# Tunnel Analysis of Dhaka Subway using PLAXIS 2D Considering Different Groundwater Level Conditions

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**A THESIS SUBMITTED**

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# THESIS APPROVAL

The thesis titled "Tunnel analysis of Dhaka Subway using PLAXIS 2D Considering Different Groundwater Level Conditions" submitted by Md. Rafid Irtiza, Sadman Sakib, Ishayet Alam, Farhan Abrar, St. No 170051007, 170051008, 170051017 and 170051024 has been found satisfactory and accepted as partial fulfillment of the requirement for the Degree Bachelor of Science in Civil Engineering.

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# DECLARATION OF CANDIDATE

We hereby declare that the undergraduate research work presented in this thesis was conducted under the supervision of Professor Dr. Hossain Md. Shahin, and that it has not been sent elsewhere for any reason other than publication.

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# DEDICATION

Our combined thesis work is dedicated to our respective parents, family, and friends who have been a constant source of support and encouragement. We also express our gratitude to our respected supervisor Professor Dr. Hossain Md Shahin. We are forever in debt to all who supported and encouraged us throughout not only this thesis but also our undergraduate journey.

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*"In the name of Allah, the most merciful and most gracious."*

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We gratefully recognize the help of the Bangladesh Bridge Authority (BBA), who graciously provided us with the data needed for continuing this research.

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# ABSTRACT

***Keywords:*** *Dhaka Subway, Tunnel, Surface settlement, Settlement trough, Ground behavior, Volume loss, Ground Water Level, Finite Element Analysis, Plaxis 2D, Lining stresses*

Dhaka subway, which will be an underground structure is being considered to combat the rising congestion in the city. As the city is very congested special consideration must be given to ground movement and surface settlement during the planning of the subway. Also, the rise in water level as the city moves away from groundwater for its water supply must also be taken into consideration for the long-term design of the tunnel. In this study, 2D finite element analysis was carried out using Plaxis 2D. Different soil profile representing different areas of the Dhaka city was considered and the surface settlement due to tunnel excavation was investigated. It was found that as the depth of the tunnel excavation increases the surface settlement decreases and the settlement trough becomes wider. Also, the volume loss and the grouting pressure required for a specific surface settlement after the tunnel was constructed was also studied and it was found that both volume loss and grouting pressure required increases with the depth of the tunnel. And also, the lining stresses of the tunnel considering different groundwater conditions was analyzed. It was found that as depth of tunnel increases the axial forces experienced by the tunnel lining increases. Also, the axial forces, bending moments and shear forces mostly increases as the ground water level increases in the future.

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# CHAPTER 1. INTRODUCTION

## 1.1. General

Man-made tunnels have existed for nearly as long a history as human civilization itself. The explanation for this is straightforward. Tunnels are used in effective sewage and irrigations system. Urban Dhaka and the municipalities have a population of over 18 million with an annual growth rate of 4.2%. Tunnel Boring Machine (TBM)-based mechanized tunneling is widely used in metropolitan settings, especially when excavation takes place under a populated city area or the groundwater table like the river and other water bodies. The city's current transportation system is incapable of meeting demand. Due to rising population and economic activities tunnels are an integral part of a fast and reliable urban commute. The use of subterranean space for transportation not only decreases travel time but also creates a new form of transportation that will improve the quality of life of the city dwellers. Due to the influence of ground deformation on many surfaces and sub-surface structures, underground construction works are extremely delicate.

The groundwater level in Dhaka city is artificially depleted via pumping. But Dhaka plans on moving its dependency on the groundwater sources and because of this, it is expected that the groundwater level will rise to the same water level as the Buriganga River. If the tunnel is under groundwater level, the groundwater flow will be at steady-state flow conditions and seepage forces exerts on the tunnel lining. (Lee et al., 1994). Tunneling beneath the water table induces porewater pressure changes which can induce lining pressure and axial stress to be developed. Groundwater inflows during tunneling can compromise the excavation's stability over time and potentially harm surface or subsurface structures as well as tunnel linings. (Shivaei et al., 2020).

The interaction between the groundwater characteristics, soil, and tunnel lining has many governing variables and it’s difficult to analyze numerically. A rigid plasticity theory, such as Terzaghi's loosening earth pressure theory, is still used to assess earth pressure acting on the tunnel lining and its stability. However, Finite Element Modeling (FEM) can be used, allowing us to assess more complicated situations with more accuracy. Tunnel excavations cause displacement in the surrounding earth, which can cause major structural damage. FEM allows us to determine which points of the Tunnel are more vulnerable to settling risk when bored into the multi-layer soil of Dhaka.

The objectives of this study are to analyze and evaluate the effects of different GWL on excavation & rising water levels on the lining the correlation between grouting pressure and tunnel depth, and perceived volume loss due to tunneling.

# 1.2. Project Background

## 1.2.1. Background

Dhaka is one of the rapidly growing megacities of the world. People from all around the country come to Dhaka to find work. Which causes a high growth rate in the city. It is also the world's fourth most densely inhabited city. It is estimated that in 12 years the population will grow more than 25%. This increment in population can cause many problems in daily transportation activities. If the transportation system of a city or country is not satisfactory enough then it will harm the productivity or financial aspects, health and environment of that particular region. As Dhaka has more economic opportunities than any other part of the country, an uninterrupted transport system is very important. To enhance the transportation capacity, the Government of Bangladesh has decided to construct a subway system which will be named Dhaka Subway. The feasibility study of the project is already done by Bangladesh Bridge Authority who appointed TYPSA, in association with PADECO, BCL Associates Ltd., BETS and KS Consultants. The subway is assumed to have four routes which will be able to solve the traffic congestion problems of the city and a significant improvement can be seen in the transportation system of Dhaka.

## 1.2.2. Project Details

The four routes which will be built initially are:

Route 1: Gabtoli - Bholabo (length 30.51 km)

Route 2: Jhilmil - Tongi junction (length 29.35 km)

Route 3: Jahngirnagar University - Narayanganj (length 47.5 km)

Route 4: Keraniganj – Sonapur (length 19.5 km)

For our particular research we have taken 6 spots in the Route 4 area. One of them was under the river Buriganga. Tunnel Boring Machine (TBM) will be used so the people around the project will not suffer from the soil digging around them. The project is assumed to be environment friendly. This will be the most economical mode of transport and this will also reduce the traffic congestion. GoB will be having a hard time regarding O&M cost, ensuring uninterrupted electricity for this project.

### 1.2.3. Objectives of the study

- Evaluating Effects on soil surface due to TBM excavation & line installation
- Evaluate Excavation and installation induced settlement
- Stress development (Axial stress, Bending moment, Shear force) in tunnel lining
- Effects of different GWL on excavation & tunneling
- Correlation between grouting pressure and tunnel depth
- Perceived Volume Loss due to tunneling
- Effects of rising groundwater level on the lining.

# CHAPTER 2. LITERATURE REVIEW

## 2.1. Introduction

Subways are used for mass rapid transit in many places around the world. And besides for subways, tunnels are used for various reasons such as underwater expressways, railway tunnels, road tunnels etc. But this technique is at its infancy as there is only one tunnel project in Bangladesh. So, even though there are a lot of tunnel related studies in the context of different places around the world, very few are available in the context of Bangladesh. This literature review identifies studies related to tunneling and describes their findings.

## 2.2. Tunnel Construction

There are many methods of excavating a tunnel. The method used depends on the type of tunnel, its usage, excavation depth, tunnel length and diameter, the soil conditions, ground water levels, surface loadings and many other parameters.

Commonly two main methods of excavations are used. They are:

1. Cut and Cover method, which excavates a tunnel by excavating open trenches and paving over it. It is usually applicable for shallow tunnels and where the surface is open and there are no structures over it.
2. Bored method, where a Tunnel Boring Machine or TBM is used to excavate the tunnel in-situ, without any excavations conducted on surface. It is suitable for dense urban areas where there is a lot of structure overhead and is most commonly used around the world. The tunnel cross-section is usually circular or in the shape of a horseshoe and is also known as shield tunneling.

## 2.3. Existing research on Tunnel excavation

- **Shahin et al. (2011)** found that during shallow tunneling crown drift is more a significant factor than volume loss for surface settlement and earth pressure distribution. But for deep tunneling, crown drift becomes less significant and surface settlement is mainly governed by volume loss. Excavation patterns heavily influence earth pressure distribution around the tunnel. Also, the surface deformation moves toward the existing foundation and maximum settlement occurs underneath the foundation.
- **Shahin et al. (2019)** came to the conclusion that 2D finite element analysis can predict ground deformation and settlement when rate of stress release is considered, but provides irrational tunnel lining stresses, for which 3D analysis is required which requires the exact construction process to be considered. A sophisticated constitutive model, which properly explains the mechanical properties of the soils is also necessary to perform proper finite element analysis.

- ➔ **Kwong et al. (2019)** conducted a study on a tunnel project in Hong Kong which involved excavation of a tunnel in recently reclaimed land. They found that The volume loss and settlement back calculated from observed values was much less than the values predicted with 2D finite element analysis except for five locations where the volume loss and settlement exceeded at a maximum of 1.3%. And the higher settlement and volume loss was mainly due to the slowing of the TBMs for scheduled maintenance.
- ➔ **Soga et al. (2017)** determined that ground movement can build up continuously after tunnel excavation; the excess pore water pressure induced during tunnel excavation dissipates with time. Also, the tunnel creates new pore water conditions which causes consolidation. Also a tunnel can be fully permeable without looking permeable as the seepage rate of clayey soil is low and the small amount of water that seeps into the tunnel can evaporate quickly. Also horizontal ground strains increase with time due to soil consolidation and can reach similar magnitude to short term ground movement induced by tunnel excavation.
- ➔ **Shahin, Nakai et al. (2004)** concluded that surface settlement at the crown decreases and the settlement trough becomes wider when the depth of the soil cover increases. Also, Earth pressure decreases at the position of excavation and increases at the surrounding of tunnel excavation due to the arching effect. Also existing building loads control the surface settlement patterns, as the maximum settlement usually occurs at existing buildings instead of the tunnel crown. The effect increases for shallow tunnels with greater depths. Also, unsymmetrical earth pressure is observed due to building loads. And earth pressure varies with construction sequences so construction sequences should be properly considered in numerical simulations.
- ➔ **Giardina et al. (2015)** suggested that the building response is dependent on the relative stiffness between the structure and the soil and also on the building weight, later of which is typically neglected in current assessment procedures.
- ➔ **Farrell et at. (2014)** found that the modification to settlement distortions is a function of both the building and the soil stiffness, in addition to the geometric parameters. Also, horizontal ground strains were found to be negligible which was transferred into model buildings. Assessing the risk of damage based on the assumption that buildings distort fully flexible, conforming to the greenfield settlement and horizontal profiles can be highly conservative. And both centrifuge modeling and field data indicate that the redistribution of building weight due to tunneling can significantly influence both the response of the building itself and of the subsoil.
- ➔ **Shahin, Naka, et al (2004)** determined that when the excavation front is very close to the measuring section, surface settlement occurs for very shallow tunnels. But for deepers tunnels it is observed that ground settlement occurs at the measuring section even though the excavation front is at a certain distance from the section. Also it was found that surface settlement of 3D sequential excavation is slightly smaller than those of 3D block by block and 3D simultaneous excavation. Also, earth pressure decreases at the position of the excavation and increases at the surrounding of the tunnel excavation due to the arching effect. Also arching is formed in both transverse and longitudinal directions. And also, soil arch is perfectly formed during continuous

sequential excavation whereas the arch is partly disturbed during stepwise block by block excavation, reducing the efficiency of the load transfer process.

- **Franza et al. (2017)** concluded that vertical settlements are primarily induced by tunnel excavations beneath piled structures. The stiffness of the building has a significant effect on the pile settlements and the resulting building deflections can be overly conservative assuming that building has a fully flexible structure. Also tunneling induced horizontal strain are negligible in the superstructure in case of a continuous foundation at the ground level but can be significant in a framed building where the pile heads aren't connected by a structural element. Also the structural configuration is very important because a different response for a piled simple beam and a piled frame is expected. And also pile-structure connection plays an important role in tunnel-pile-structure interaction for simple beams and structures whose stiffness is concentrated at the ground level. And it was found that the results from the Winkler based TSAM elastic analysis and results from 3D finite element analysis compare with each other.

## 2.4. Research in the context of Bangladesh

As Bangladesh is at its infancy in tunnel construction projects, very little research has been done. Nonetheless there are some available and one related to our study is given below.

- **Azam et al. (2016)** conducted a study and concluded that finite element analysis using the elastoplastic subloading tij model can be more practically simulated and gives more realistic results compared to conventional analysis. Also it found that the cut and cover method was more suited to open spaces like Tongi to Uttara and is cost effective to perform. Whereas for congested places of Dhaka with many structural obstructions like at flyover junction points in cantonment and from Farmgate to Sayedabad, NATM is more preferable as NATM shows more stability in soil retention for congested areas in Dhaka.

# CHAPTER 3. METHODOLOGY

The surface settlement, ground response, lining stresses etc. during and after tunnel excavation can be calculated using methods such as empirical analysis, numerical analysis or finite element analysis. Empirical analysis is by far the oldest and most used method for calculating these forces which were established by using recorded data or laboratory tests. And although they are less complicated to apply, they may not provide accurate data due to unforeseen conditions in the site. Numerical Analysis is a method where algorithms are created and used to determine the best possible within the margin of error. It can give results within the desired accuracy but whereas it is easy to develop a numerical model for less complicated scenarios, as the complexity and variables of the problems increases, it becomes increasingly difficult to manually develop a numerical model. So, Finite element modeling is a method of numerical analysis where a complex problem is divided into small and simple parts for which it can be solved.

For this study we utilized Finite Element modeling (FEM) for our analysis as it would take into account the different specific effects of the soil profiles and provide accurate results.

## 3.1. Finite Element Method (FEM)

Finite Element Method or FEM is a numerical method used to perform finite element analysis of any structure or model. In this method a large model is subdivided into much smaller and simpler parts by constructing a mesh of the object. These smaller parts are called finite elements. This makes calculation of a complex structure much easier and accurate. It can also predict local effects on the model. After the analyses of the finite elements are complete, the simpler equations that represent the finite elements are combined into a larger system of equations that represents the full problem. This approach allows the simulation to show localized affects like deformations or displacements on the structure.

Plaxis 2D was used in the research. The software handles Plane strain and Axial Symmetry geometric types. Plaxis performs finite element analyses and is used in geotechnical engineering. In Plaxis 2D two dimensional finite element analyses are done including deformation, stability, water flow etc.

## 3.2. Tunnel Boring Machine (TBM)

Different methods of tunneling are present at hands, but the method we have chosen for constructing the tunnel is TBM technology. The Tunnel Boring machine (TBM) is a machine used to excavate tunnels and install lining with a circular cross section. It can bore through various kinds of soil at once. The machine bores through soils with minimal disturbance in the surrounding soil. The amount of excavated area can be quite large in diameter. Tunnel diameters can be of one meter to about 17.6 meters. Compared to drilling, blasting or cut and cover methods the TBM can generate smooth tunnel walls because of the low disturbance on the surrounding ground. Also for this reason, it is highly preferable to use it in urbanized areas. The boring machine excavates the ground and installs the lining simultaneously, which is why it is more efficient than the conventional method and has faster completion time. The disadvantages of the machines are that they have a high upfront cost. Assembling them can be costly and since they're used to bore tunnels of massive sizes, they're also difficult to transport. But due to TBM being more efficient, if the required tunnel excavation is long enough, it is relatively cheaper compared to other methods.

## 3.3. Soil Models

For the accuracy of the simulation, there are several kinds of soil models present in Plaxis. Such are:

- Linear Elastic Model (LE)
- Mohr-Coulomb Model (MC)
- Hardening Soil Model  (HS)
- Hardening Soil Model with small stress-strain stiffness (HS small)
- Soft Soil Model (SS)
- Soft Soil Creep Model (SSC)
- Jointed Rock Model (JR)
- Modified Cam-Clay Model (MCC)
- NGI-ADP Model (NGI-ADP)
- UDCAM-S Model (UDCAM-S)
- Sekiguchi-Ohta Model (Seki guchi-Ohta)
- Hoek-Brown Model (HB)
- UBC3D-PLM Model (UBC3D-PLM)
- Concrete Model (Concrete)

For this research, soil was modeled with Mohr-Coulomb Model, HS small or Soft Soil Model.

Mohr-Coulomb Model is a straightforward model and the simplest of the bunch. This model uses functions such as cohesion, angle of friction, dilatancy, yield strength of the soil etc. These parameters are commonly tested. This makes this a preferable soil model to use.

