

EFFECT OF ROCK WEATHERING ON THE SEISMIC STABILITY OF DIFFERENT SHAPES OF THE TUNNEL

¹Mohammad Zaid ([0000-0001-6610-8960](https://orcid.org/0000-0001-6610-8960)), ^{2,*} Mohd. Faraz Athar (<https://orcid.org/0000-0003-3409-567X>), ³Md. Rehan Sadique (<https://orcid.org/0000-0002-9570-6801>)

¹ P.G Student, Dept. of Civil Eng., ZHCET, Aligarh Muslim University, U.P, India,

² U.G Student, Dept. of Civil Eng., ZHCET, Aligarh Muslim University, U.P, India

³ Assistant Professor, Dept. of Civil Eng., ZHCET, Aligarh Muslim University, U.P, India

*faraz.athar12@gmail.com

Abstract. Tunnels in rock are integral part of contemporary old and modern smart cities in hilly terrain to provide services and transportation. Tunnels have been the lifeline of the metropolitan cities since decades. Tunnelling have reduced the time of travel, saved money, reduced number of accidents and also reduced the human impact on the ecology of the hilly regions. Hilly regions are seismically active zones and have several minor earthquakes at a shorter span of time. Himalayan mountains are young folded mountains and have been affected by several earthquakes of large magnitude in last century. Hence, stability study of tunnels in hills is very crucial. This present study focuses on the effects of rock mass weathering, due to geological and other changes, on the stability of tunnels subjected to earthquakes. The 2D plane strain elastoplastic model has been adopted for the numerical analysis using finite element software. A model of dimensions 42m x 42m has been developed having an overburden of 500 m. The different shapes of the tunnel are also varied to understand their stability. Plasticity theory of failure given by Mohr-Coulomb has been incorporated to simulate the constitutive properties of rock mass. The physical properties of basalt have been adopted for this study. The different weathering classes of basalt used in this study are fresh basalt, slightly weathered basalt, medium weathered basalt and highly weathered basalt. The earthquake data of acceleration time history has been taken from the records of the Koyna earthquake, which was a 6.4M magnitude earthquake. This study will help to understand the stability of the smart city tunnels subjected to the earthquake in hilly regions. This paper concluded that weathering has detrimental effects on the seismic stability of smart city tunnels. The deformations reduce by 34% with the increase in the depth of overburden in case of arch-shaped tunnels, in case of circular-shaped tunnels the deformations reduce by 42% and in case of horse-shoe shaped tunnels deformations reduces by 28% of deformations at shallow depth of overburden.

Keywords: Smart city Tunnels, Finite element, Mohr-Coulomb, Seismic, Koyna.

1 Introduction

Among the major civil engineering structures, underground tunnels are considered of utmost importance due to its vast uses and strategic importance. Development of smart cities is an ambitious project of 21st century [1]. In India also, few cities on hills such as Munnar (Kerala), Shillong (Meghalaya), Kodaikanal (Tamil Nadu), Ooty (Tamil Nadu), Mussoorie (Uttarakhand), Nainital (Uttarakhand), Darjeeling (West Bengal) etc., has been selected to be developed as a smart city. In this pursuit of establishing smart cities, Tunnels may serve different purposes depending upon the requirements of the particular area.

Due to rapid urbanization in the Indian subcontinent and Government projects like “smart city”, several cities are being converted into metropolitans at a very high pace. This process in old cities where availability of land is a major problem can easily be sought out by constructing underground tunnels for metros, subways, underpasses etc.

The structure with that much of importance requires high precision and accuracy while constructed, the stability of tunnels when constructed in the rock mass is also very important aspect before actual construction of the tunnel. Albino et al. [2] had presented a comparative study on the definitions of smart city provided by different sources and concluded that many cities calling themselves as smart, lacks universality. In the modern world fast transportation facility is a prerequisite for any developed country. Underground tunnels play a vital role in achieving the fast transportation facilities. Metro-rail, bullet train, high-speed highways can only be made possible by constructing underground tunnels to ensure uninterrupted traffic movement. Most of the underground tunnels are situated in metropolitans and on hills, thus, their structural safety must be ensured. The vulnerability of lands on hills to seismic events cannot be discarded.

