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Finite Element Analysis of Soil Reinforced Canal Tunnel

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Abstract. Tunnel lining is permanent ground support system to the periphery of a tunnel or shaft excavation and generally constitutes 30 % to 40 % of the total cost of the tunnel. In the hilly region, terrain is undulated and it is very difficult to construct canal without elevated section or underground section. Gradient in downstream side should be maintained in canal for flow of water and if elevated ground surface is in the alignment of canal, then it is highly necessary to construct underground tunnel. Philips and Allen (1968) analysed different shapes of tunnel. Bending moment, thrust and shear coefficient were determined at various locations, and are expressed in terms of unit intensity of loading and unit internal crown radius. IS: 4880-Part IV (1971) has set basic equations for calculating various stresses in concrete lining and surrounding rock mass. Mandal and Singh (2018) has analyzed D - shaped tunnel without earth reinforcement using "GTS-NX" software.

The forces acting on tunnel lining are dead load, horizontal earth pressure, overburden pressure and water pressure. In case of fully saturated soil in backfill (rainy season and flood), the saturated unit weight of backfill soil is the most critical condition of tunnel. Empty condition of canal tunnel makes the tunnel more critical during flood with respect to stability and design. The objective of this study is to reduce the horizontal earth pressure acting on the vertical face of tunnel and study the arching effect on the crest of D – shaped tunnel. The earth reinforcement (Geo-net/Geo-grid) placed in the backfill retained by tunnel lining counterbalance the earth pressure by offering frictional resistance up to a great extent. As a result, thickness of the vertical wall of 1 D – shaped tunnel can be reduced.

Keywords: FEM[1], tunnel[2], geogrid[3], soil reinforcement[4], GTS-NX[5]

1 Introduction

In developing countries, scarcity of land occurs due to rapid increasing industrialization, development and civilization. Industrialization and urbanization cannot be stopped instead it may be limited up to an extent. One of the best alternative is to use underground space i.e. basement, cavern, tunnel, etc. The need of tunnel and underground structures is progressively growing for a variety of facilities need to be provided, i.e. water conductor system for power generation, irrigation, road traffic and underground metro railway. Also, sewerages, electrical cables in metropolitan cities, underground oil storage and for extraction of valuable ore require the construction of tunnel.

In hilly areas, so much undulation is encountered that makes construction difficult, costlier and hectic. It is necessary to make an underground or elevated structure. If a hill is encountered in the way of canal then, it becomes a compulsion to pass the canal through a tunnel, as it will be costly and tedious process to cut the hill completely.

In the process of designing tunnel, factors taken into consideration are geological strata, type of soil, seepage pressure, type of surcharge, etc. Loads considered are pressure exerted by ground, pressure exerted by water, self weight, surcharge, sub-grade reaction, etc. Subsequent loading conditions may also occur i.e. loads from the inner side of tunnel, loads throughout construction stage, earthquake loads, effect of adjoining tunnel, settlement effects and other loads.

Many Finite Element method and Finite Difference method software are available like FLAC-3D, PLAXIS, ANSYS, GTS-NX, ABAQUS, UDEC, etc to analyze tunnels and other structures. Results generated from the software are precise thus reliable and is able to compare with analytical solution.

Geogrid is a geosynthetic material used for reinforcing the soil. This material has high tensile strength and low elongation (high stiffness). The shearing resistance is high along soil reinforcement interface.

Karparapu and Bathurust (1995) has done finite element modeling (discrete type) for soil walls reinforced by geosynthetic in addition the material models employed to replicate the behavior of a variety of components in these types of structures. Tsukamoto et al. (1999) have studied the effect of geogrid on earth pressure against model retaining wall. It has been demonstrated that the active earth pressure coefficient was effectively reduced in case of unattached geogrid to the face of wall consequently, the earth pressure on the wall was found to be reduced. Zeigler (2009) has investigated the confining effect of geogrid with plane strain model wall tests. With the help of series of triaxial test, he showed the confining effect of geogrid. He concluded that the horizontal earth pressure was decreased due to geogrids and also bearing capacity of triaxial specimen increased. Ahmed et al. (2015) have done the experimental and numerical analysis to find out the role of geogrid reinforcement in reducing earth pressure on buried pipes. He concluded that the radial pressure was reduced in reinforced case as compared to the unreinforced case due to the involvement of geogrid. Banerjee et al. (2018) have done experimental and 3D finite element analysis o geocell reinforced embankments using GTS NX software. They concluded that The ultimate capacity of the reinforced embankment was four times of the capacity of unreinforced embankment. Mandal and Singh (2018) have done the finite element analysis of tunnel lining. They verified their results with USBR monogram.