Soft Soil model is used for near normally consolidated clays. In order to get an accurate representation, parameters such as Compression Index(Cc) and Swelling Index(Cs) were also provided when modeling the soil.

HS small models are designed to reproduce basic phenomena exhibited by soils such as Densification, Stiffness stress dependency, plastic yielding, dilatancy etc.

## 3.4. Method of Analysis

- Analysis done with Plaxis 2D software
- Considered 15 nodded elements
- Used Plane Strain model for 2D ground model
- Soil models used - Mohr-Coulomb Model, HS small and Soft Soil Model
- Microsoft Excel for generating tables and graphs

## 3.5. Calculation Phases

To properly simulate the effects of tunneling on the ground, the tunneling process was divided into several phases. These were also in the order of actual construction methods and these phases are not interchangeable.

Phase 1: The initial state of the ground. This phase represents the soil profile before the excavation had started. It is also referred as K0 stage or initial stress condition stage. The deformation is set to zero by default at the end of this stage.

Phase 2: In this stage the Tunnel Boring Machine excavates the soil by boring through it. After the Boring Machine leaves the area excavated, the surrounding soil caves in and gets contracted because of the slight conic shape of the boring machine. This is why this phase also simulates the decompression of the ground behind the tunnel face and the contraction of the excavated section due to TBM conicity.

The displacement caused in this phase is also reset to zero.

Phase 3: The grouting pressure is assigned in this phase. Grouting is given to fill up the gap between the soil and lining. Grouting strengthens the supporting ground and keeps the tunnel stable. When constructing tunnels that are under water level, proper grouting is extremely important. Grouting also prevents water flow.

Phase 4: The tunnel linings are installed simultaneously with the excavation of the machine. Lining is casted with concrete. Sections of lining are installed which creates a smooth tunnel wall.

Phase 5: The last stage of calculation simulates the rise of the ground water level for long term consequences.

## 3.6. Mesh Generation

For FEM analysis the software generates finite element mesh. The mesh can be generated in smaller or coarser elements. Generating fine mesh will result in the software dividing the model into a higher number of subdivisions.

Medium mesh generation in Plaxis 2D was used for the analysis carried out in this study.

## 3.7. Grouting Pressure

The grouting pressure is an important variable. This criterion is important to stabilize the ground surrounding the tunnel. The displacement of the top soil can vary depending on the amount of grouting pressure. In order to reach a conclusion, we needed a proper way to compare the results. So, the grouting pressure needed for 10mm of displacements was determined. This allowed us to get a fair comparison between results. The surface settlement of 10mm was chosen due to the congested nature of Dhaka city, as settlement higher than this can adversely affect structures in congested areas.

## 3.8. Volume Loss

After excavating a tunnel section, the soil tends to relax and cave in. This causes the actual section to be smaller than the initial excavated section. The difference in these areas over the initial one is referred to as Volume Loss. The Volume Loss is represented by its percentage.

In the simulation software lots of nodes are created using the finite element method. From the software we can get coordinates of each node and also the distances they have deformed. We had already defined the tunnel lining as plate elements. By comparing the change in the distance of the nodes that create the tunnel face, we can calculate the volume loss.

## 3.9. Results Collection

The following criteria were found and recorded for analysis

- Surface settlement was collected during phase 2 as that represents the surface settlement induced by the excavation of the tunnel.
- Axial forces, Shear forces and bending moments were collected during phase 4 and phase 5 which represent, in order, the finished tunnel during original ground water level and the finished tunnel after the groundwater level has risen.
- Grouting pressure required to achieve e 10mm surface settlement in phase 4 was also recorded.
- Volume loss of the tunnel in phase 4 was also recorded as that would indicate the volume loss of the finished tunnel.

# CHAPTER 4. MODEL CONSIDERATIONS

While modeling the soil profiles these factors were taken into consideration

- Finite Element Analysis of Tunnel
- Contraction, cr=0.5%, Deconfinement = 85%
- Tunnel lining and TBM shell was defined as Plate Elements
- Considering pumping wells are replaced by other water sources for the city. Groundwater Table will rise to a similar elevation level as the Buriganga river
- It was ensured that the distance between the terminal boundary of the last soil layer and the Tunnel invert was at least double the excavation diameter.
- Tectonic movement of groundwater flow was not considered

## 4.1. Soil Parameters of the Study Area

The geological parameters of each and every type of soil were collected from Bangladesh Bridge Authority. In order for the simulation of the geological profiles to be accurate key soil parameters are crucial.

**Table 1: Soil Parameters**

| Properties | | Artificial fills | Holocene soft | Holocene dense | Madhupur clay | Dupi Tila coarse | Dupi Tila fine |
|---|---|---|---|---|---|---|---|
| General Description | | Heterogeneous soils | Fine Soils | Sands SM | CL, CH clays | Sands SM | Fine Soils CL, ML, CH |
| Density | $\gamma_{ap}$ | 19.1 | 18.6 | 20.2 | 18.6 | 19 | 19 |
| | $\gamma_{sat}$ | 19.8 | 18.7 | 20.5 | 19.1 | 20 | 19.2 |
| Permeability (hydraulic conductivity) | K (m/s) | 1.0E-04 | 5.0E-07 | 1.0E-05 | 1.0E-08 | 1.0E-06 | 5.0E-08 |
| Stress-strain relationship (FEM models) | Constitutive model | Mohr-Coulomb | Soft Soil | HS-Small | Soft Soil | HS-Small | HS-Small |
| | Parameters (moduli in Mpa) | E = 20<br>n = 0.3 | Cc = 0.26<br>Cs = 0.03<br>OCR = 1.2 | $E_{50ref}$ = 15.7<br>$E_{urref}$=47<br>$G_{0ref}$=104.3<br>m = 0.28<br>$g_{0.7}$ = 1.0E-4 | Cc = 0.21<br>Cs = 0.02<br>OCR = 2.0 | $E_{50ref}$ = 26.4<br>$E_{urref}$= 79.3<br>$G_{0ref}$= 158.7<br>m = 0.25<br>$g_{0.7}$ = 1.0E-4 | $E_{50ref}$ = 19.5<br>$E_{urref}$= 58.4<br>$G_{0ref}$= 146.1<br>m = 0.30<br>$g_{0.7}$ = 1.4E-4 |
| Strength parameters | Cohesion c' (kPa) | 1 | 20 | 5 | 25 | 5 | 20 |
| | Friction (ϕ) | 28 | 23 | 32 | 23 | 35 | 24 |
| | Dilatancy | 0 | 0 | 2 | 0 | 5 | 0 |
| | Tensile Strength (kPa) | 0 | 5 | 0 | 10 | 0 | 5 |
| Interfaces | Rinter | 0.65 | 0.65 | 0.65 | 0.7 | 0.75 | 0.7 |
| Overconsolidation ratio | OCR | 1 | 1.2 | 1.1 | 2 | 1.5 | 1.5 |
| Initial stresses | $K_0$ | 0.53 | 0.7 | 0.5 | 1 | 0.52 | 0.76 |

# 4.2. Tunnel Geometry

The tunnel is circular in shape. As the TBM face is also circular it bores through a tunnel of its own shape. The tunnel size is also similar to the size of the TBM.

In order to figure out the effects of excavation depth on the soil profile, we had analyzed tunnels in various depths. So the depth of the tunnel varied from 25m to 75m.

The Tunnel Diameter was 10 meter.

## 4.2.1. TBM parameters

The boring machine had the following specifications:

TBM Shell Thickness = 0.08m

Weight = 32.16 kN/m

Young's modulus of Steel, E = 210E6 kN/$m^2$

Moment of inertia, I $= \frac{bh^3}{12} = \frac{1 \times 0.08^3}{12}$ = 4.26E-5 $m^4$

TBM Axial Modulus, EA = 16.8E6 kN/m

TBM Bending Modulus, EI = 8960 $kNm^2$

## 4.2.2. Lining Parameters

The lining was made from precast concrete segments and had the following parameters:

Lining Thickness = 0.4 meter

Weight = 9.6 kN/m

Concrete Strength = 40MPa

Concrete unit weight = 24 kN/m

Poisson's Ratio = 0.15

Modulus of Elasticity of Concrete, E = $4700\sqrt{40}$ = 29725.41 N/$m^2$ =29.725E6 kN/$m^2$

Moment of inertia, I $= \frac{bh^3}{12} = \frac{1 \times 0.4^3}{12}$ = 5.33E-3 $m^4$

Lining Axial Modulus, EA = 11.89E6 kN/m

Lining Bending Modulus, EI = 158.5E3 $kNm^2$

## 4.3. Groundwater Table

Two cases of ground water level were used for analysis for every soil profile. In central Dhaka the maximum depth of GWL is seen to be 60m. However, the city outskirts have a groundwater level of around 20m. This is due to the fact that the groundwater table has been artificially depressed by excessive pumping of wells in central Dhaka. Areas adjacent to Buriganga have a groundwater level on the same height as the river table elevation.

If the pumping wells are shut down in future, the groundwater table will recover to its natural state. In order to predict long term consequences, the GWL of every soil profile was also increased from 20m and 60m depth to its original state at 4m depth and analyzed.

## 4.4. Soil Profiles

6 soil profiles were considered. Profile 1A and 1B representing central Dhaka area, 2A and 2B representing Holocene basins, 3A representing the areas near Buriganga river and finally profile 3B presents conditions where the tunnel goes under the Buriganga river.

### 4.4.1. Profile #1A

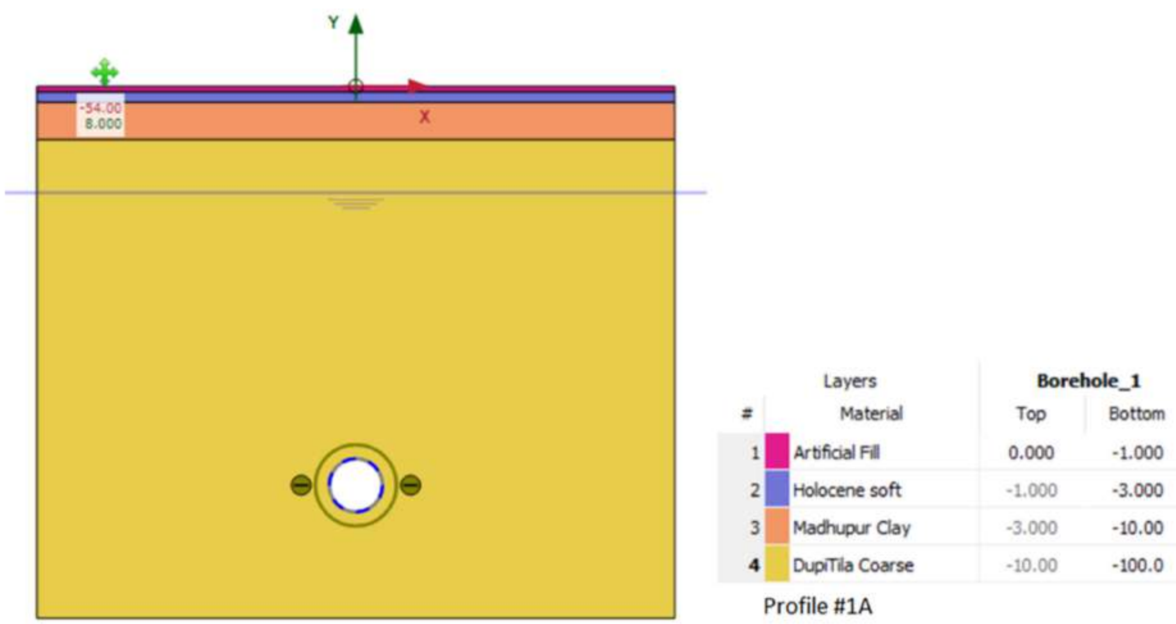
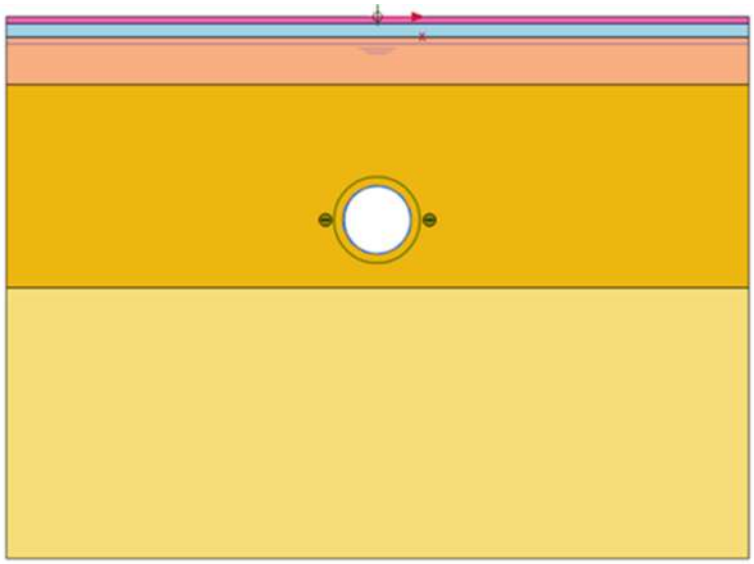



**Figure 1: Soil Profile #1A**

### 4.4.2. Profile #1B

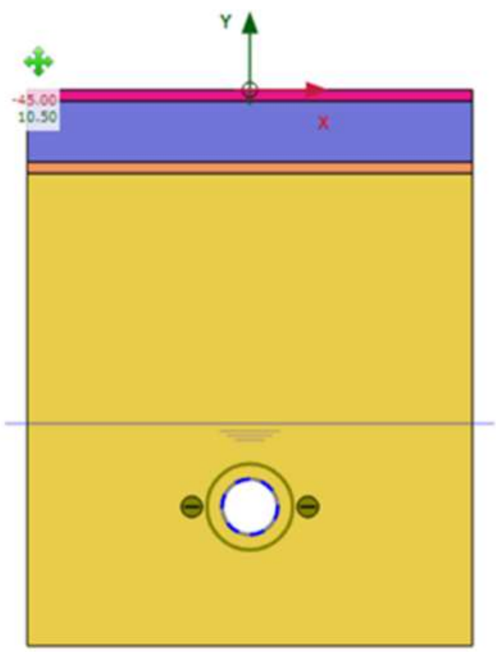


| # | Layers Material | Borehole_1 Top | Borehole_1 Bottom |
|---|---|---|---|
| 1 | Artificial Fills | 0.000 | -1.000 |
| 2 | Holocene Soft | -1.000 | -3.000 |
| 3 | Madhupur Clay | -3.000 | -10.00 |
| 4 | Dupi Tila Fine | -10.00 | -40.00 |
| 5 | Dupi Tila Coarse | -40.00 | -80.00 |

Profile #1B

**Figure 2: Soil Profile #1B**

### 4.4.3. Profile #2A

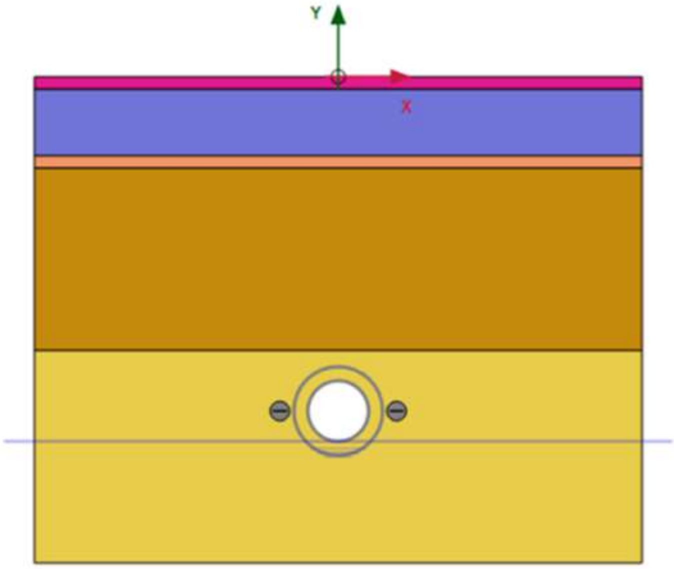



| # | Layers Material | Borehole_1 Top | Borehole_1 Bottom |
|---|---|---|---|
| 1 | Artificial Fill | 0.000 | -2.000 |
| 2 | Holocene soft | -2.000 | -13.00 |
| 3 | Madhupur Clay | -13.00 | -15.00 |
| 4 | DupiTila Coarse | -15.00 | -100.0 |

