis between multiple horse shoe tunnels and hence a systematic parametric analysis has been carried out and reported in this paper. The present study depicts the plain strain elastic and elasto-plastic finite element analysis of two parallel interacting horse shoe deep tunnels. For the elasto-plastic analysis Hoek-Brown yield criteria has been adopted. Three pillar width (W) to diameter (D) ratios (W/D) have been introduced for each of the three considered *in situ* stress ratios (Ko = 0.5, 1.0 and 1.5) in the rock mass. The tunnels have been considered to be excavated simultaneously. Variation of principal stresses in the pillar zone and at the tunnel boundary have been studied in the analysis. The results have also been compared with the results of that excavation of a single horse shoe tunnel. It is concluded that for W/D = 0.3, in the case of elasto-plastic analysis of interacting tunnels most of the rock mass in the pillar zone shows yielding resulting in the development of very low principal stresses. For elasto-plastic analysis of interacting and single tunnels, it is observed that the difference in major principal stresses are largest for Ko = 1.5 and least for Ko = 0.5 at W/D = 0.3. From the study of comparison of principal stresses in interacting tunnels (elasto-plastic and elastic analysis), it is founded that difference in principal stresses are maximum for Ko = 0.5 and least for Ko = 1.5 at the centre of pillar for higher W/D of 1.2. For lower W/D of 0.3, marginal difference isobserved between principal stresses for the three *in situ* stress ratios.

KEYWORDS: deep tunnels, finite element analysis, Hoek-Brown yield criterion, underground opening.

1 INTRODUCTION

Nowadays construction of multiple tunneling in urban areas are mostly taking place due to less availability of land for infrastructure development. When tunnels are excavated in close proximity, there exists an interaction effect between the tunnels which significantly affects the existing stress field and generates deformations around the excavation periphery (Fotieva and Sheinin, 1966; Lo and Ramsay, 1991; Soliman et al., 1993; Karakus and Fowell, 2003; Mohamad et al., 2010; Chakeri et al., 2011; Salim, 2013; Satici and Unver et al., 2015; Fu et al., 2015; Fang et al., 2016). The deformed shape of tunnels largely depends on the pillar width between the tunnels, depth of tunnels, type of support, method of installation of tunnels, excavation sequence and plastic yielding of the surrounding medium (Ghaboussi and Ranken, 1977; Kim et al., 1996; Addenbrooke and Potts, 2001; Sharma et al., 2001; Chehade and Shahrour, 2008; Chen et al., 2009; Huang et al., 2011; Zhang et al., 2013;). Mostly the available closed-form solutions involve only circular openings therefore only numerical analysis are carried out for the study of the openings with conventional shapes and excavated in elasto-plastic rock masses (Gercek, 2005). In this paper interaction of two horse shoe tunnels excavated in a rock mass representing Indian geological conditions have been analyzed and presented. Plain strain elastic and elasto-plastic finite element analysis have been considered because longitudinal axes of tunnels are parallel to each other and also to principal stress components of existing stress field (Gercek, 2005). Along with the shape of tunnels, effect of pillar width and *in situ* stress ratio have been studied in this research. Results of stresses developed in twin tunnels have also been compared with that of a single tunnel in both elastic and elasto-plastic condition of the surrounding rock mass.

2 GEOTECHNICAL PROPERTIES OF THE ROCK MASS

The rockmass considered in the analysis is good quality basalt which is found abundantly in western coast of Indian peninsula (Srivastava, 1985). Table 1 describes the geological and geotechnical properties of the intact rock and rock mass used in the modeling and analysis.

Field stress ratio (Ko) is the next important parameter used in the finite element analysis which is considered as 0.5, 1.0 and 1.5 by using different approaches (Hoek and Brown, 1982; Sheorey, 1994; Zhang, 2005). Vertical stress (σ_v) is 6.75 MPa (Srivastava, 1985).

3 NUMERICAL MODELLING

The maximum height and width of the section of a horse shoe tunnel is 8.0 m which is generally used in hydroelectric projects and also in highway and railway networks (Srivastava, 1985).