Many researchers in the past have studied seismic vulnerability of underground tunnels [3-6]. Carlos A. Jaramillo et al. [7] shows the seismic design impact on tunnels in rock through various case histories. Several researchers carried out the study for the damage caused by an earthquake on tunnel stability [4,7,8]. The underground tunnels constructed in soil-mass are considered to be more resistant towards seismic attacks than tunnels that are constructed in rockmass [7]. Corigliano et al. [9] shows the seismic stability of deep tunnels situated in rock mass. Stratification in soil-mass also affects the stability of tunnels when subjected to dynamic loads such as earthquake [10]. Naqvi et al. [11] shows the seismic stability of tunnels constructed in jointed rock mass.

Above studies conclude that it is important to study the seismic stability of underground tunnels before going for their construction. The weathering effect of rock mass is an important consideration while constructing any structure in rock mass [12-14]. Ki-II Song studied the behavior of underground structures under the effect of spatially variable weathered rock mass and shows that the spatially variable rockmass induces large deformation as compared to the homogenous rockmass on ground surface [20].

Tunnels are of various shapes ranging from circular to horseshoe to box etc. Navid Hosseini et al. [21] analyzed the seismic stability of horseshoe tunnel for different type of rock mass. Somnath Mondal et al. [22] also carried out seismic analysis of horseshoe tunnel in soil, in both the cases numerical modelling is adopted to solve the problems. Arash Rostami et al. [23] studied the effect of different shapes of tunnel gates on the settlement of soil, their study shows that the rectangular shape has maximum settlement and circular shape has least settlement. Although, horseshoe shape has settlement similar to that of circular shape. Yamamoto et al. [24] carried out the static stability of different shapes of tunnels under the surcharge loading constructed in cohesive soil whereas Elshamy et al. [25] take the case of different shapes of twin tunnels and their behavior under soft clay soil. These studies establish that shape of the tunnel are a crucial factor for ensuring its safety against various static and dynamic conditions. Finite element analysis has been widely accepted as main tool for the design and analysis of the complex structures like tunnels [26].

In past, different parameters were adopted for the stability of tunnel by different researchers. The problem of seismic stability of tunnels on account of rock weathering along with different shape of tunnels are very rare. In this study, authors will be dealing with seismic effect under the influence of rock weathering in case of different shaped tunnels. There are many methods to analyze the problems, one can do it either by the experimental approach, or analytical approach or numerical approach etc. The experimental work requires sophisticated machineries and models to analyze the problem. On the other hand, numerical simulation is a very effective way of solving real-life problems with a mere application of computing system. The effectiveness of numerical techniques is that, it proves to be economical as a single

parameter can be varied or changed at any point of analysis without much affecting the cost of study and for any geometry or condition. The availability of digital computing system and dedicated numerical modelling software made the task easier for researchers to solve these complex real-valued problems easily and accurately. The numerical approach has been adopted for solving out the current problem. Numerical solution may be done in different ways like domain reduction method (DRM), used by Corigliano et al. [9], finite difference method used by Ki-II Song et al. [20], boundary value problem, finite element method etc. Naqvi et al. [11] and Abakanov et al. [27] used the finite element method to analyze the problem. Naqvi et al. [11] used Abaqus/CAE to analyze the problem, whereas Abakanov et al. [27] used Ansys software for numerical solution of their problem. The finite element method is a bit easier to deal with, in comparison to the other numerical techniques available. The authors have adopted a finite element technique to carry out the present study.

In this study, a 2D elastoplastic model of the tunnel is generated through Abaqus/CAE. The analysis is carried out for various tunnel geometries such as circular, horseshoe, and arch shape tunnels. The analysis has been performed for Basalt rock on different stages of weathering. Stages of weathering considered are fresh basalt, slightly weathered, medium weathered, to highly weathered basalt. The seismic analysis has been done considered Koyna earthquake (1967) of magnitude 6.4M on Richter scale under different depth of tunnel. The analysis is carried out for the depth of 5 m, 10 m, 17.5 m from the crown to the ground level.

2 Numerical Modelling and Analysis

A 2D elastoplastic model of the tunnel is generated through finite element software Abaqus. The tunnel box is of the dimensions 42m x 42m and the tunnel has the diameter of 7 m in all the three geometrical cases. The circular, horseshoe and arch shape tunnel lining has also been adopted in the study, the thickness of the tunnel lining is taken as 120 mm, the height of tunnel from crown to invert in all the cases is 7 m. the tunnel geometries for circular, horseshoe, and arch shape tunnel is shown in



Figure 1.