Profile #2A

**Figure 3: Soil Profile #2A**

## 4.4.4. Profile #2B

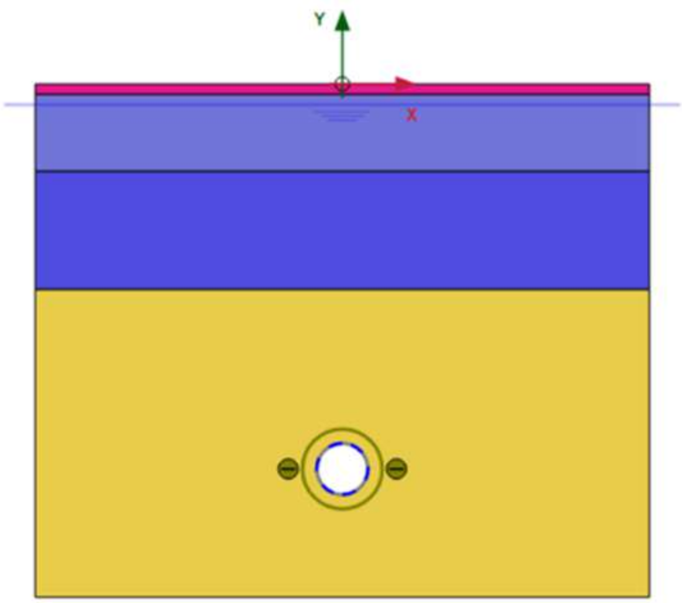



| # | Layers Material | Borehole_1 Top | Bottom |
|---|---|---|---|
| 1 | Artificial Fill | 0.000 | -2.000 |
| 2 | Holocene soft | -2.000 | -13.00 |
| 3 | Madhupur Clay | -13.00 | -15.00 |
| 4 | DupiTila Fine | -15.00 | -45.00 |
| 5 | DupiTila Coarse | -45.00 | -80.00 |

Profile #2B

**Figure 4: Soil Profile #2B**

## 4.4.5. Profile #3A

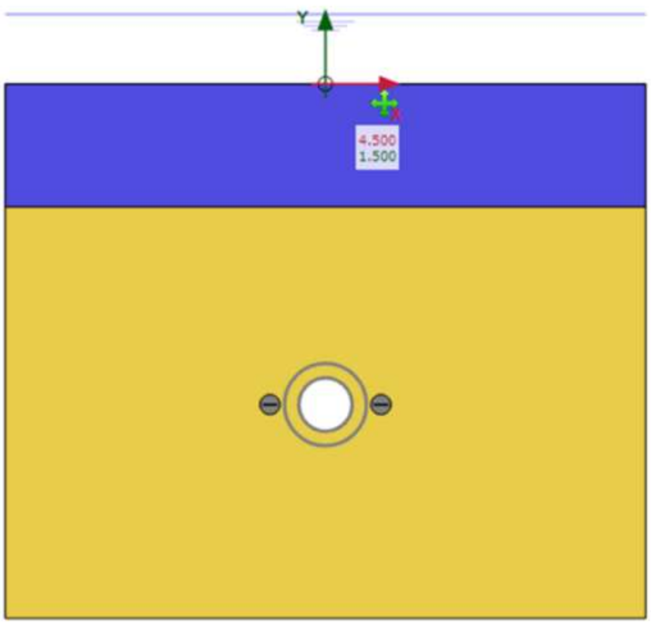



| # | Layers Material | Borehole_1 Top | Bottom |
|---|---|---|---|
| 1 | Artificial Fill | 0.000 | -2.000 |
| 2 | Holocene soft | -2.000 | -17.00 |
| 3 | Holocene Dense | -17.00 | -40.00 |
| 4 | DupiTila Coarse | -40.00 | -100.0 |

Profile #3A

**Figure 5: Soil Profile #3A**

### 4.4.6. Profile #3B




| | Layers | Borehole_1 | |
|---|---|---|---|
| # | Material | Top | Bottom |
| 1 | Holocene Dense | 0.000 | -23.00 |
| 2 | DupiTila Coarse | -23.00 | -100.0 |

Profile #3B

**Figure 6: Soil Profile #3B**

# CHAPTER 5. RESULTS & DISCUSSION

The results that were found from Plaxis simulation under different circumstances are shown here. Every soil profile has a set of results for shallow groundwater level (-20m depth) and deep groundwater level (-60m depth). Effects on the tunnel lining after the rise of water level (-4m depth) were also collected. Results include displacement induced by the tunnel excavation, forces such as the axial force, shear forces, bending moment on the tunnel lining, effective principal stress and finally the change in forces on lining after water level has risen to its original state. The required grouting pressure for 10mm settlement and volume loss are also presented in this section.

The grouting pressures required for achieving 10mm settlement were recorded in a tabulated format. This settlement is not to be confused with the previously mentioned excavation induced settlement, as both are taken from different stages of the tunneling process. It is necessary to mention that the grouting pressure is connected with the stability and settlement of the top soil after the lining has been installed. It is seen that deeper excavation requires larger grout pressure for stability. In our research, grout pressure varied between 100kPa to 700kPa. For soil profiles under water body, it varied between 500kPa to 800kPa.

Volume loss of the tunnel was calculated for each profile after the lining installation phase. The volume loss of each soil profile for both deep and shallow groundwater level was recorded. Volume loss is shown in percentage for each soil profile.

With the recorded data graphs were generated. Graphs help to visualize the correlation between all the factors. How the depth of excavation affects the surface settlement is visualized by the surface settlement vs excavation depth graph. Grouting pressure vs tunnel depth was plotted. The vast change in the stress formation in tunnel lining after the rise in water level is presented using bar diagrams. The change in volume loss in response to tunnel depth is also plotted.

# 5.1. Results from Plaxis

Along with giving us values, Plaxis 2D software also generates images of the deformed mesh and visualizes how the displacement looks like.