Table 1. Geotechnical properties of intact rock and rock mass

Intact Rock properties		
Unconfined Compressive Strength, (UCS)	122.364 MPa	(Hoek and Brown, 1982)
Young's modulus, (E)	35000 MPa	(Srivastava, 1985)
Tensile strength, (σ_t)	0.2879 MPa	(Hoek et al., 2002)
Poisson's ratio, (υ)	0.21	(Srivastava, 1985)
Unit weight, (Y)	0.028 MPa/m	(Srivastava, 1985)
Cohesion, (c)	1.752 MPa	(Hoek et al., 2002)
Friction angle, (ϕ)	48.34°	(Hoek et al., 2002)
Hoek-Brown material constant, (m_i)	17	(Hoek and Brown, 1982)
Disturbance factor, (D)	0.8	(Hoek et al., 2002)
Rock Mas Properties		
m_b	1.7	(Eberhardt, 2012)
s	0.004	(Eberhardt, 2012)
(Geological strength index), GSI	62	(Hoek and Brown, 1997)
E	6734 MPa	(Hoek and Diederichs, 2006)
Residual Values		
m_b	0.2206 (resid.)	(Cai et al., 2007)
s	0.00001575(resid.)	(Cai et al., 2007)
c	0.7010 Mpa (resid.)	(Cai et al., 2007)
ϕ	32.21° (resid.)	(Cai et al., 2007)
GSI	27.01(resid.)	(Cai et al., 2007)

Finite element software Phase^2 was used for modeling and analysis purpose. To simulate the infinite extent of the geological medium, the external boundary of the finite element discretization has been fixed at eight times the radius of the opening (Kulhawy, 1974). The outer boundary of the mesh is assumed to be rigid and rough. For the purpose of analyses of the two interacting tunnels, depth of tunnels from ground surface equal to 250 m have been adopted (Srivastava, 1985). Three pillar width to tunnel diameter (W/D) ratios of 0.3, 0.6 and 1.2 have been chosen to study the variation of interaction effects (Ghaboussi and Ranken 1977). Both the tunnels have been considered to be excavated simultaneously. On the pillar side, where stress concentration is expected, finer mesh is used. Larger size elements are used away from the tunnel boundary whereas at tunnel boundary finer mesh is used. Three noded triangular elements were chosen as mesh element type. Material type was chosen as elastic as well as plastic for the analysis of different cases. Failure criteria was chosen as original Hoek-Brown failure criteria because it is a good rock mass controlled by tightly interlocking angular rock pieces. With this type of rock masses original Hoek Brown criteria works well (Hoek et al., 2002).

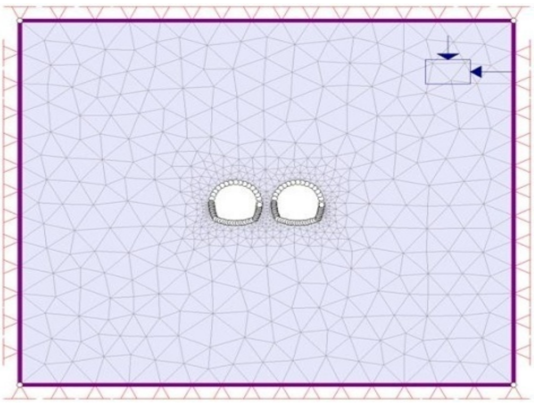
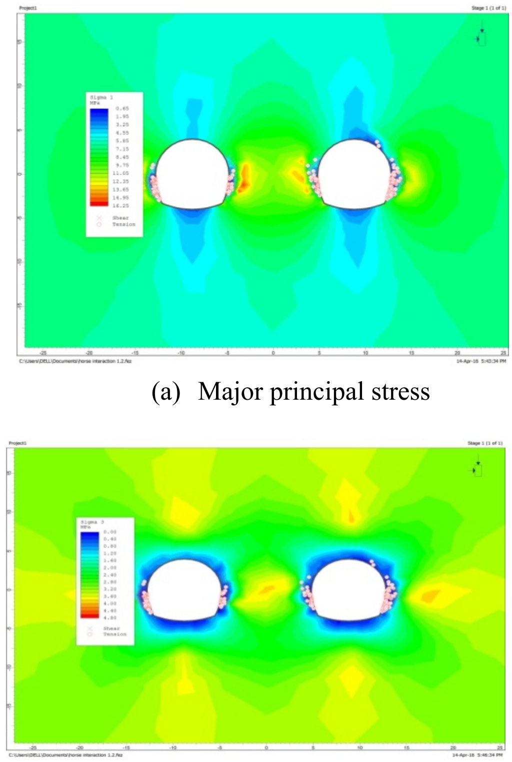