(a)

(b)

(c)

Fig. 1. Geometry of (a) Arc, (b) Circular, and (c) Horse Shoe tunnels

Mohr-Columb elastoplastic constitutive material model is adopted for the material properties of the tunnel. The material parameter for finite element modelling are shown in Table 1. The concrete lining is modelled as linear elastic in Abaqus/CAE. The properties of 2D plain strain finite element model has been taken up from Gahoi et al. [12-19].

Table 1. Input parameters of the numerical model

Weathering Stage	Density (kg/m ³)	Young Modulus (GPa)	Poisson's Ratio	Friction Angle (°)	Cohesion (MPa)
W ₀	2960	46.5	0.186	63.38	26.25
W ₁	2740	20.6	0.260	53.71	18.50
W ₂	2470	2.80	0.272	33.33	8.08

W_3	1820	0.6	0.272	43.87	1.64
Concrete	2400	31.6	0.150	-	-

5 Analysis

The analysis has been carried out in two steps using Abaqus. The first is Static General step and second one is Dynamic Implicit Step. The Static step analysed the settlement of the tunnel under self-weight during static conditions with an overburden of 500m at the top. Whereas, in dynamic step earthquake loading has been applied and its effect on the tunnel geometry are analysed. Earthquake loading is assigned by providing an accelerating boundary condition to the base of the model in Dynamic step. The duration of the earthquake is taken as the step time (step time = total time of earthquake occurrence) for the analysis is Dynamic step. Static step has been considered for 1 second in each case. The base of the model has been fixed in all directions in the Static step and the sides have applied for roller support by allowing deformation in the vertical direction. Figure 2 shows the loading and boundary conditions applied to the model. In Dynamic step, boundary condition at the base has been discarded for the application of earthquake.

The model has been meshed by element type CPE3R- 3 Node Linear triangular, reduced integration, and hourglass control for Rockmass excluding boundaries. The boundary elements are meshed with element type CINPE4- 4 Node Linear quadrilateral, reduced integration element in Abaqus/Standard. The meshed geometry is shown in Figure 3.

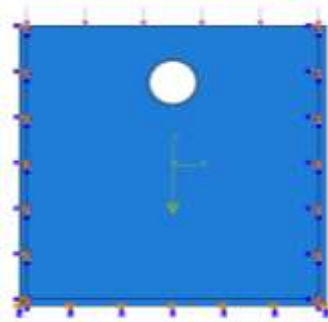


Fig. 2. Load and boundary condition assembly.

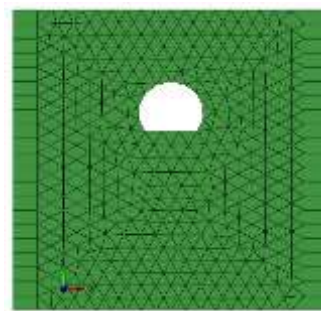


Fig. 3. Mesh of the model.

In the present study effect of Koyna earthquake (11 December 1967) were considered. The magnitude of the earthquake as recorded on Richter scale is 6.4M reported by Indian Metrological Centre. The earthquake is the consequences of the fault along the Malabar coast [28]. The acceleration versus time history curve of the earthquake is shown in Figure 4.