In this study, the finite element analysis of tunnel lining with unreinforced and reinforced backfill has been done. Geogrid is used as a reinforcing material. Analysis has been done with varying overburden pressures (4m, 8m, & 12m). Thrust, Shear force and bending moment have been found for unreinforced and reinforced case and then compared for both the cases.

2 Finite Element Analysis

GTS-NX software has been used for finite element analysis in this work.

2.1 Problem Description

While doing the structure design of lining, earth pressure plays an important role. Two cases are analysed and then compared. First case consists of the finite element analysis of tunnel lining with unreinforced backfill and then the results were compared with USBR monogram (Mandal and Singh, 2018). The second case consists of finite element analysis of tunnel lining with reinforced backfill. Then both the cases has been compared and accordingly thickness of lining has been designed. The concept behind placing the geogrid in backfill is that the geogrid offers high frictional resistance that counterbalance a part of earth pressure induced in the backfill. As a result the resultant earth pressure gets reduced, consequently thickness of lining gets reduced. In case of reinforced backfill, the geogrid was placed in the backfill and attached to the walls of tunnel in perpendicular direction as shown in Fig. 1. Analysis has been done by varying the overburden pressure (4m, 8m & 12m).

2.2 Geometry and Model Creation

The model is created using finite element analysis software GTS-NX. A tunnel lining having 5 m height is modeled. After that, meshing has been done and 56 elements and 57 nodes has been created. After that ground meshing has been done having dimensions according to the amount of overburden to be placed above tunnel lining. Then, modeling of geogrid is done. Geogrid having 1 m length is placed at a distance of 0.5 m throughout the wall of tunnel lining (perpendicular to lining). After that boundary conditions are placed. Fixed supports are provided to the ground and geogrids are restrained against moment as it cannot takes bending. The forces acting on the tunnel lining are (1) Selfweight (2) Horizontal earth pressure (3) Vertical overburden pressure. Uplift force is neglected as it is on advantageous side because it counteracts the vertical overburden pressure. Also, empty condition of canal is taken into consideration because hydrostatic pressure exerted by water flowing through canal will reduce the horizontal earth pressure. So, analysis is done for critical condition i.e. empty condition of canal and no uplift pressure.

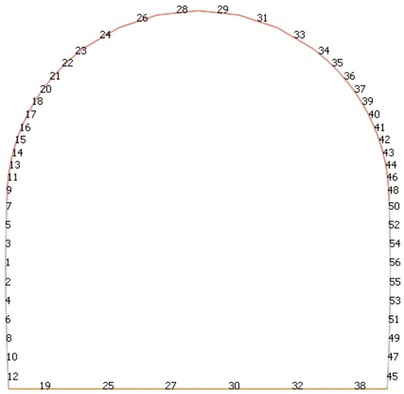

Fig. 1(a). Tunnel lining model (showing element number)