Figure 1. Numerical model of tunnel in basalt rock mass with W/D = 0.3., Ko = 1.5

Different numbers of nodes and elements for different W/D ratios are used for finite element discretizations as the area occupied under pillar zone are different for different W/D ratios. For W/D ratios of 0.3, 0.6 and 1.2 the mesh has 1412, 1602 and 1686 elements and 797, 892 and 935 nodes respectively.

4 DISCUSSIONS OF RESULTS

4.1 Variation Of Principal Stresses Along Pillar Width



(a) Major principal stress

(b) Minor principal stress

Figure 2. Variation of principal stresses and yielded mesh elements around interacting tunnels for W/D = 1.2, Ko = 0.5, elasto-plastic analysis

Figure 3 shows the variation of principal stresses along pillar width for W/D = 1.2 for elastic analysis. It is observed that at tunnel boundary, major principal stresses are larger than that observed at the centre of pillar zone. Also at tunnel boundary, for Ko = 0.5 major principal stresses have the highest value whereas for Ko = 1.5 values are found to be least. At centre of pillar zone, major principal stresses as well as minor principal stresses are highest for Ko = 1.5 and least for Ko = 0.5. It is observed that at tunnel boundary minor principal stresses have marginal difference.

Figure 4 shows the variation of principal stresses along pillar width for W/D = 1.2 for elasto-plastic analysis. It is observed that in case of elasto-plastic analysis, major principal

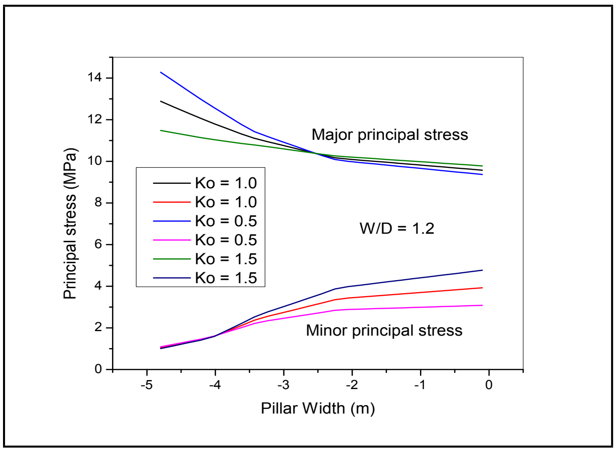


Figure 3. Variation of principal stress along pillar width – elastic analysis

stresses are larger at centre of pillar zone as compared with that at tunnel boundary. This shows reversal in trend as that for elastic analysis. Also the differences in major and minor principal stresses for three *in situ* stress ratios is observed to be marginal at tunnel boundary and at centre of pillar zone.

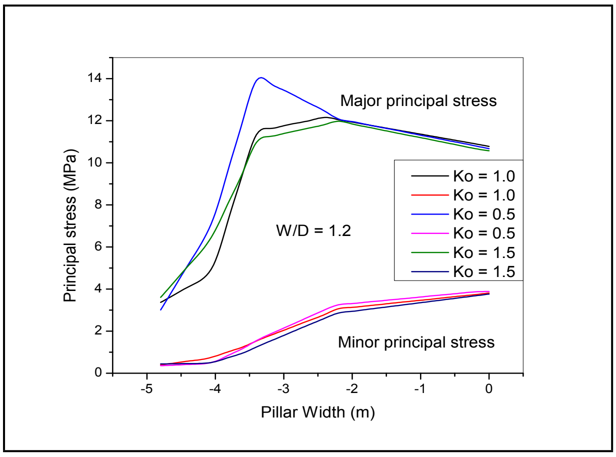


Figure 4. Variation of principal stress along pillar width – elasto-plastic analysis

Figure 5 shows the variation of principal stresses along pillar width for W/D = 0.6 for elastic analysis. In this case major principal stresses are observed larger both at the tunnel boundary as well as at the centre of the pillar zone as compared with W/D = 1.2. Major principal stresses are observed largest for Ko = 0.5 and least for Ko = 1.5 at tunnel boundary but at the centre of pillar zone, the difference is marginal. Minor principal stresses shows marginal difference in thiscase.