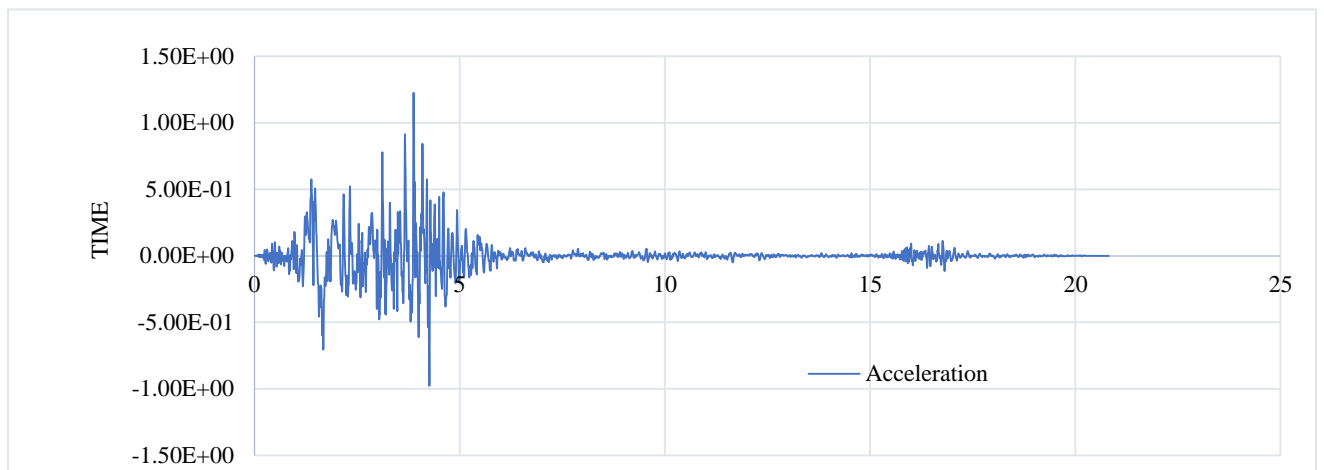


Fig. 4. Acceleration Vs. Time History of Koyna Earthquake 1967 [28]

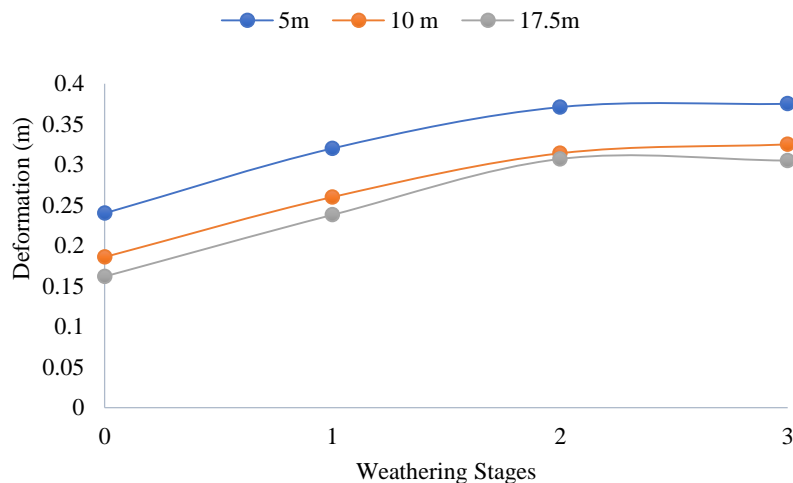
6 Result & Discussion

The study has been carried for the seismic stability of tunnel having different shapes. Weathering effect has also been considered for the stability analysis. Finite element methods analysis has been adopted and Abaqus/Implicit was used for the analysis. The results are as follows.

Figure 5 shows maximum deformation for different stages of weathering in basalt rock with varying depth of overburden for Arch, Circular, Horse Shoe shaped tunnels respectively. The graphs depict that as the depth of overburden increases the tunnels leads to stability. There is increase in magnitude of deformation as the rock leads to higher stage of weathering.

The comparison of different shapes of tunnels for different weathering stages of basalt is plotted in Figure 6. It shows the deformation behavior for different shaped tunnels with varying stages of weathering and for different depth of overburden. The figure shows that the magnitude of deformation increases with increase in stage of weathering. Thus, tunnel becomes stable for a particular depth if it is being constructed in fresh rock. For shallow tunnels (5 m depth of overburden), horse-shoe shaped tunnels are more stable as compared to arch shaped and circular shaped tunnels and the circular shape tunnels are most unstable. For intermediate depth tunnels (10 m depth of overburden), circular shaped tunnels are most stable and for deep tunnels (17.5 m depth of overburden) also circular tunnels shows more stable behavior. Figure 7 has been plotted for the comparison of different stages of weathering of basalt rock at different depth of overburden. The tunnels constructed in highly weathered rocks and medium weathered rocks shows similar behavior in terms of deformation. The deformation decreases with depth of overburden for a particular stage of weathering. The tunnels constructed in fresh (no weathering) rock are most stable.

Figure 8 and Figure 9 shows different contours for arch and circular tunnels for 10 m depth of overburden for different stages of weathering of basalt rock