## 5.1.1. Profile #1A, Tunnel depth 25m, GWL= -20m

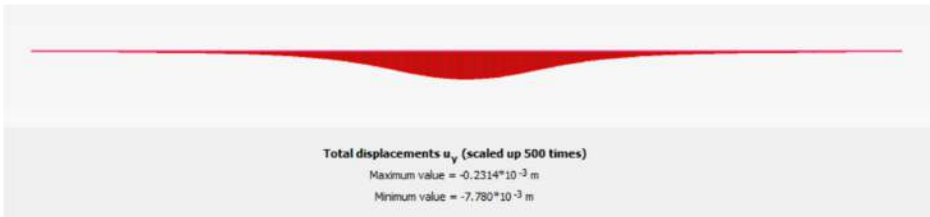



**Figure 7: Excavation induced Settlement (#1A, 25m depth, GWL=-20m)**

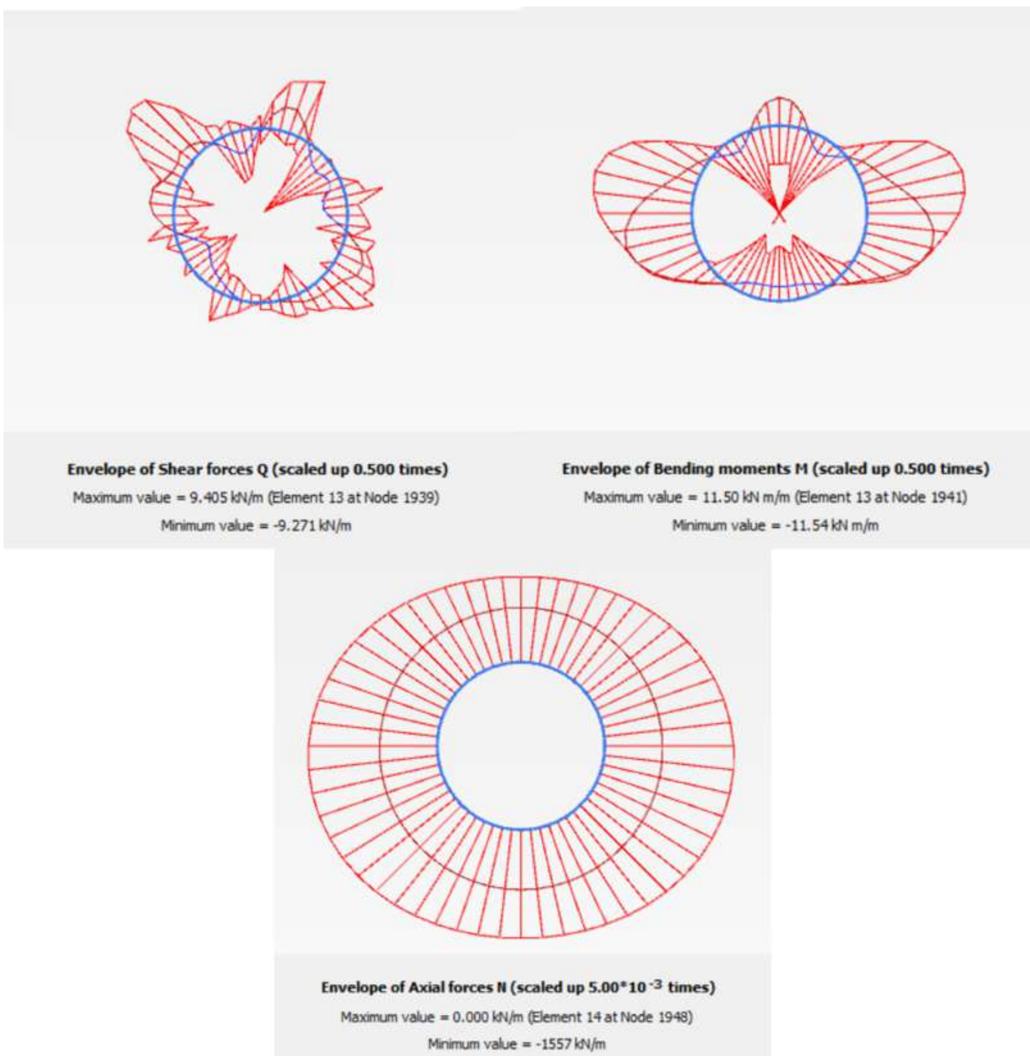



**Figure 8: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 25m depth, GWL=-20m)**

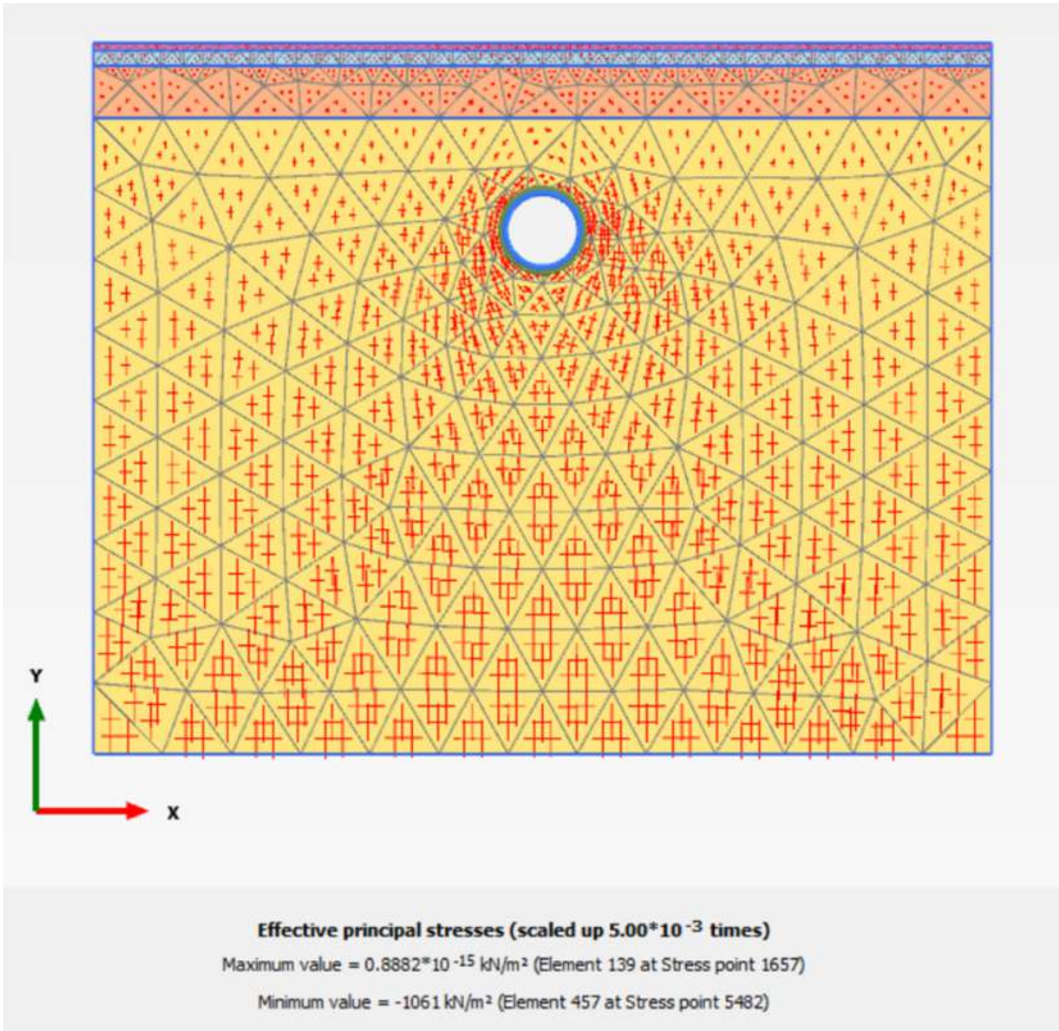



**Figure 9: Effective Principal Stress (#1A, 25m depth, GWL=-20m)**

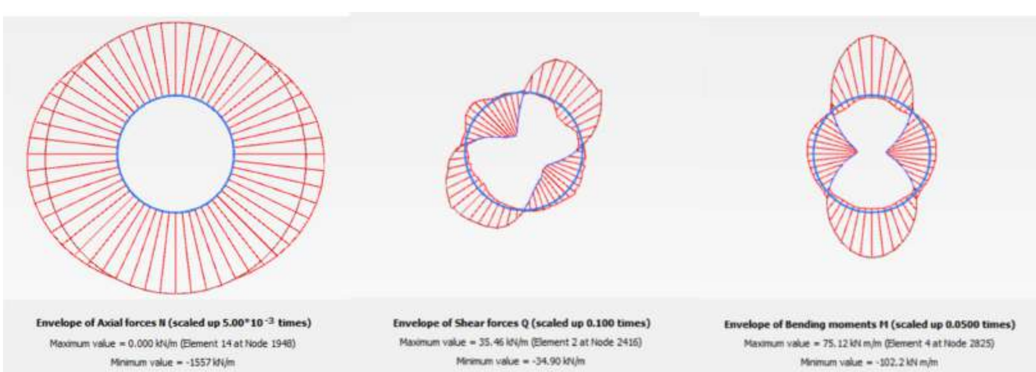



**Figure 10: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 25m depth, GWL=-20m)**

## 5.1.2. Profile #1A, Tunnel depth 25m, GWL= -60m

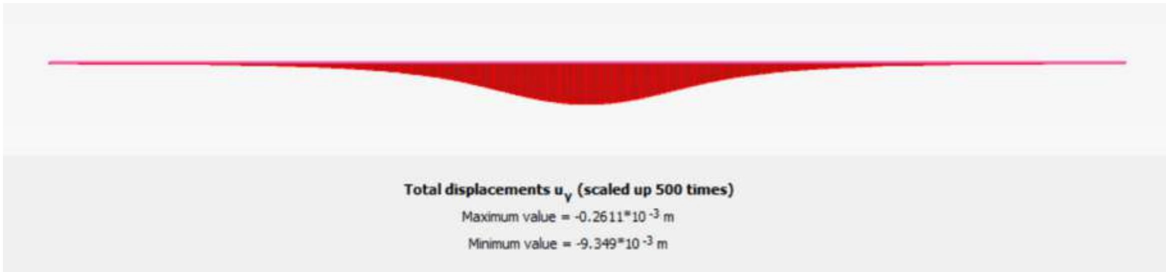



**Figure 11: Excavation induced Settlement (#1A, 25m depth, GWL=-60m)**

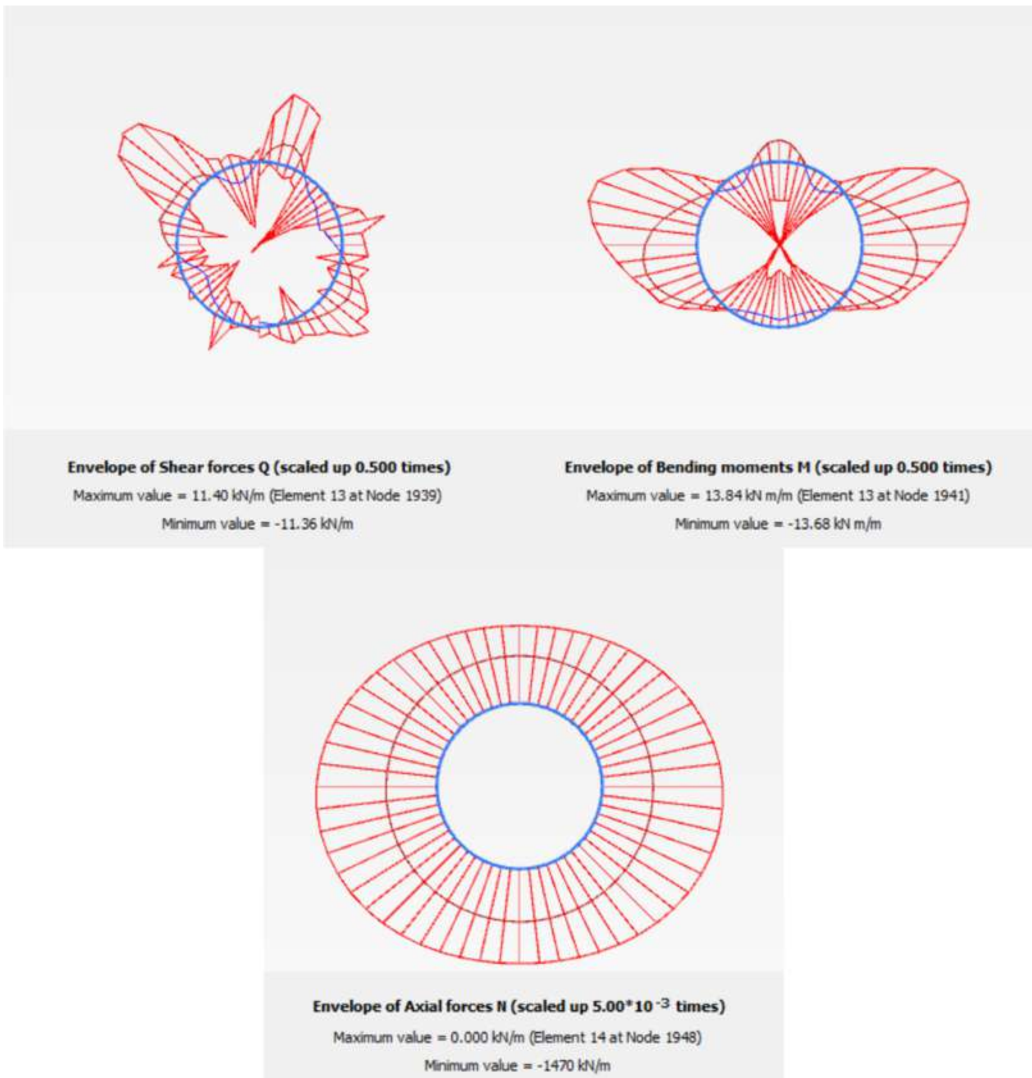



**Figure 12: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 25m depth, GWL=-60m)**

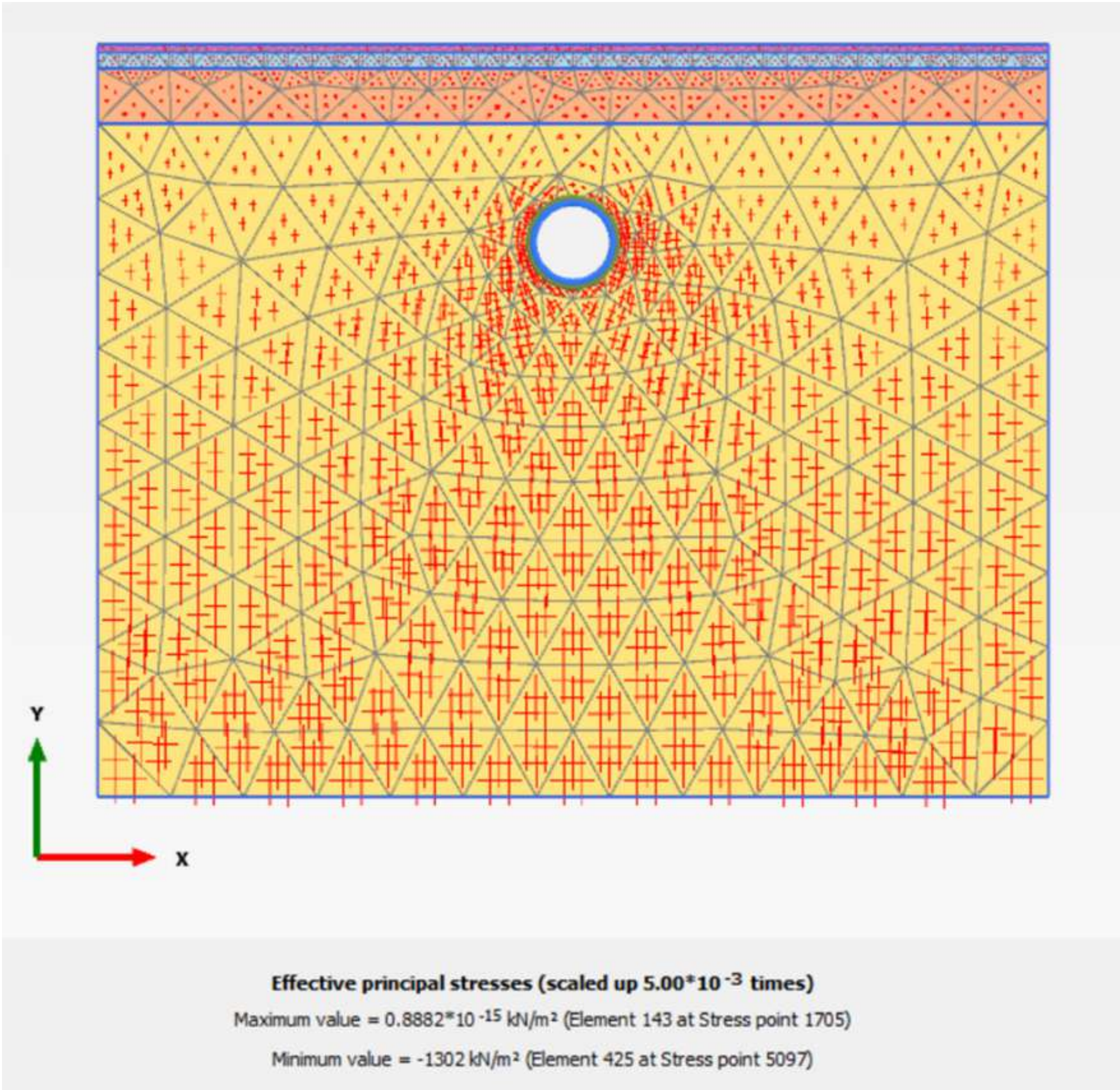



**Figure 13: Effective Principal Stress (#1A, 25m depth, GWL=-60m)**

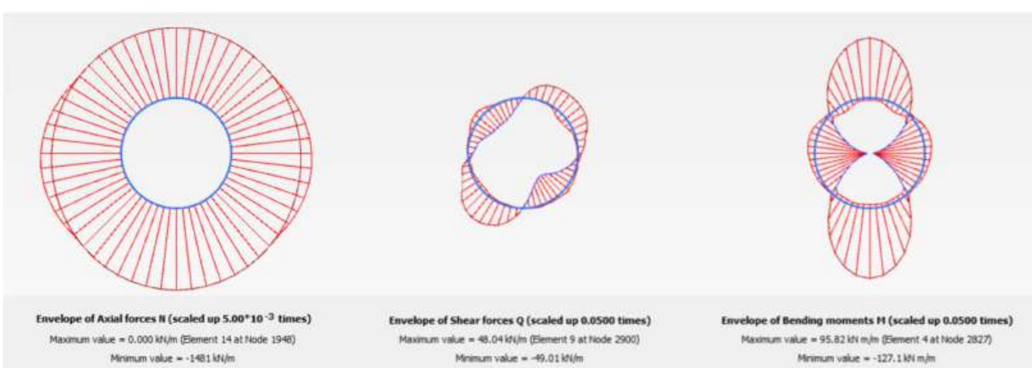