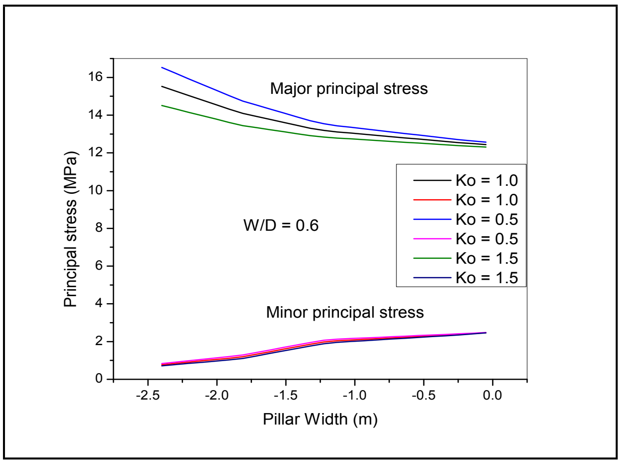


Figure 5. Variation of principal stress along pillar width – elastic analysis

For the elasto-plastic analysis for W/D = 0.6, the variation of principal stresses along pillar width is shown in figure 6. At centre of the pillar zone, the major principal stresses are comparatively much higher than that observed for the case of W/D = 1.2 because of the interaction effects that developed due to closeness of the tunnels. Major principal stresses are observed largest for Ko = 0.5 and least for Ko = 1.5 both at the tunnel boundary and at the centre of the pillar zone. Minor principal stresses have the marginal difference for three *in situ* stress ratios.

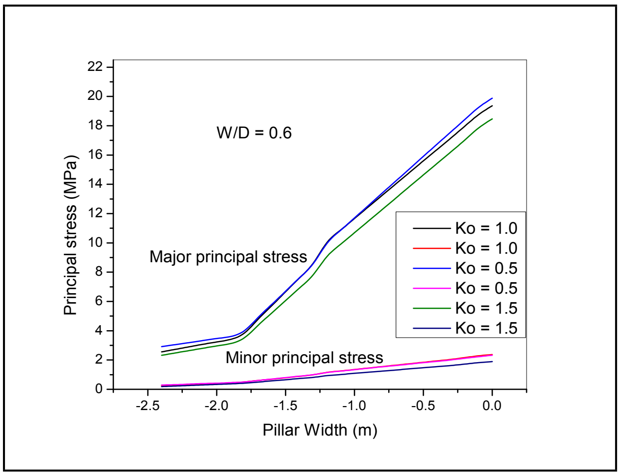


Figure 6. Variation of principal stress along pillar width – elasto-platic analysis

Variation of principal stresses along pillar width for W/D = 0.3 for elastic analysis is shown in figure 7. Major principal stresses have much higher value at the tunnel boundary as compared to cases of Ko = 1.2 and 0.6. Major principal stresses are largest for Ko =0.5 and

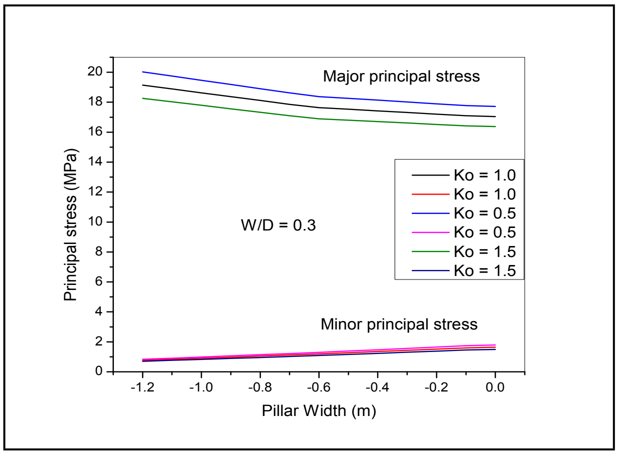


Figure 7. Variation of principal stress along pillar width – elastic analysis

least for Ko = 1.5 both at the tunnel boundary and centre of pillar zone. Minor principal difference shows the marginal difference for three *in situ* stress ratios.