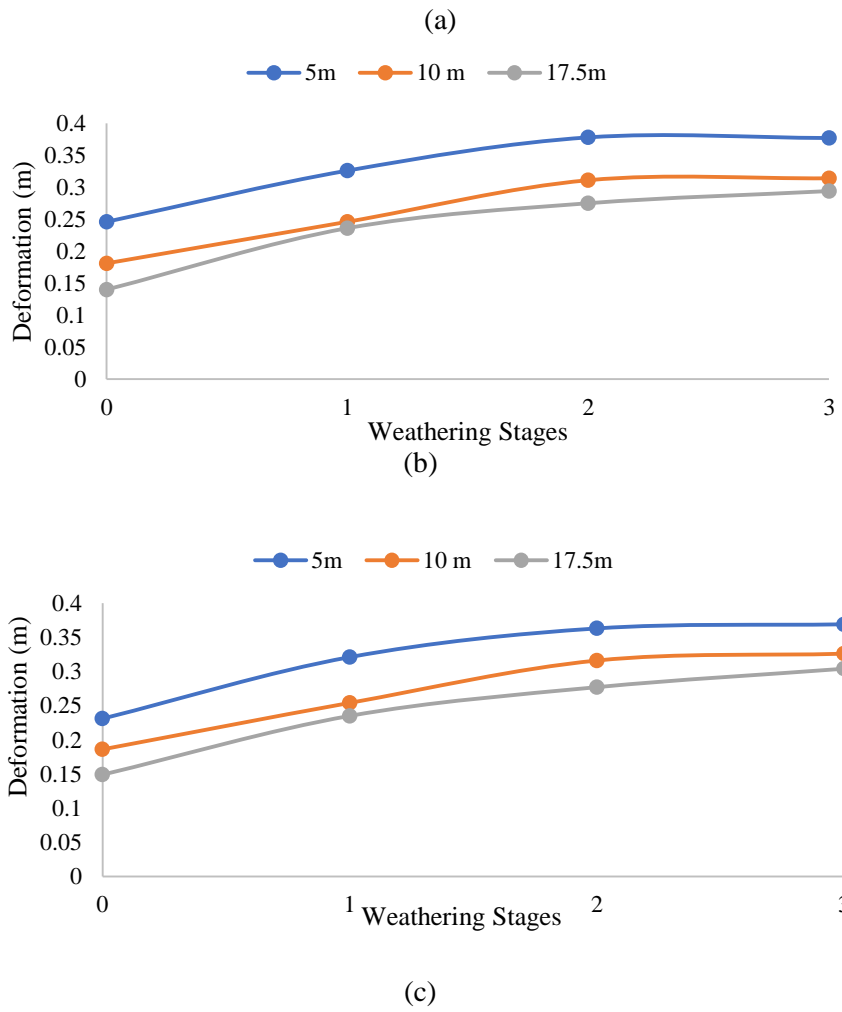
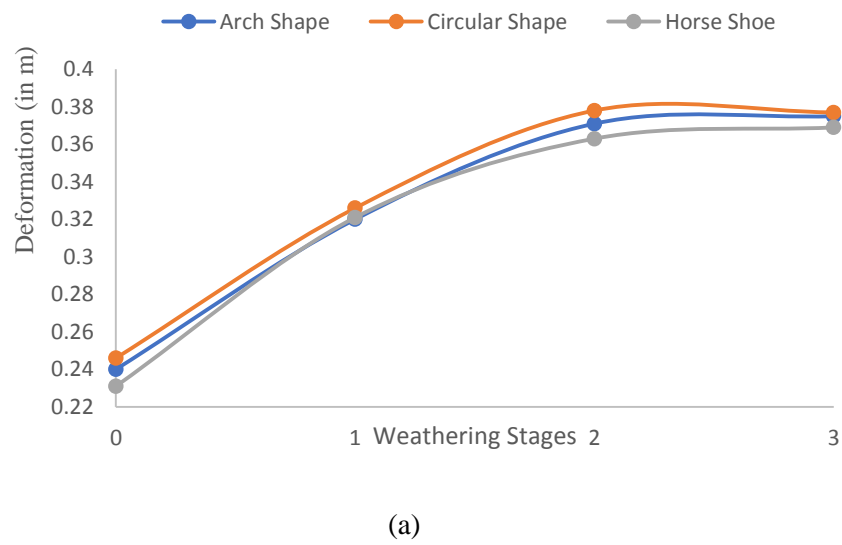
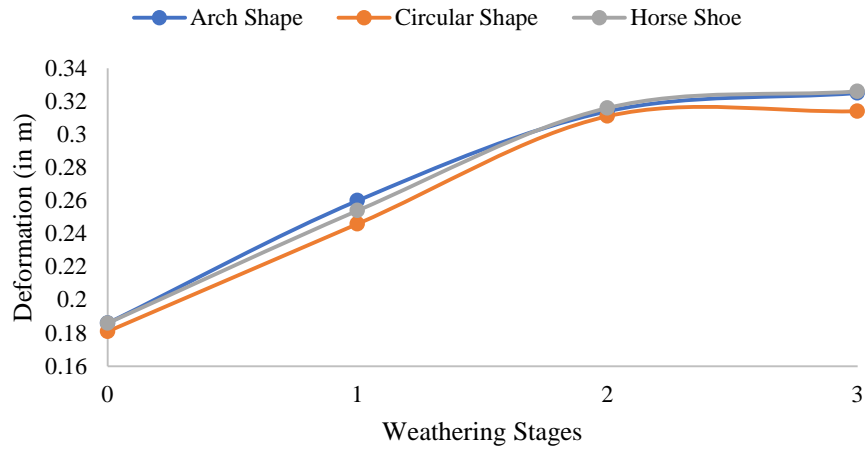
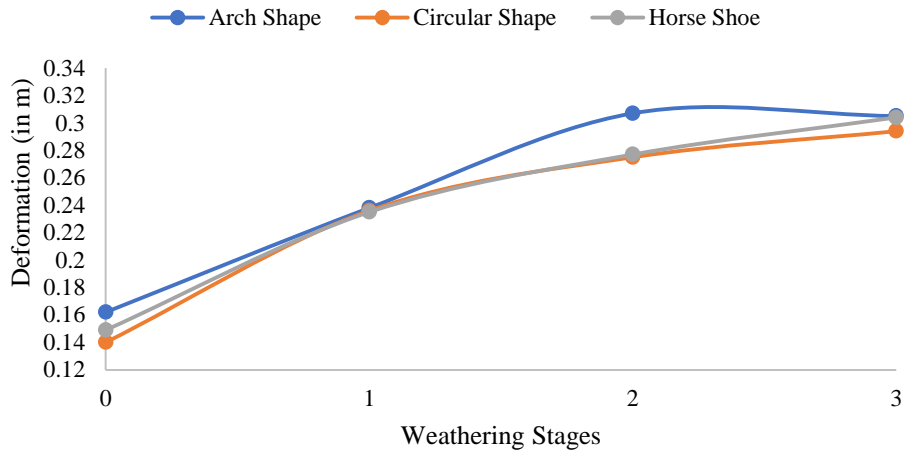