**Figure 14: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 25m depth, GWL=-60m)**

## 5.1.3. Profile #1A, Tunnel depth 35m, GWL= -20m

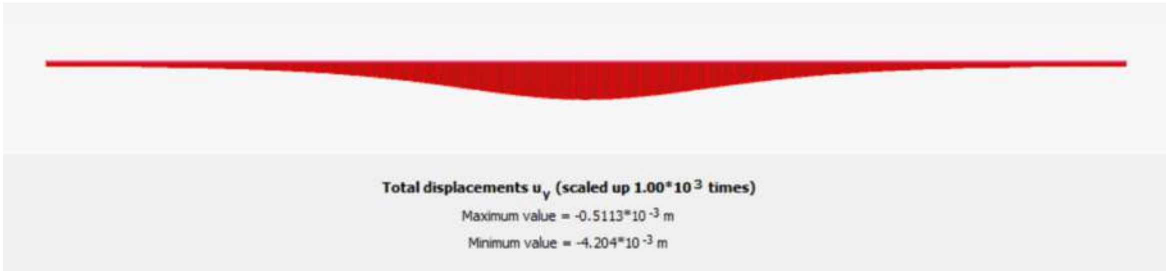



**Figure 15: Excavation induced Settlement (#1A, 35m depth, GWL=-20m)**

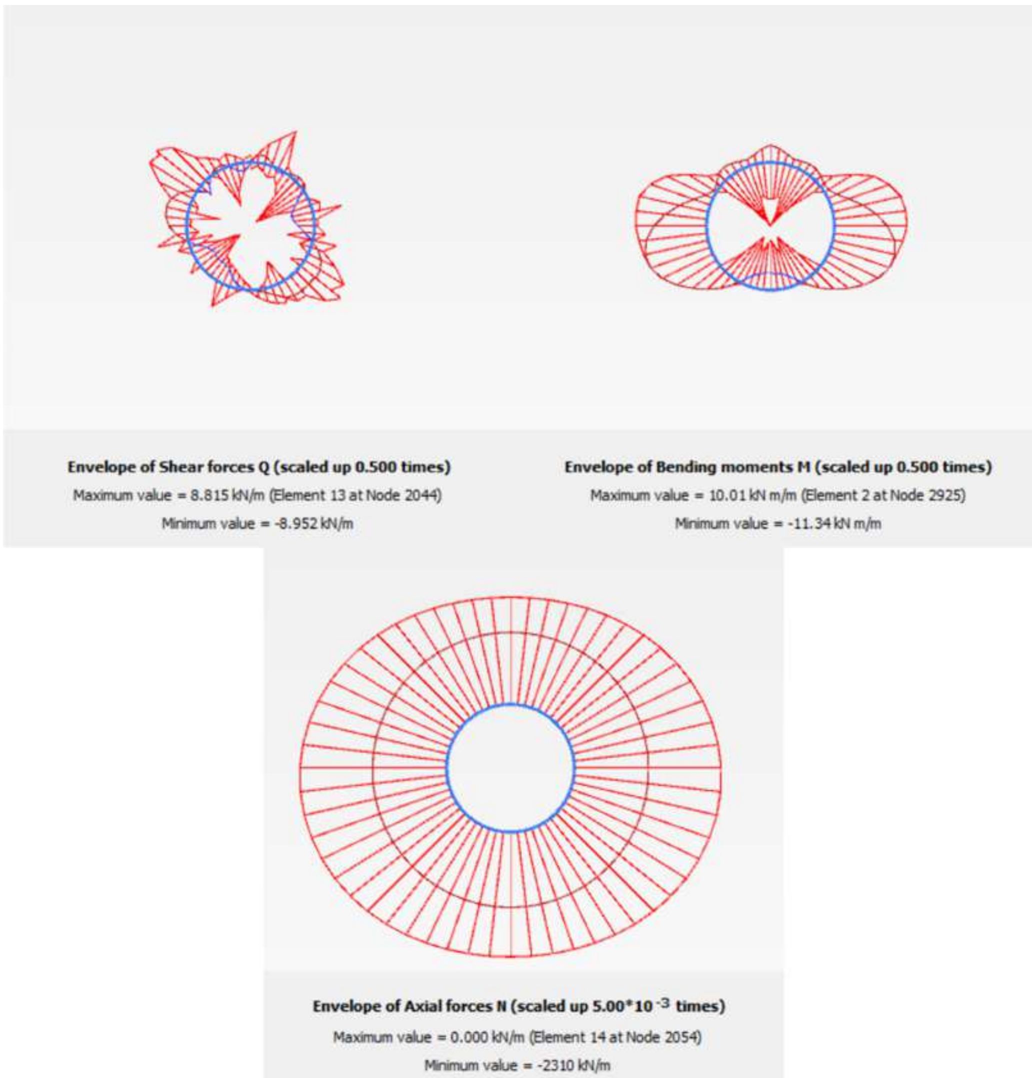



**Figure 16: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 35m depth, GWL=-20m)**

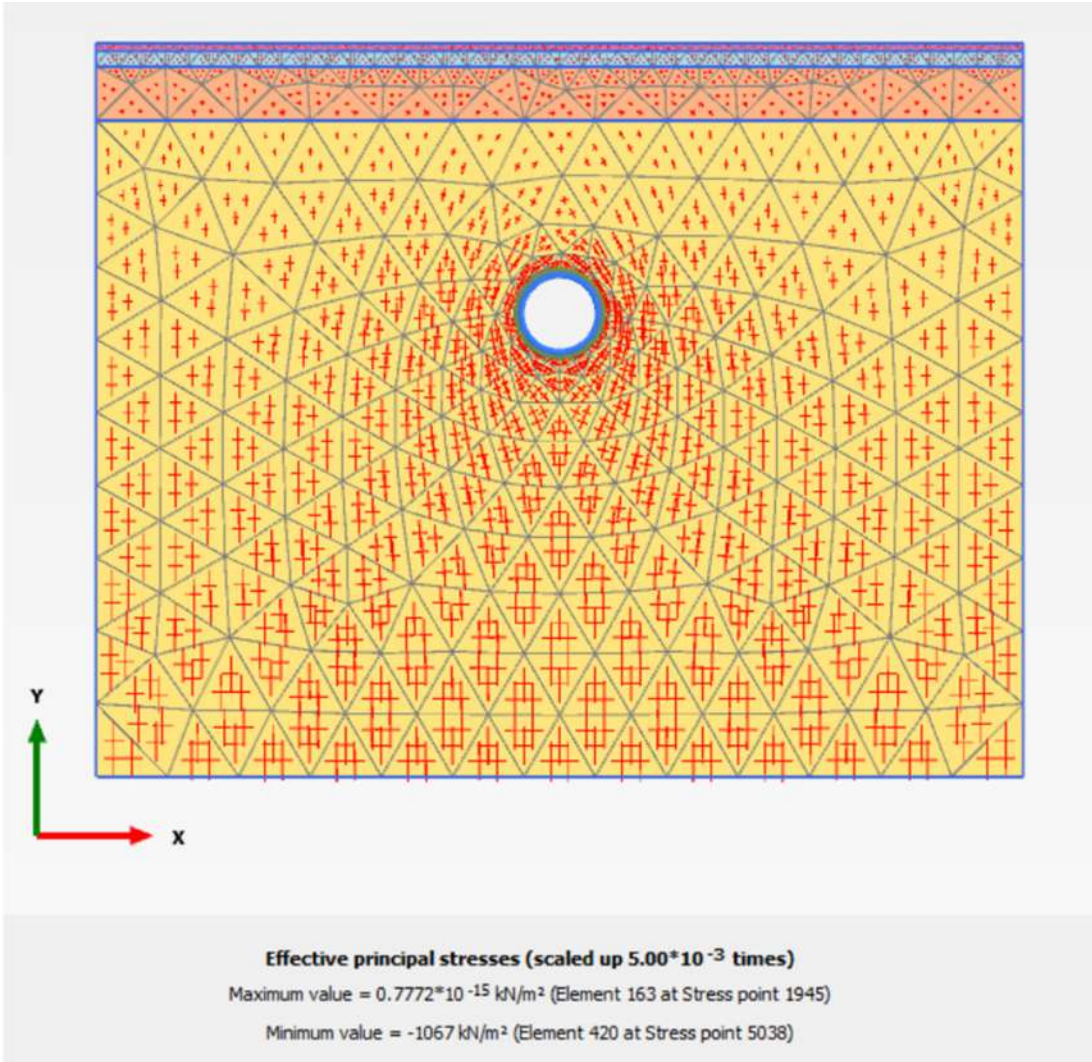



**Figure 17: Effective Principal Stress (#1A, 35m depth, GWL=-20m)**

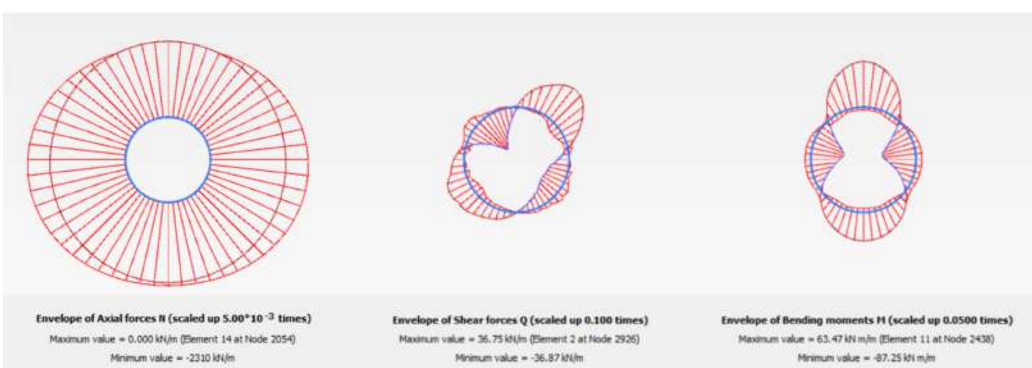



**Figure 18: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 35m depth, GWL=-20m)**

## 5.1.4. Profile #1A, Tunnel depth 35m, GWL= -60m

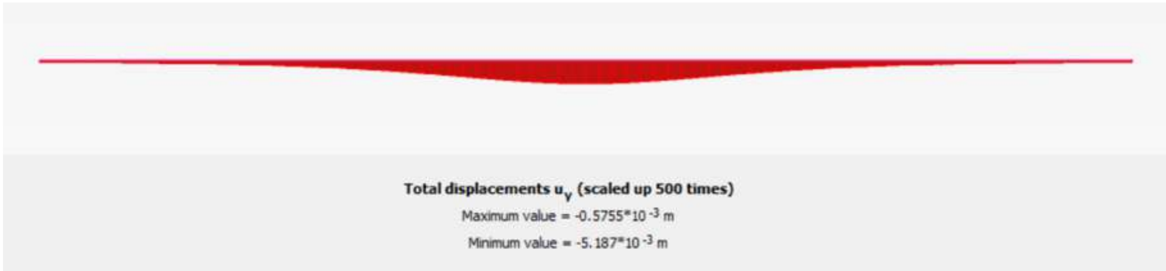



**Figure 19: Excavation induced Settlement (#1A, 35m depth, GWL=-60m)**

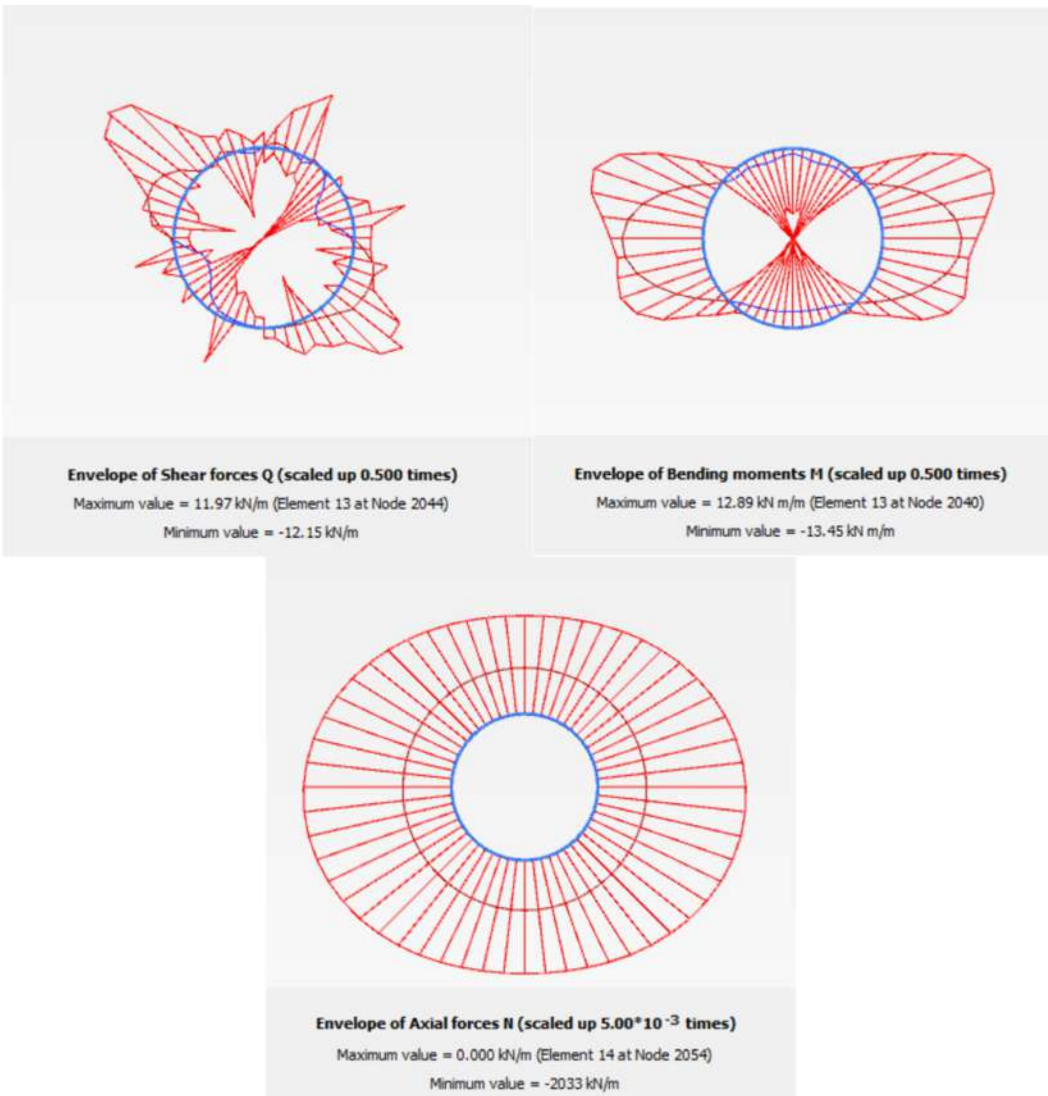



**Figure 20: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 35m depth, GWL=-60m)**

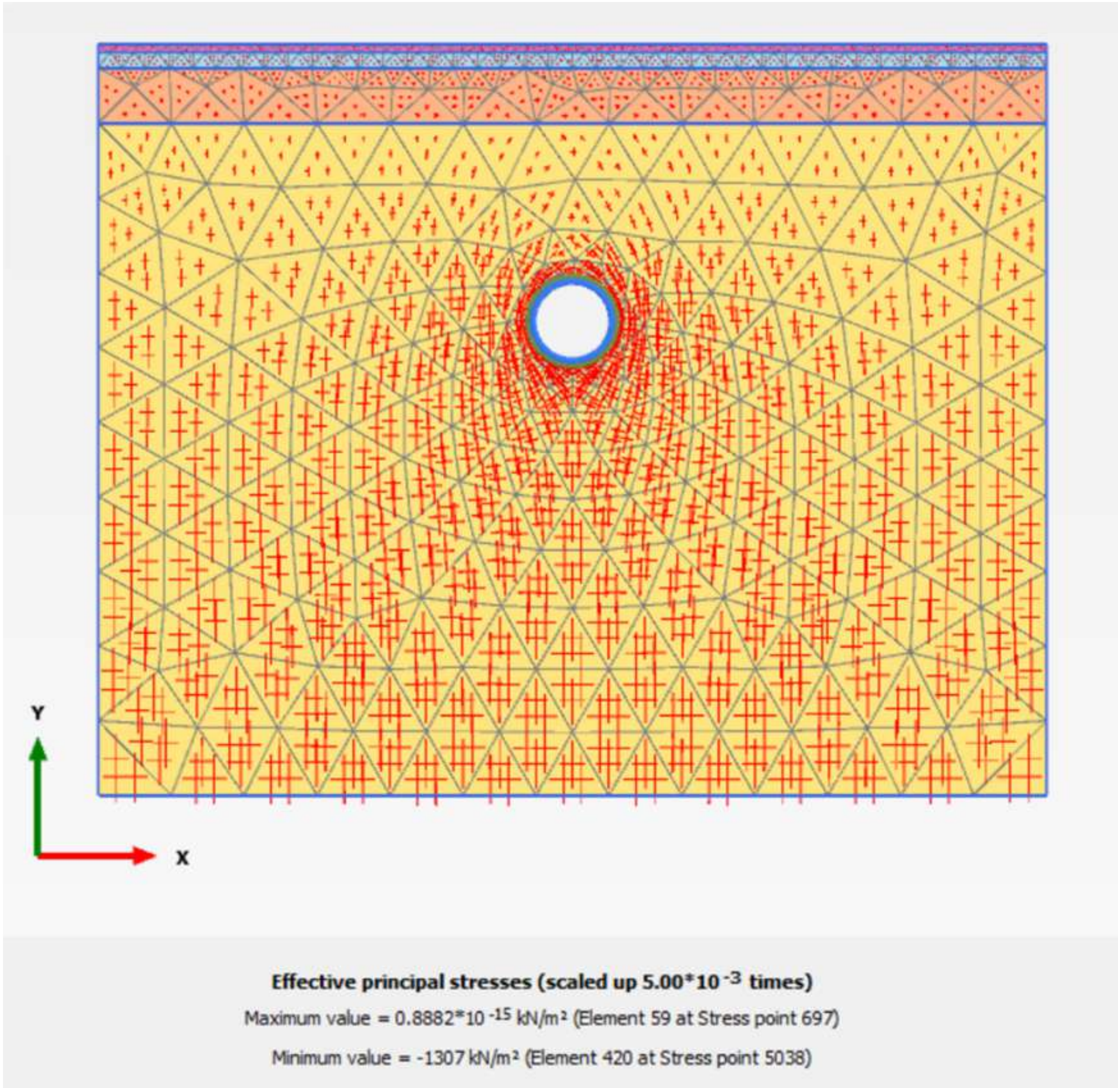



**Figure 21: Effective Principal Stress (#1A, 35m depth, GWL=-60m)**

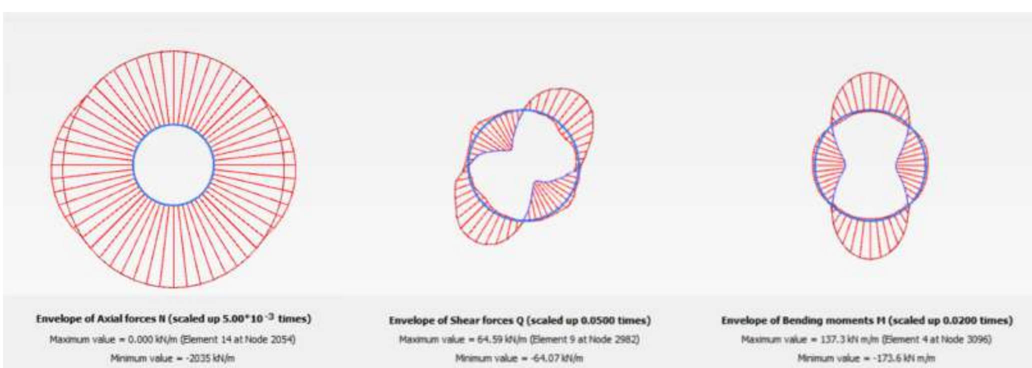