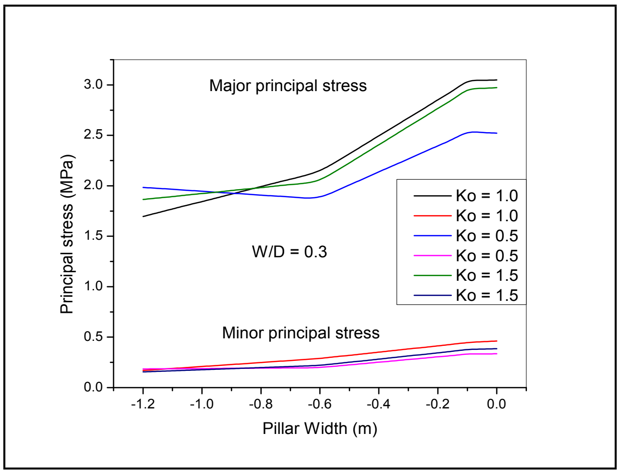


Figure 8. Variation of principal stress along pillar width – elasto-plastic analysis

Variation of principal stresses along pillar width for W/D = 0.3 for elasto-plastic analysis is shown in figure 8. The principal stresses in this case are having much lesser values especially at the centre of the pillar zone due to the yielding of most of the rock material within the pillar area. Major principal stresses are largest for Ko = 0.5 and least for Ko = 1.0 at the tunnel boundary. But the pattern reverses at the centre of pillar zone. Minor principal stresses are having marginal difference at the tunnel boundary but at centre of pillar zone, minor principal stresses are largest for Ko = 1.0 and least for Ko = 0.5.

4.2 Comparison Of Principal Stresses Between Interacting And Single Tunnels (Elastic Analysis)

Figure 9 shows the variation of percentage difference between principal stresses with W/D for interacting and single tunnel at tunnel boundary and at centre of pillar zone for elastic analysis.

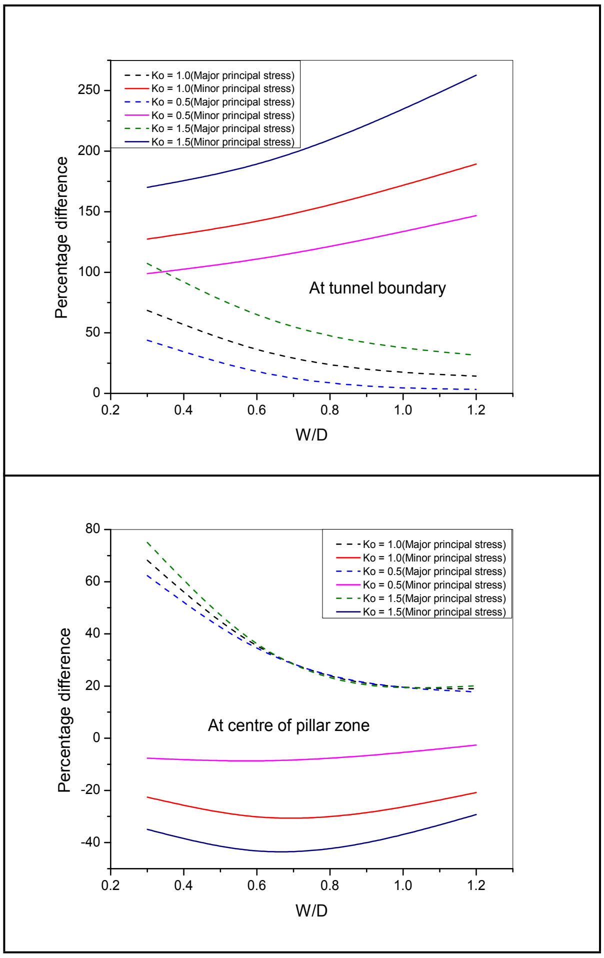


Figure 9. Variation of percentage difference in principal stresses between interacting and single tunnels with W/D (elastic analysis)

The percentage difference for major principal stresses between single and interacting tunnels is largest for W/D = 0.3 and Ko = 1.5. As the W/D increases to 1.2 the percentage difference tends to reach zero value which is expected also because at higher W/D ratio, the interaction effect will be weaken and both the tunnels will behave as a single tunnel. At W/D = 0.3 and for Ko = 1.5 the percentage difference between major principal stresses is highest which tends to become zero as W/D reaches to 1.2. The percentage difference between minor principal stresses are having negative values at W/D = 0.3 which tends to become zero as W/D approaches to 1.2.