Fig. 5. Graph of Maximum Deformation vs. Weathering Stages for Different Depths of Tunnel at the crown of (a) Arch, (b) Circular, and (c) Horse Shoe Tunnel.



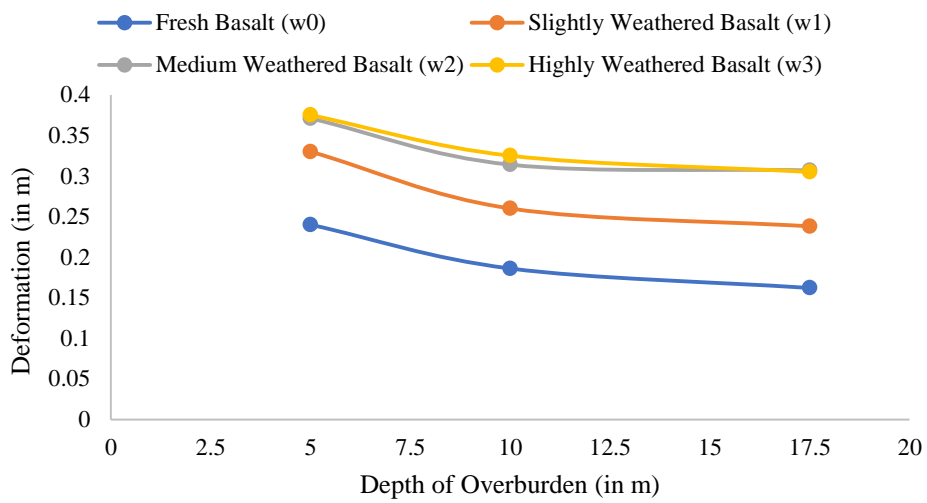


(b)