**Figure 22: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 35m depth, GWL=-60m)**

## 5.1.5. Profile #1A, Tunnel depth 45m, GWL= -20m

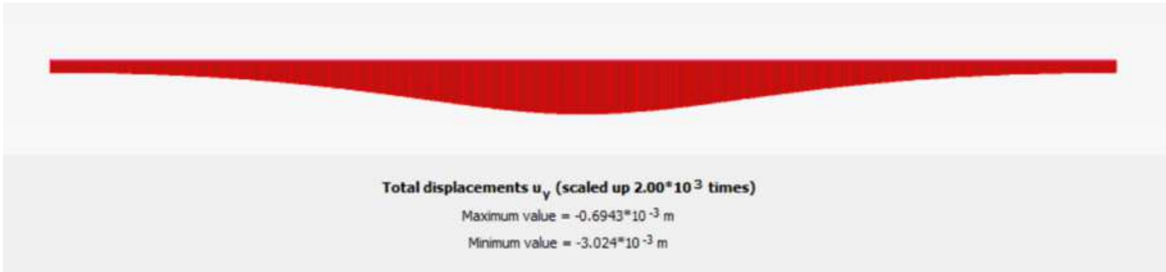



**Figure 23: Excavation induced Settlement (#1A, 45m depth, GWL=-20m)**

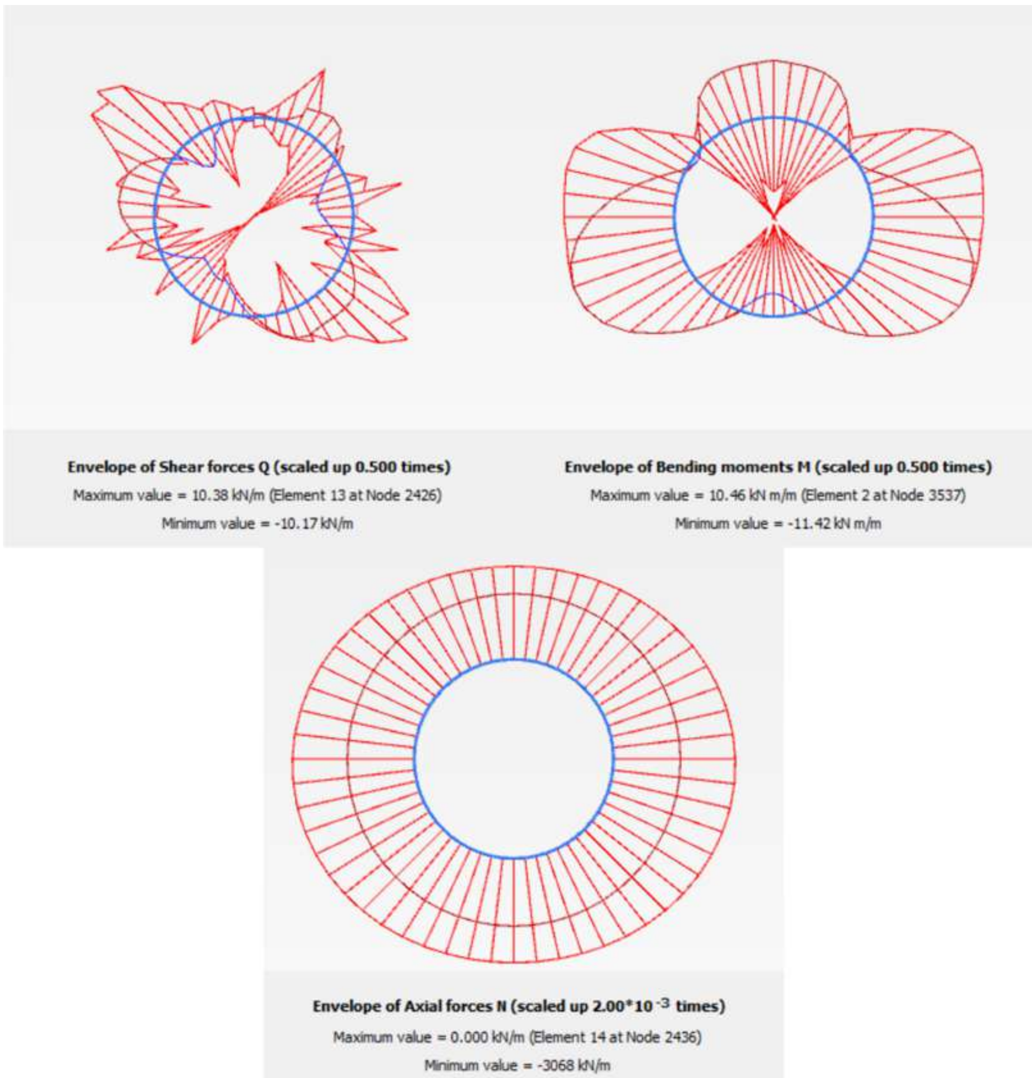



**Figure 24: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 45m depth, GWL=-20m)**

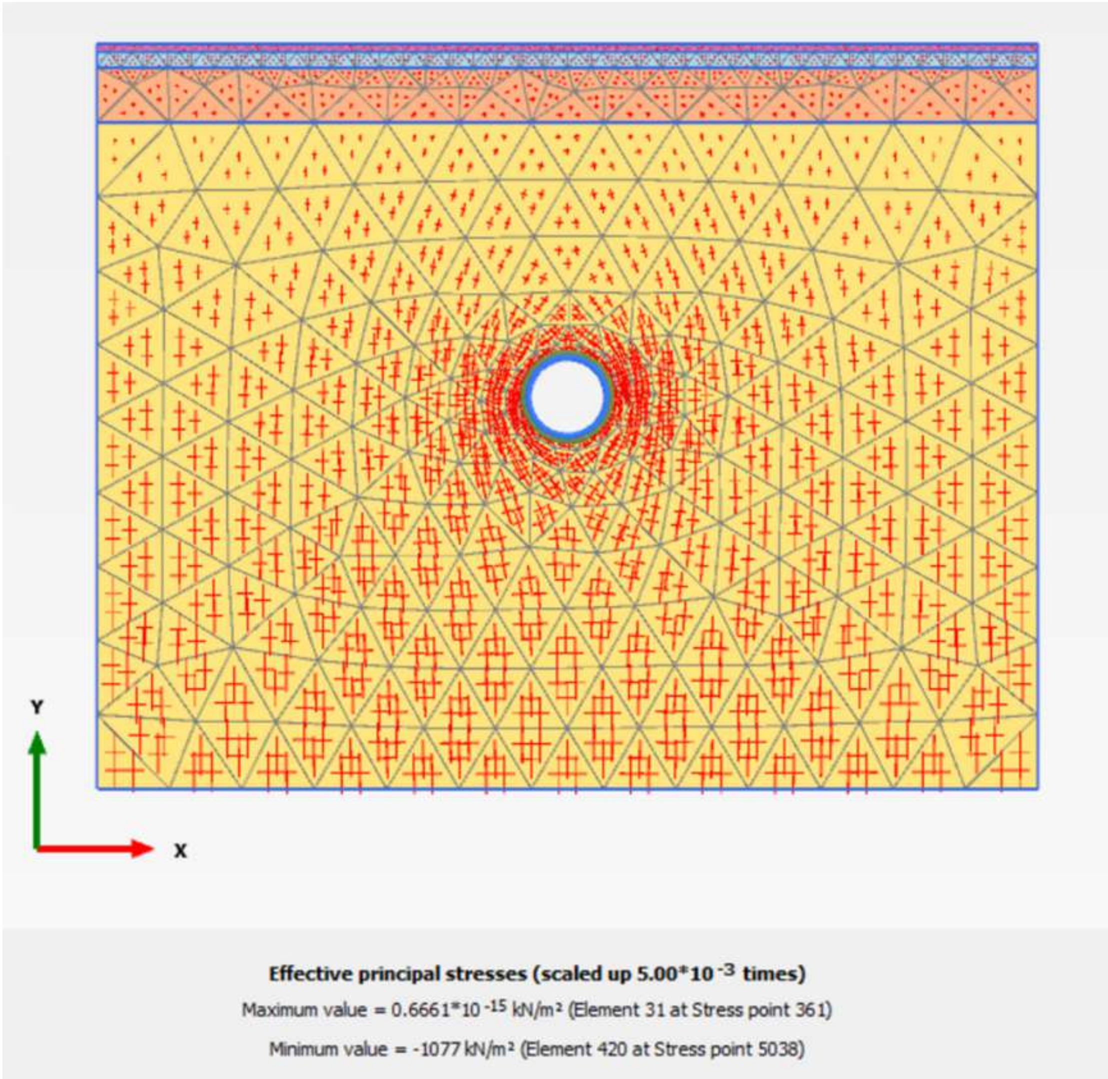



**Figure 25: Effective Principal Stress (#1A, 45m depth, GWL=-20m)**

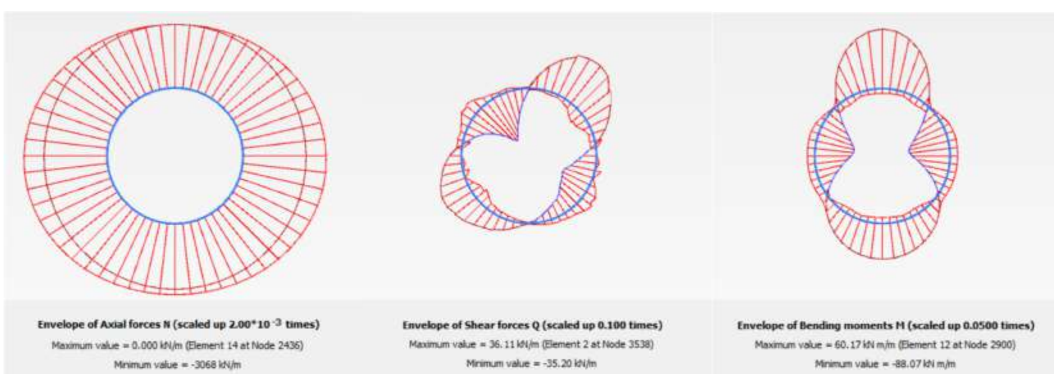



**Figure 26: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 45m depth, GWL=-20m)**

### 5.1.6. Profile #1A, Tunnel depth 45m, GWL= -60m

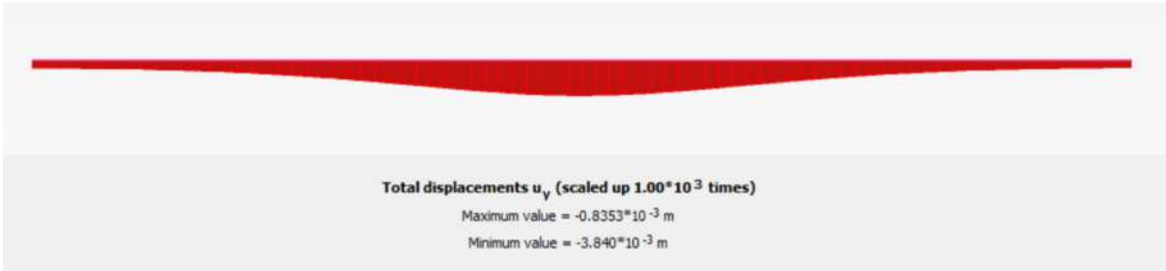



**Figure 27: Excavation induced Settlement (#1A, 45m depth, GWL=-60m)**

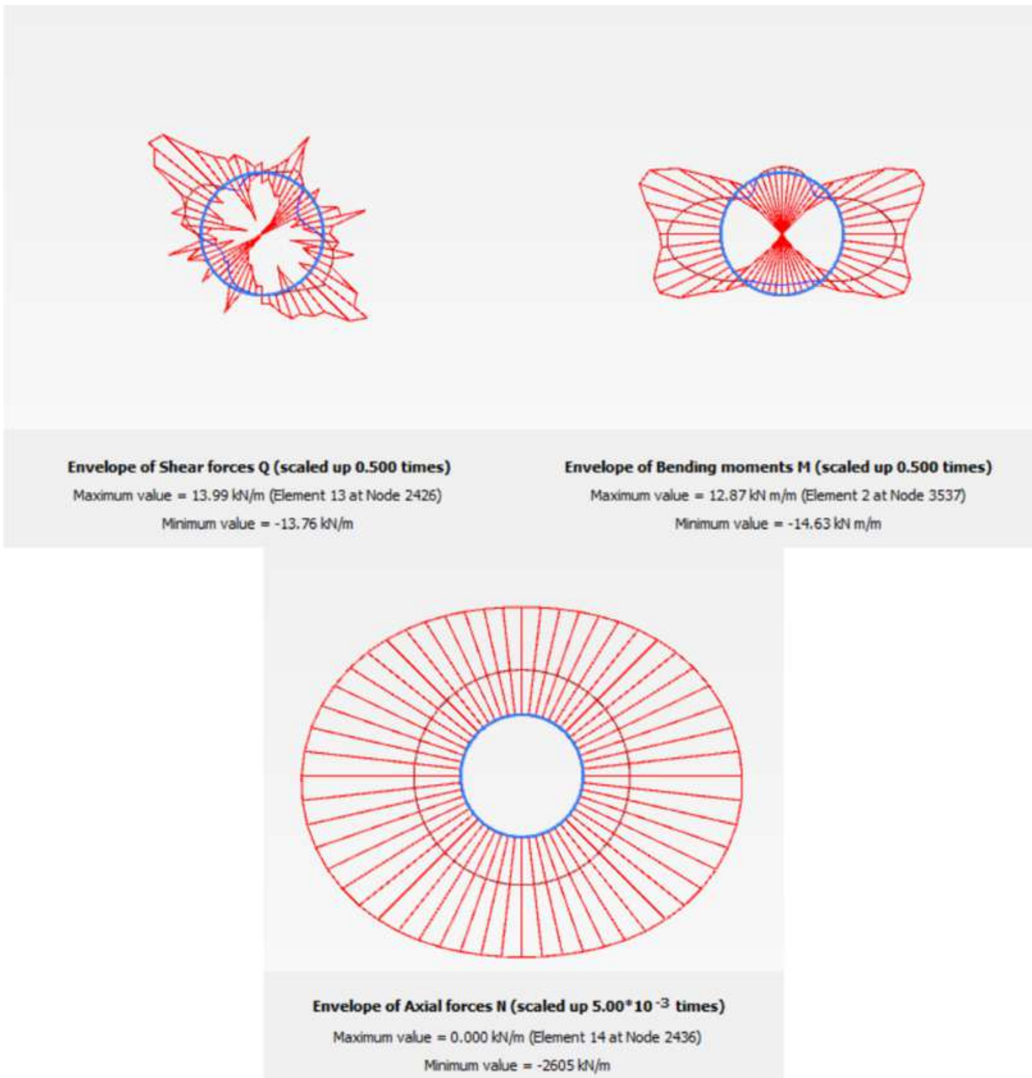



**Figure 28: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 45m depth, GWL=-60m)**

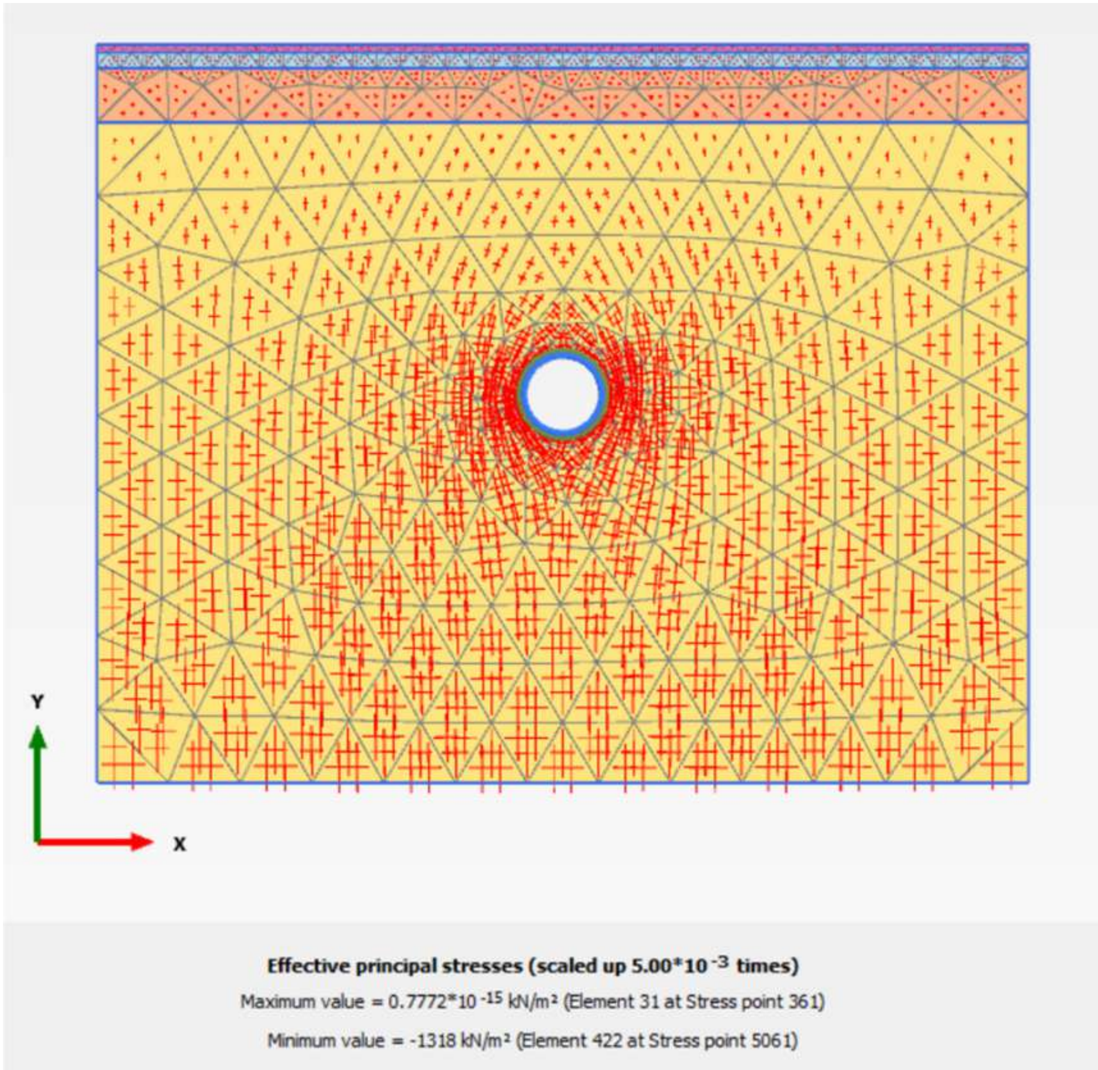