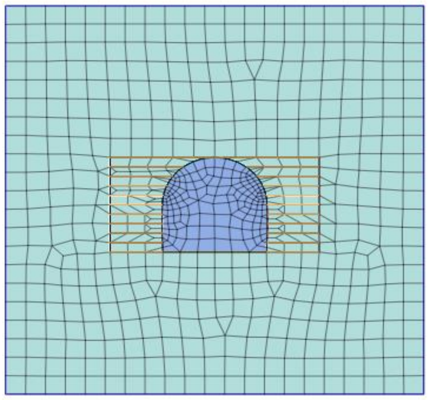

Fig. 1(b). Ground and tunnel lining attached with geogrid

Model validation . The model of this current study is based on a live project constructed at Sundernagar (Jharkhand) for a canal starting from Ganjia Barrage (Kharkhai river) towards Jadugora, Jamshedpur, Jharkhand. Canal tunnel is passing under road and railway track. Tunnel is 1.3 Km long and highest crest height is 13 m. It is an irrigation canal constructed under Swarnarekha Multipurpose Project, Jamshedpur. It is designed using USBR Monogram. The thickness of tunnel lining is 500 mm and base slab is 600mm in this project. Mandal and Singh (2018) have done the analysis and designed the wall thickness 450 mm and base slab thickness 500 mm.
The model in current study has also validated with the model created by Mandal and Singh (2018).

2.3 Properties of Material

Properties of material are given in Table 1, Table 2 and Table 3 below.

Table 1. Properties of soil

Properties	Soil
Model	Mohr- Coulomb
Elastic Modulus	50000 kN/m^2
Cohesion	0.2 kN/m^2
Friction Angle	40 degrees
Unit Weight	22 kN/m^3
Poisson Ratio	0.3

Table 2. Properties of Concrete used for Lining

Properties	Concrete
Model	Elastic
Elastic modulus	20000000 kN/m^2
Unit Weight	25 kN/m^3
Poisson Ratio	0.2

Table 3. Properties of Reinforcement

Properties	Geogrid
Model	Elastic
Elastic modulus	150000 kN/m^2
Unit Weight	0.5 kN/m^3
Poisson Ratio	0.2

3 Results and Discussion

In the current work, analysis of forces and moments acting upon ‘D’ shaped tunnel lining without geogrid and with geogrid has been analyzed. The most critical loading condition due to empty condition of canal tunnel with saturated backfill is considered. If flow condition in canal is taken into consideration, then it will counterbalance the horizontal thrust acting on the lining. In rainy season, the backfill get fully saturated hence, increase the earth pressure. Finite element analysis has been done for both unreinforced and reinforced case and then compared with each other.

The results of this study is validated with the live project of Sundernagar canal tunnel (designed using USBR monogram)

3.1 Comparison of FEM analysis of tunnel lining with Unreinforced and reinforced Backfill

The breadth of the lining is 5.0 m, height of crest is 5.0 m, radius of arch is 2.5 m, height of overburden crest is 4.0 m, width of trench at crest level is 7.0 m, and saturated unit weight of backfill is 22 kN/m^3, depth of overburden = 8 m.
The comparison of Axial force distribution is given below in Fig. 2 And Fig. 3

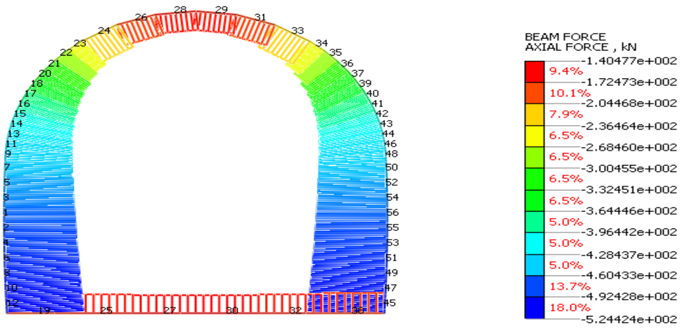

Fig. 2. Axial thrust distribution for unreinforced backfill

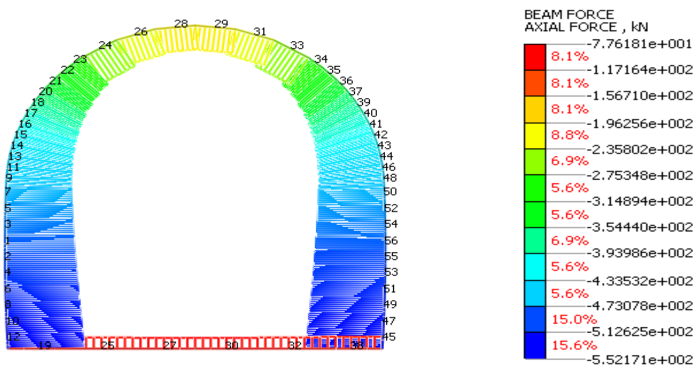

Fig. 3. Axial thrust distribution for reinforced backfill

As it is clear by comparing Fig. 2 and Fig. 3 that in the bottom slab (element no. 19, 25, 27, 30, 32, 38) the axial thrust is decreasing in reinforced case as compared to unreinforced case. In case of walls and crown of tunnel axial force is increasing in case of reinforced backfill as compared to unreinforced backfill.