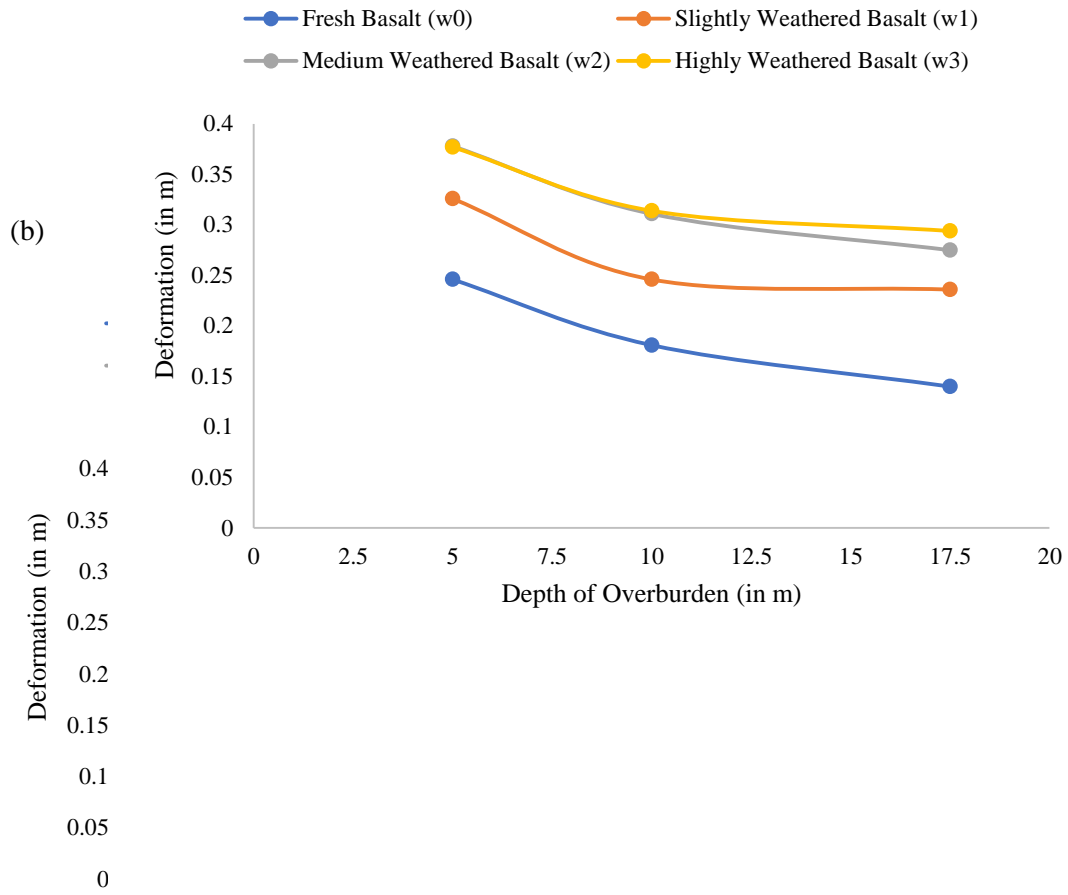


(c)

Fig. 6. Deformation Vs. Weathering Stages for comparison of Shapes of Tunnels for (a) 5m depth, (b) 10m depth, and (c) 17.5m depth, of tunnel



(a)



(c)

Fig. 7.
Deformation
Vs.
Depth
of
Overburden for
Comparison of
Different
Weathering
Stages
for (a)
5m, (b)
10m,
and (c)