4.3 Comparison Of Principal Stresses Between Interacting And Single Tunnels (Elasto-Plastic Analysis)

Variation of percentage difference for principal stresses between interacting and single tunnels with W/D for elasto-plastic analysis at tunnel boundary and at centre of pillar zone are shown in figure 10. It is observed that at tunnel boundary from W/D = 0.3 to W/D = 0.6, the slope of the curves representing percentage difference in major principal stresses are higher as compared to the slope of the curves from W/D = 0.6 to W/D =1.2. The reason is that beyond W/D = 0.6 to W/D =1.2 the interaction effect become weaken, and therefore percentage difference tends to minimize as two tunnels now behave as single tunnels. At W/D = 0.3, most of the rock material at the tunnel boundary gets yielded resulting in residual stresses which ultimately gives the lesser percentage difference between principal stresses of interacting and single tunnels. Percentage difference is largest for Ko = 1.0 and least for Ko = 0.5.

At centre of pillar zone, the percentage difference is negative for principal stresses at W/D =0.3 further it become positive and reach highest positive value, from where it starts to decrease and tends to reach zero value at W/D 1.2. Negative value is due to the fact that due to yielding of rock material in pillar zone for interacting tunnels results in lesser residual stresses as compared to stresses developed at

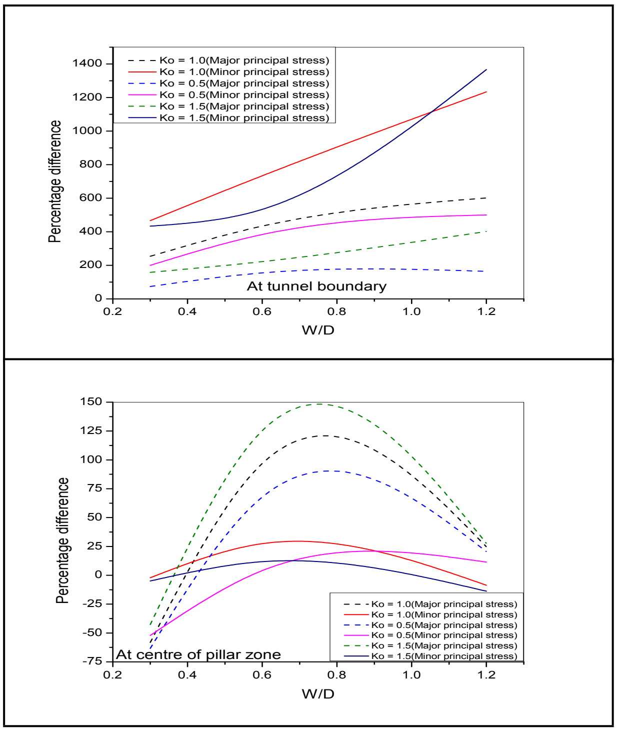


Figure 10. Variation of percentage difference in principal stresses between interacting and single tunnels with W/D (elasto-plastic analysis)

that location in case of single tunnels where the rock material is not yielded. Further when the tunnels are at larger W/D than 0.3, the developed stresses in interacting tunnels become comparatively higher as compared to stresses of that developed in a single tunnel resulting in a positive percentage difference which again tends to become zero at W/D = 1.2 as interaction effect tends to die at larger W/D. The difference in major principal are largest for Ko = 1.5 and least for Ko = 0.5.