**Figure 29: Effective Principal Stress (#1A, 45m depth, GWL=-60m)**

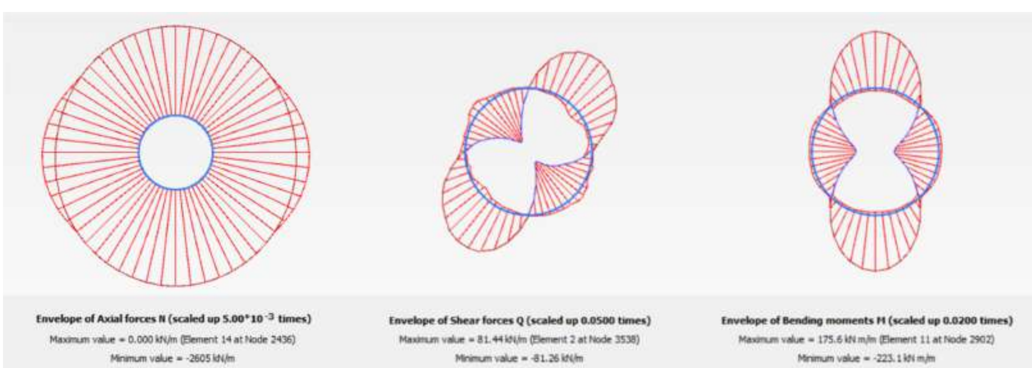



**Figure 30: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 45m depth, GWL=-60m)**

## 5.1.7. Profile #1A, Tunnel depth 55m, GWL= -20m


**Figure 31: Excavation induced Settlement (#1A, 55m depth, GWL=-20m)**

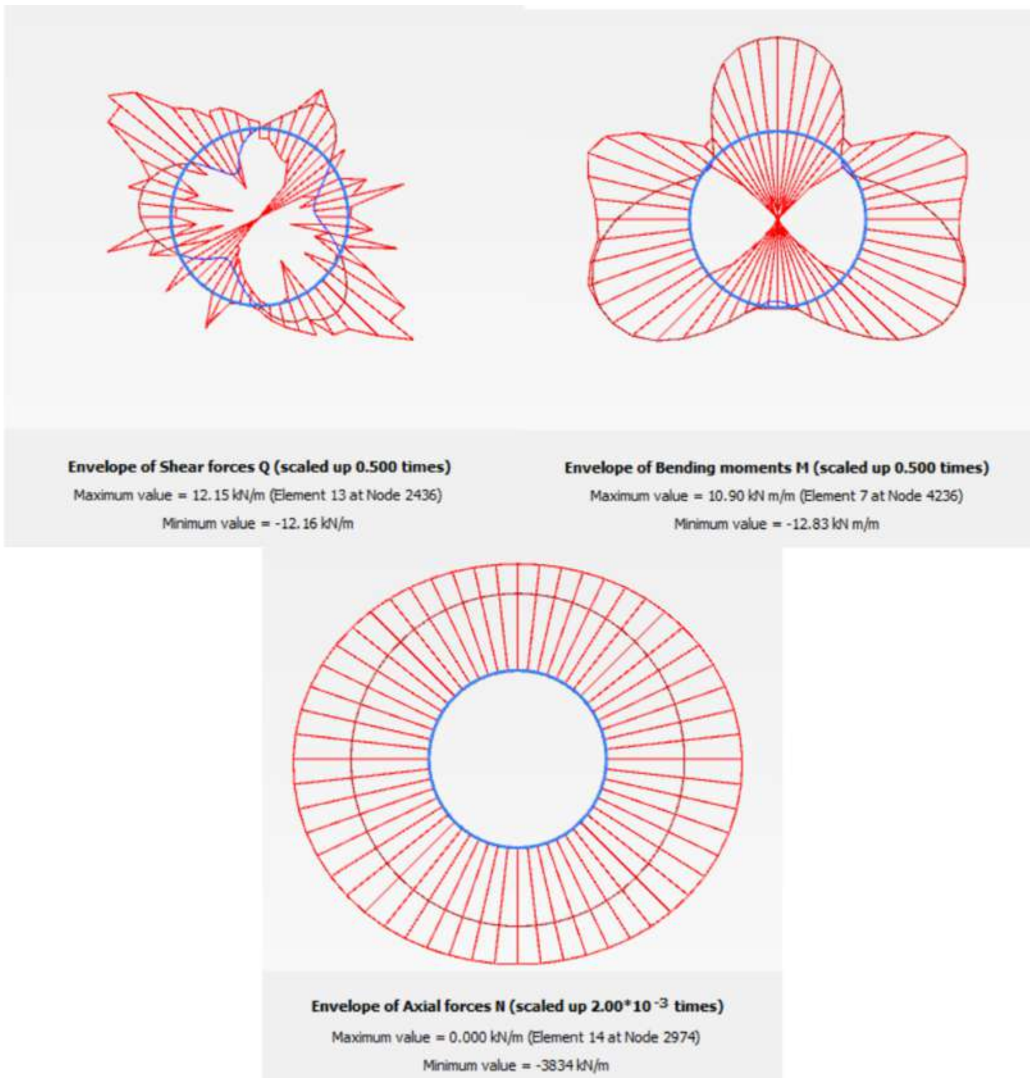



**Figure 32: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 55m depth, GWL=-20m)**

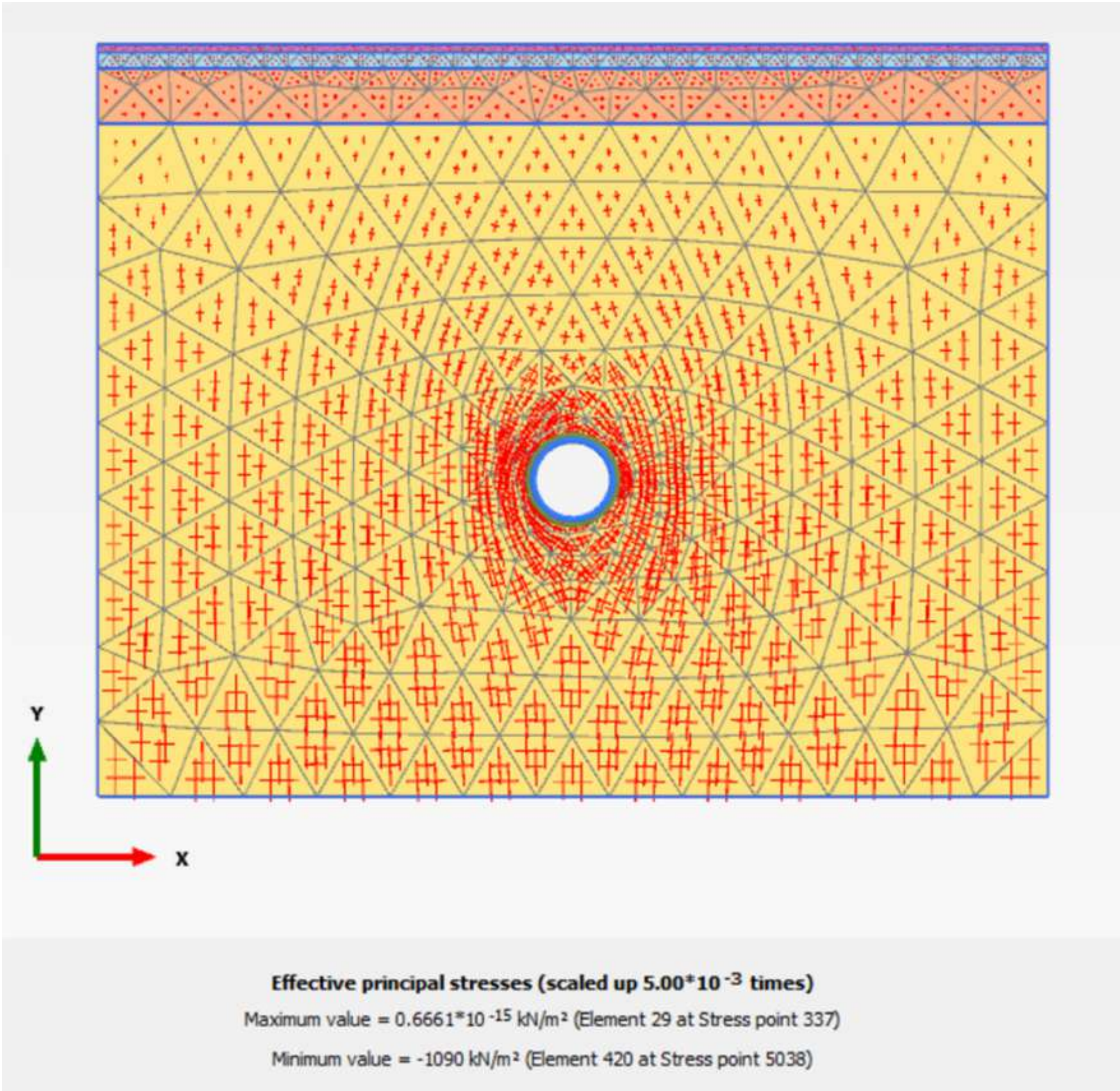



**Figure 33: Effective Principal Stress (#1A, 55m depth, GWL=-20m)**

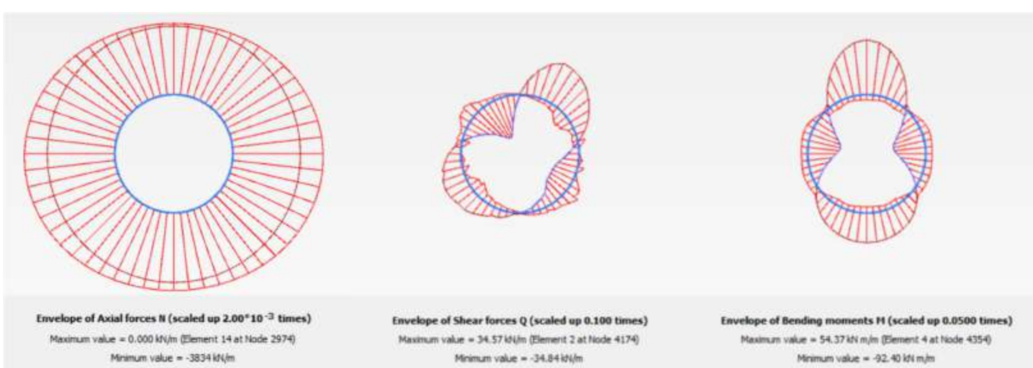



**Figure 34: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 55m depth, GWL=-20m)**

## 5.1.8. Profile #1A, Tunnel depth 55m, GWL= -60m


**Figure 35: Excavation induced Settlement (#1A, 55m depth, GWL=-60m)**

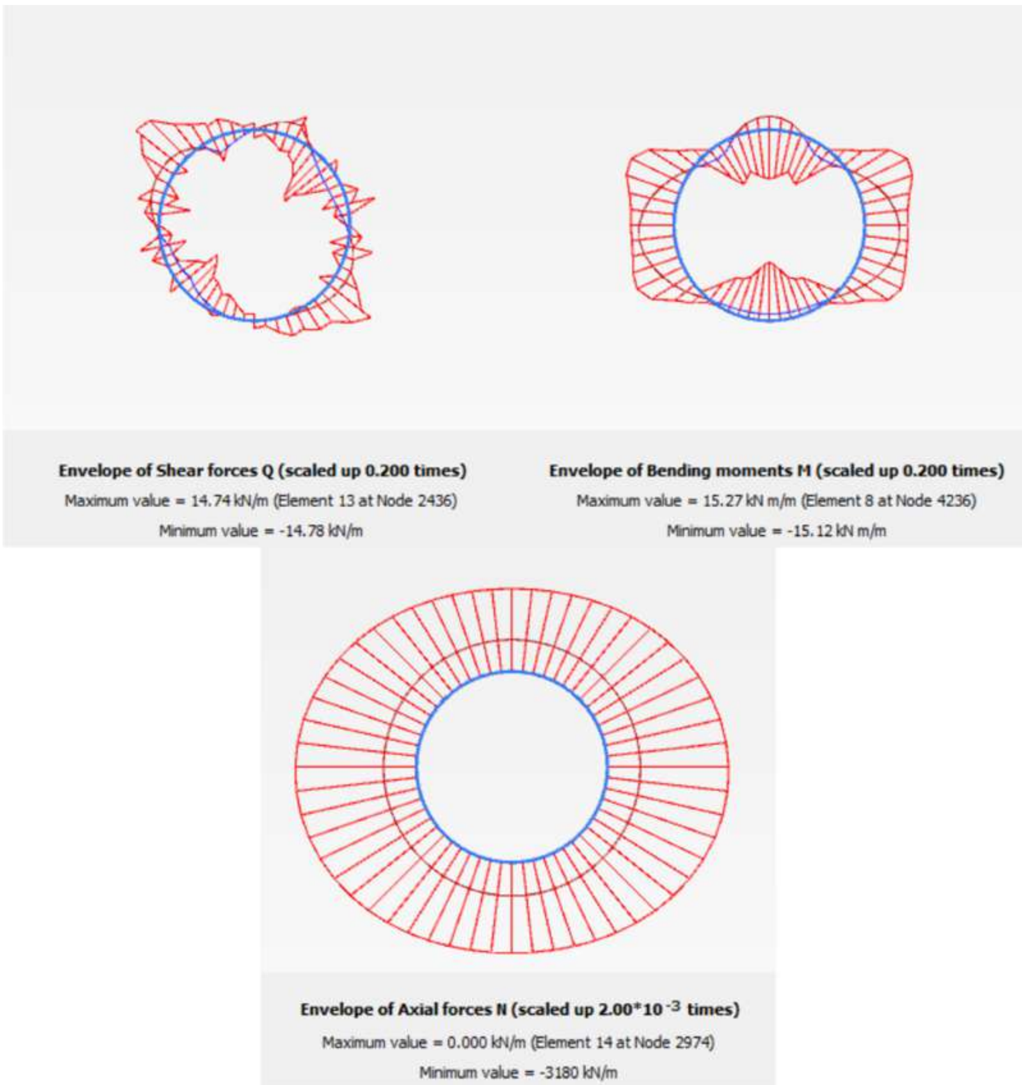



**Figure 36: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 55m depth, GWL=-60m)**

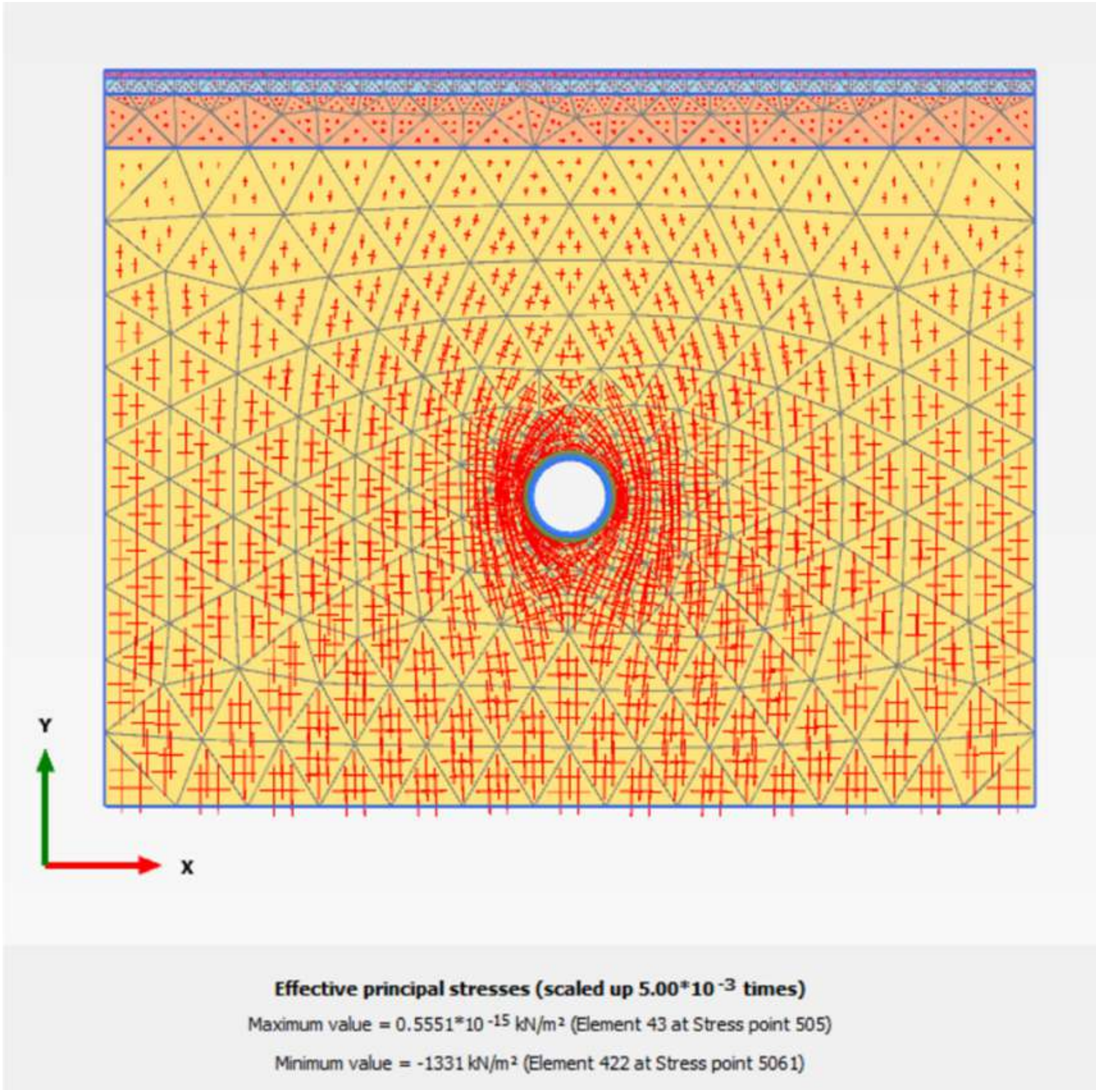