The comparison of Shear force distribution is given below in Fig. 4 and Fig. 5

As it is clear from Fig. 4 and 5 that in the bottom slab, the decrease in shear force is slight in case of reinforced backfill as compared to unreinforced backfill. This is because, there is no geogrid in the bottom slab. In walls and crown of tunnel, shear force is decreasing considerably in case of reinforced backfill as compared to unreinforced backfill.

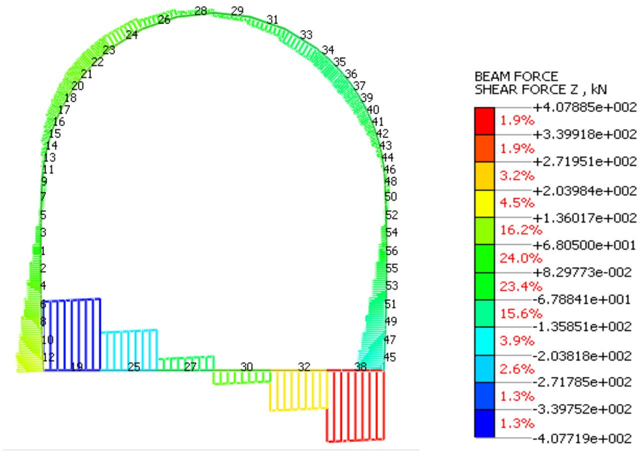

Fig. 4. Shear force distribution for uneinforced backfill

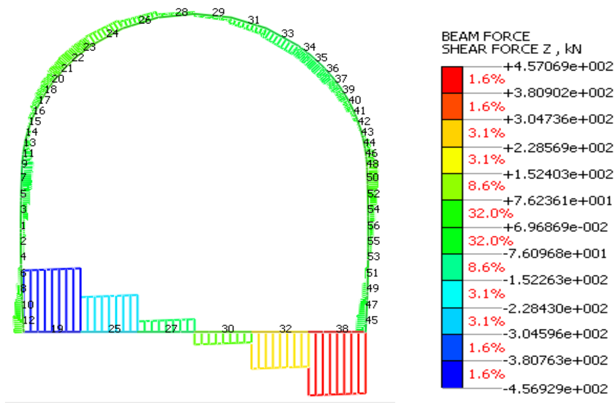

Fig. 5. Shear force distribution for reinforced backfill

The comparison of Bending moment distribution is given below in Fig. 6 and Fig. 7