17.5m

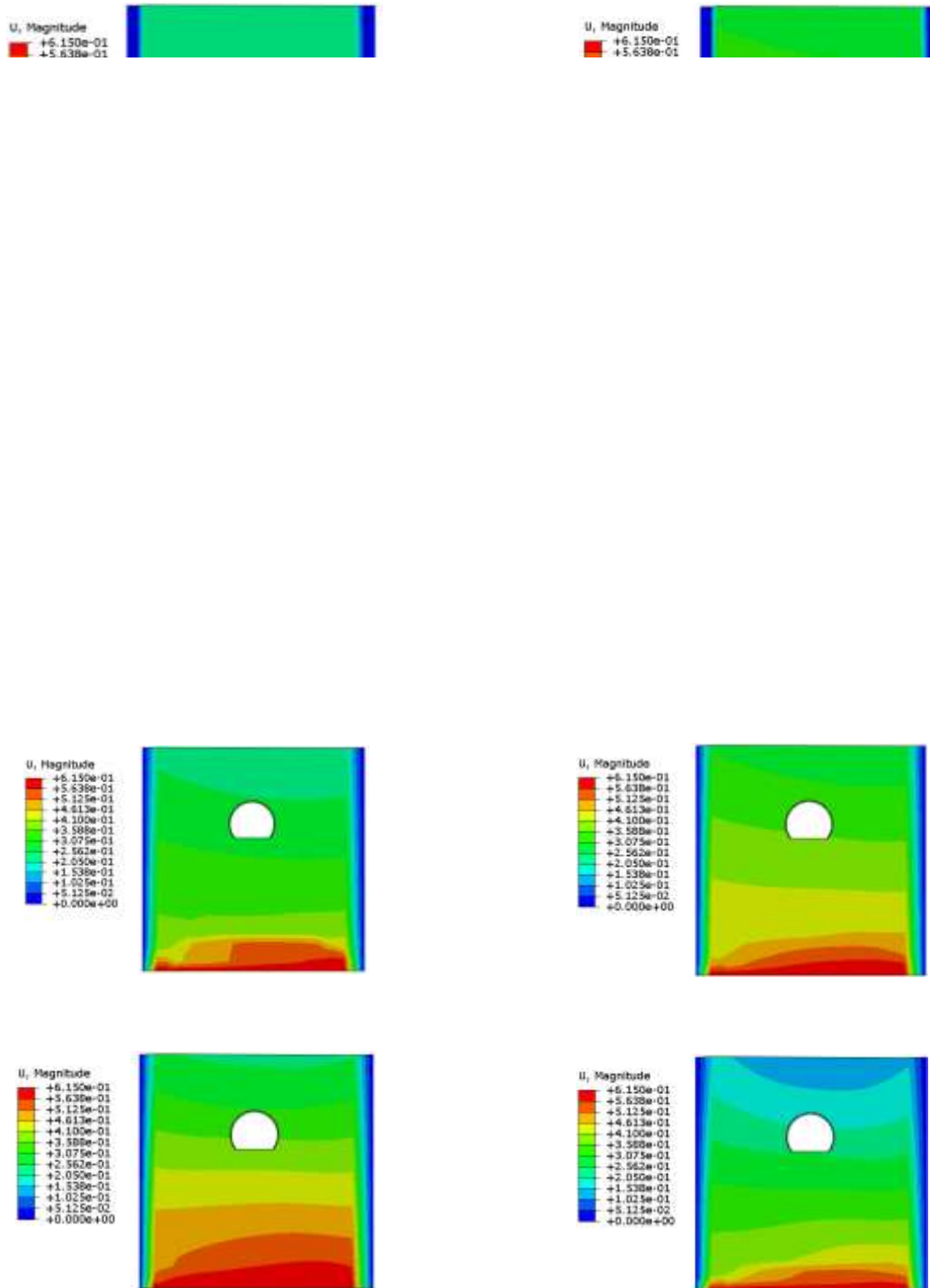


Fig. 8. Contours for Total Maximum Deformation at 10m of Overburden for Arch Tunnel for (a) Fresh Basalt(w0), (b) Slightly Weathered Basalt(w1), (c) Medium Weathered Basalt(w2), and (d) Highly Weathered Basalt(w3)

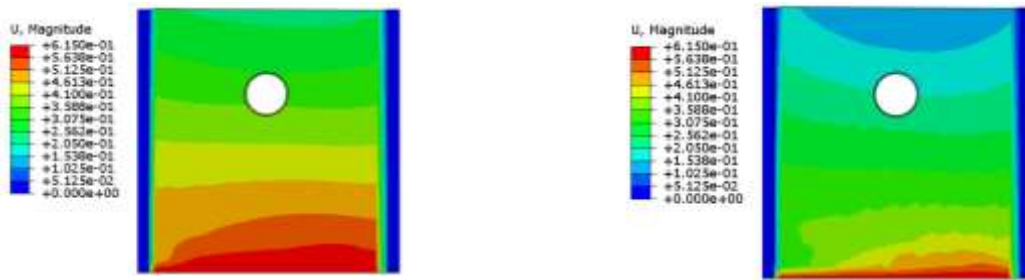


Fig. 9. Contours for Total Maximum Deformation at 10m of Overburden for Circular Tunnel for (a) Fresh Basalt(W_0), (b) Slightly Weathered Basalt(W_1), (c) Medium Weathered Basalt (W_2), and (d) Highly Weathered Basalt (W_3)

7 Conclusion

The following conclusion can be drawn from the study above:

1. Stability increases with increase in depth of tunnel for all weathering stages.
2. Fresh basalt rock is the most stable weathering stage for tunnel stability as compared to the other weathering stages of basalt rock.
3. For shallow depth tunnels, horse-shoe shaped tunnels are much stable as compared to circular and arch shaped tunnels
4. As the depth of over burden increases tunnel having circular shape becomes more stable in comparison to arch shape and horse shoe shape.
5. Irrespective of weathering stage of a basalt rock, as the depth of tunnel increases, deformations decreases leading to the stability of tunnel

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