4.4 Comparison Of Principal Stresses In Interacting Tunnels (Elasto-Plastic And Elastic Analysis)

Variation of percentage difference in interacting tunnels for elasto-plastic and elastic analysis at tunnel boundary and at the centre of pillar zone for major and minor principals stresses are shown in figure 11. Large negative percentage differences in major as well as in minor principal stresses are observed at lower W/D ratio of 0.3 due to lesser value of residual stresses developed due to yielding of rock mass around tunnel boundary in case of elasto-plastic analysis. Further increase in W/D tends to reduce the percentage difference due to subsequent decrease in interaction effects between tunnels. Principal stresses are maximum for Ko = 1.5 and least for Ko = 0.5 at tunnel boundary for higher W/D of 1.2. For lower W/D of 0.3, marginal difference is observed between principal stresses for three *in situ* stress ratios.

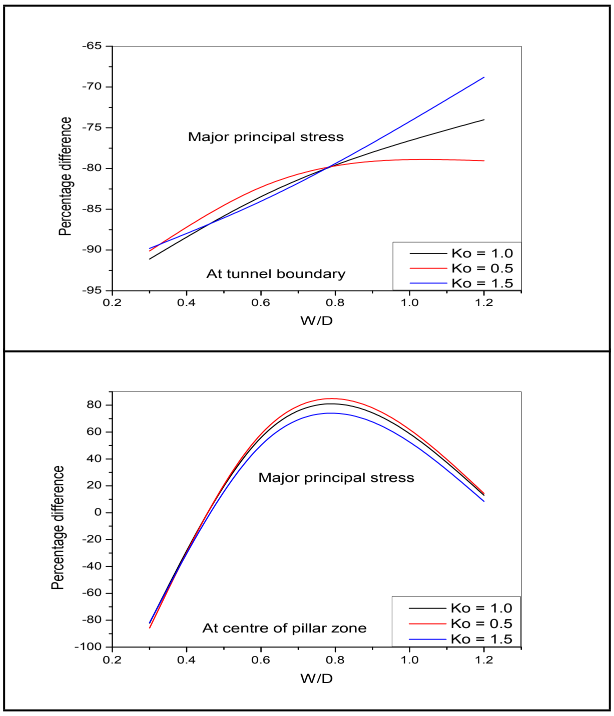


Figure 11. Variation of percentage difference in major principal stresses between interacting tunnels (elasto-plastic analysis) and interacting tunnels (elastic analysis) with W/D

At lower W/D of 0.3 in case of elasto-plastic analysis, most of the rock mass near centre of pillar yielded which results in residual stresses which are lesser than that of stresses developed in case of elastic analysis. That is why the percentage difference in principal stresses shows negative values for lower W/D of 0.3 for all insitu stress ratios. Beyond W/D of 0.6, stresses in elasto-plastic analysis become higher than that of stresses in elastic analysis resulting in positive percentage difference near W/D of 0.6 or more. After that it starts to decrease and tends to reach zero value as the interaction effect gets weaker and less yielding of rock mass near centre of pillar at higher W/D of 1.2 or more. Principal stresses are maximum for Ko = 0.5 and least for Ko = 1.5 at centre of pillar for higher W/D of 1.2. For lower W/D of 0.3, marginal difference is observed between principal stresses for three *in situ* stress ratios

5 CONCLUSIONS

From the elastic and elasto-plastic finite element analysis of single and interacting deep horse shoe tunnels considering three W/D and three *in situ* stress ratios, following conclusions have been drawn :

In case of comparison between interacting and single tunnels for elastic analysis, it is observed that the percentage difference in principal stresses between single and interacting tunnels is largest for W/D = 0.3 and Ko = 1.5 which tends to reach zero value at higher W/D ratio and low *in situ* stress ratio.

In case of comparison between interacting and single tunnels for elasto-plastic analysis, it is observed that the percentage difference in major principal stresses between single and interacting tunnels is largest for Ko = 1.5 and least for Ko = 0.5 at W/D = 0.3.

For W/D = 0.3, in the case of elasto-plastic analysis of interacting tunnels it is observed that most of the rock mass in the pillar zone yields resulting in the development of very low principal stresses.

In case of interacting tunnels for comparison between elastic and elasto-plastic analysis, it is observed that difference in principal stresses are maximum for Ko = 0.5 and least for Ko = 1.5 at centre of pillar for higher W/D of 1.2. For lower W/D of 0.3, marginal difference is observed between principal stresses for three *in situ* stress ratios.

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