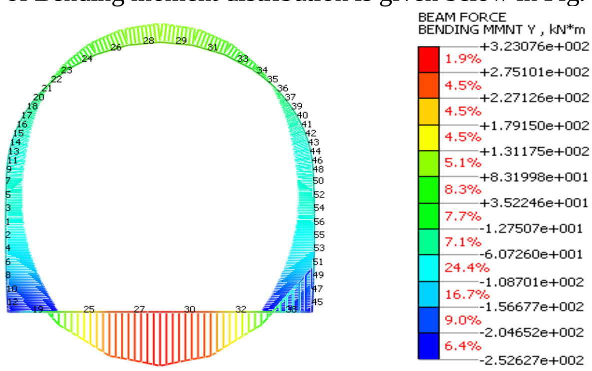

Fig. 6. Bending moment distribution for unreinforced backfill

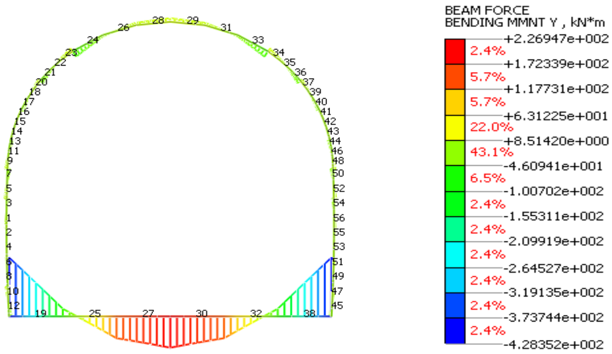

Fig. 7. Bending moment distribution for reinforced backfill

As it is clear by fig. 6 and fig. 7, in every element (floor, walls & crown) moment is decreasing in case of reinforced backfill as compared to the case of unreinforced backfill. That will further leads to reduction in thickness of tunnel lining.

3.2 Graphical Representation of Results

The graphical representation of Axial thrust for both the cases (unreinforced and reinforced) is shown in fig. 8

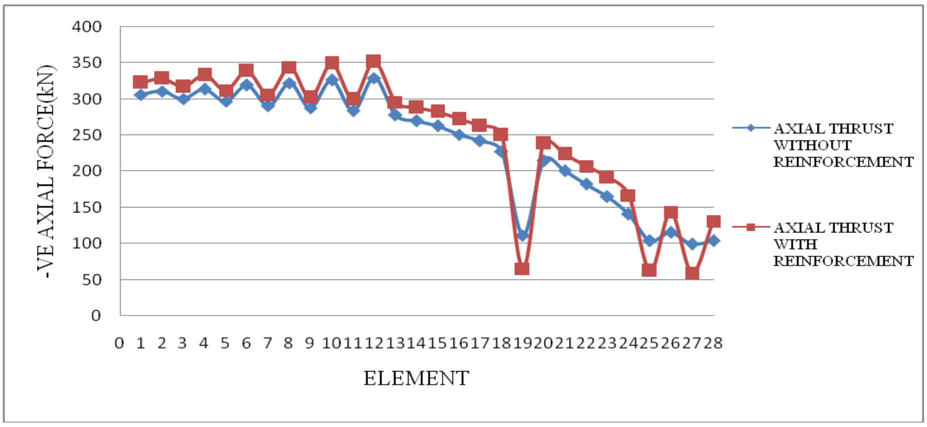

Fig. 8. Axial thrust for unreinforced and reinforced backfill

Axial thrust is increasing as we move from upward to downward. The nature of the graph is zig-zag because elements have been numbered randomly as shown in Fig. 1(a). Elements 2,4,6,8,10, 12 are in downward position whereas, elements 3,5,7,9 etc are in upward direction. Also elements 19, 25 and 27 are in base slab.

As it is clear from fig. 8, the axial thrust in walls of tunnel has been increased marginally in case of reinforced backfill case as compared to unreinforced backfill. Refer fig. 1 for location of elements.

The graphical representation of Shear Force for both the cases (unreinforced and reinforced) is shown in fig. 9

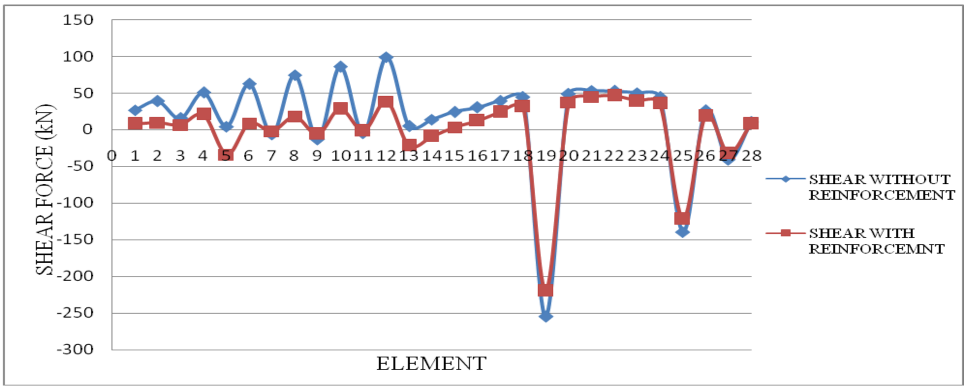

Fig. 9. Shear force for unreinforced and reinforced backfill

Nature of shear force can be seen in fig. 4 and 5 (shear force diagram). As it is clear from fig. 9, that shear force in vertical walls of tunnel is decreasing in reinforced backfill case as compared to shear force in unreinforced backfill case. The zig zag nature of graph is zig zag because elements are numbered randomly as shown in fig 1(a). Refer fig. 1 for location of elements.

The graphical representation of Moment for both the cases (unreinforced and reinforced) is shown in fig. 10

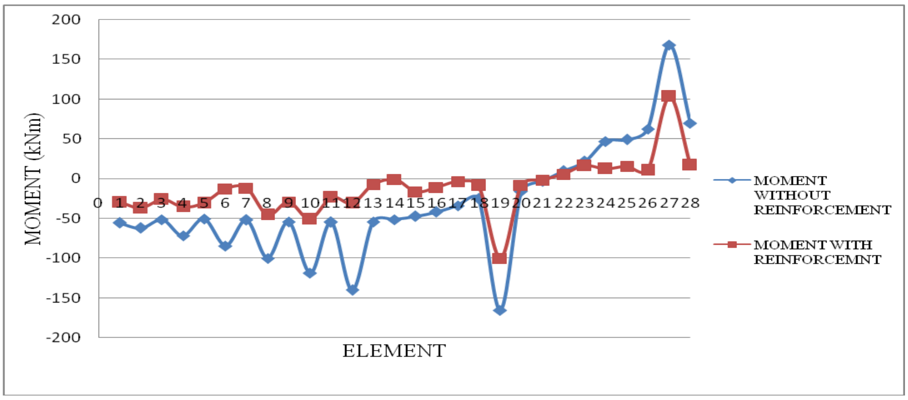

Fig. 10. Moment for unreinforced and reinforced backfill

Nature of Bending Moment is shown in fig 6 and 7 (bending moment diagram). Negative moment at the ends of base slab and positive moment in the centre of base slab. Negative moment is developed in the walls of tunnel lining and positive moment is developed at the crown.
As it is clear from the fig. 10, the bending moment in case of reinforced backfill is decreasing considerably as compared to bending moment in unreinforced case. This will lead to decrease in wall thickness of tunnel lining.

3.3 Thickness of Lining Section

Table 4. Thickness and reinforcement for different overburden (without and with reinforcement)

Overburden (m)	Thickness of the section required (mm) (without reinforcement)	Thickness of the section required (with reinforcement)	Reinforcement Details
4	350	300	12 mm ϕ @125 mm c/c
8	450	350	16 mm ϕ @125 mm c/c
11	550	450	20 mm ϕ @ 100 mm c/c

Table 5. Thickness and reinforcement for different soil parameters (without and with reinforcement)

Soil Parameters γ (kN/m^3) ϕ (degrees)	Thickness of the Section Required (mm) (without reinforcement)	Thickness of the Section Required (with reinforcement)	Reinforcement Details
γ= 18, ϕ= 30	375	300	12 mm ϕ @125 mm c/c
γ= 20, ϕ=35	425	350	16 mm ϕ @125 mm c/c
γ= 22, ϕ=40	450	375	20 mm ϕ @ 100 mm c/c

4. Conclusions

1. The values of thrust, shear and moment obtained by Mandal and Singh (2018)is compared with the values obtained in the present study. It has been seen that values obtained in both the cases are matching to a great extent. The variation is due to the difference in modeling problem in both the cases.
2. The thickness of tunnel lining which was found to be 450 mm according to Mandal and Singh (2018) is reduced to 350 mm in the present study.

3. The most critical loading condition is due to overburden, backfill, self-weight of structure and empty condition of the canal. Buoyant force, uplift pressure and seepage force don't play important role in most critical loading condition.
4. Shear force and Moment on the lining has decreased in case of reinforced backfill in comparison with without reinforced backfill.
5. Thrust on the wall of lining has increased marginally in case of reinforced backfill as compared to the thrust in unreinforced backfill.
6. Lining thickness has been reduced by 25% (approx.) in backfill i.e. reinforced as compared to unreinforced backfill with different overburden pressure and soil parameters.

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