**Figure 37: Effective Principal Stress (#1A, 55m depth, GWL=-60m)**

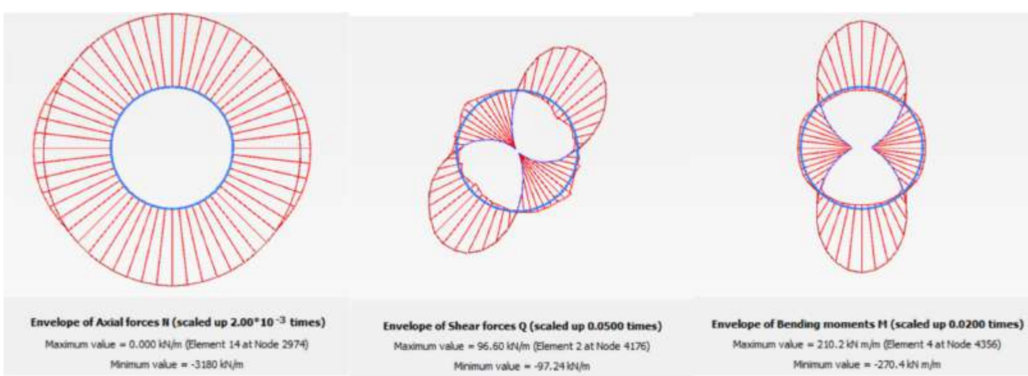



**Figure 38: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 55m depth, GWL=-60m)**

## 5.1.9. Profile #1A, Tunnel depth 65m, GWL= -20m


**Figure 39: Excavation induced Settlement (#1A, 65m depth, GWL=-20m)**

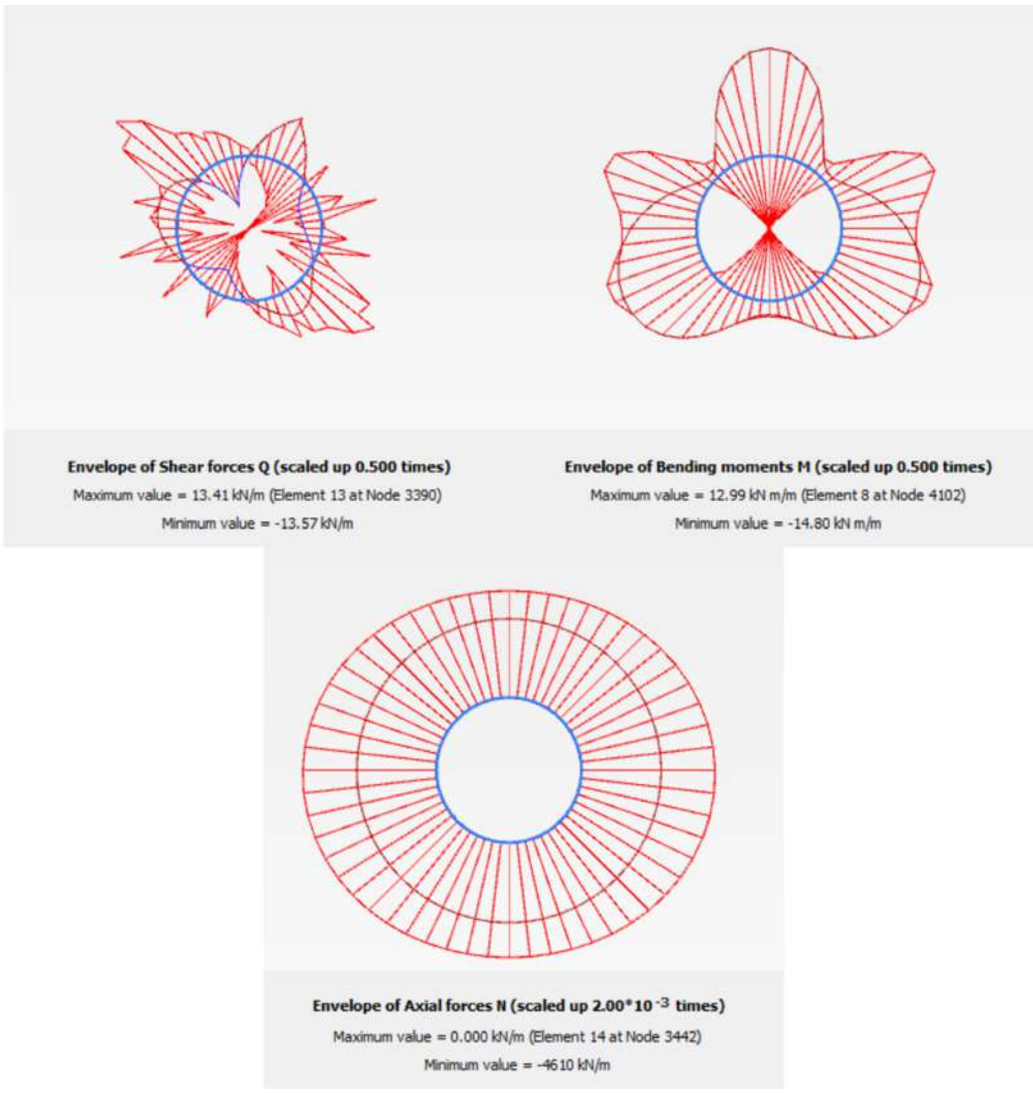



**Figure 40: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 65m depth, GWL=-20m)**

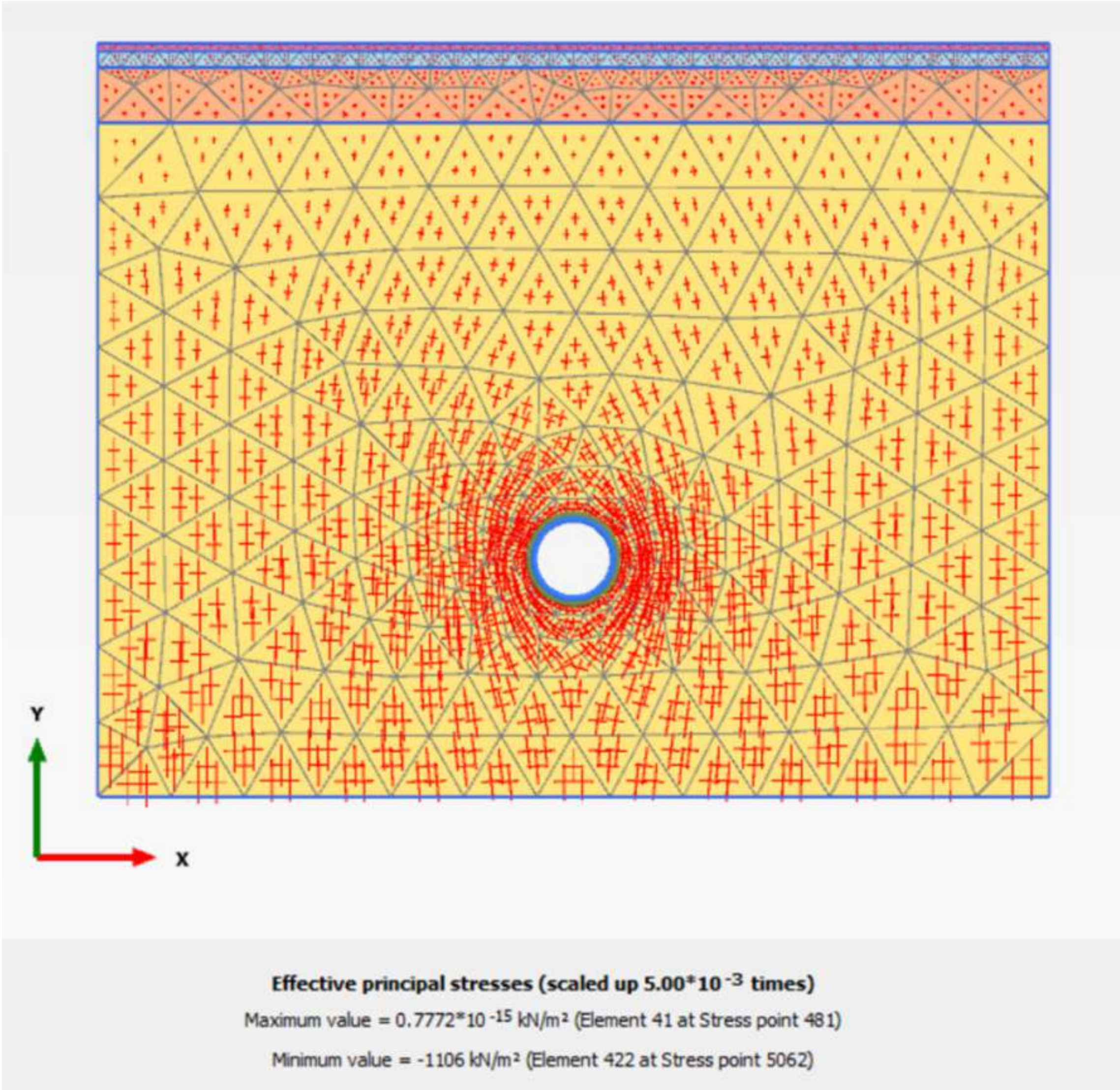



**Figure 41: Effective Principal Stress (#1A, 65m depth, GWL=-20m)**

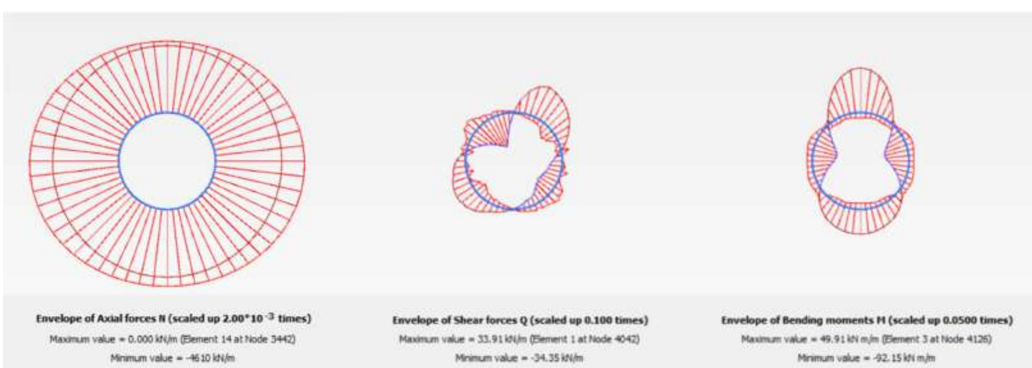



**Figure 42: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 65m depth, GWL=-20m)**

## 5.1.10. Profile #1A, Tunnel depth 65m, GWL= -60m


**Figure 43: Excavation induced Settlement (#1A, 65m depth, GWL=-60m)**

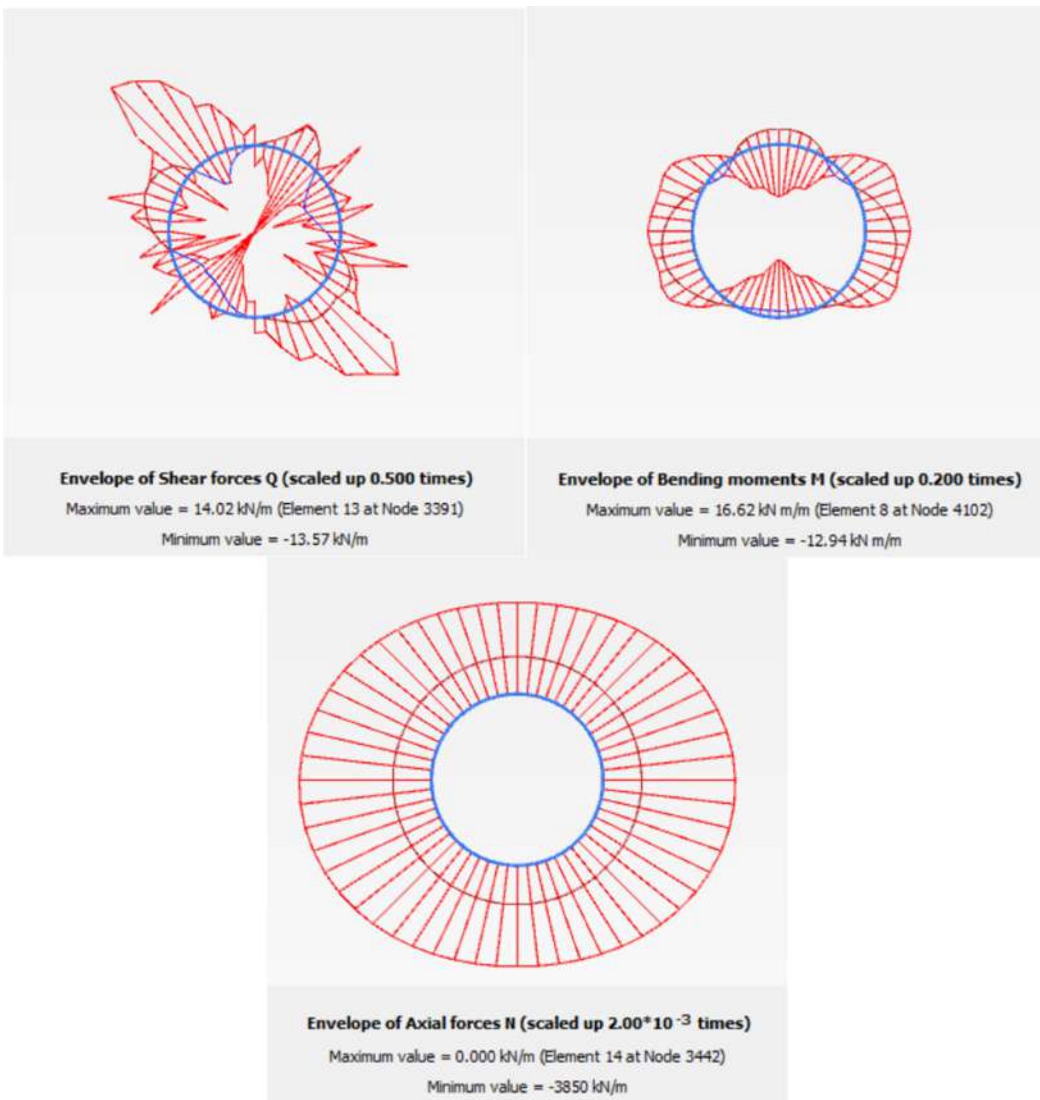



**Figure 44: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 65m depth, GWL=-60m)**

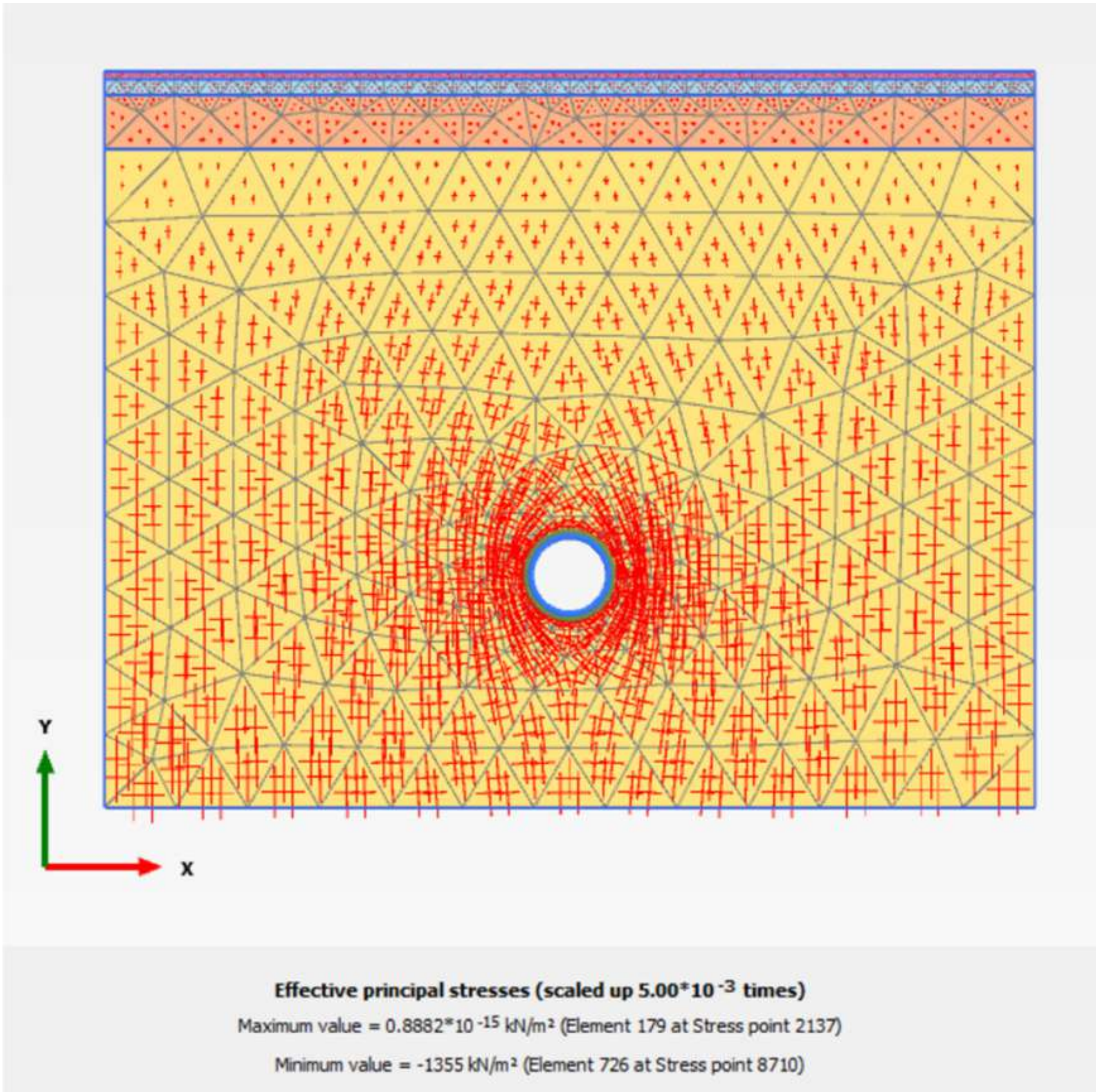



**Figure 45: Effective Principal Stress (#1A, 65m depth, GWL=-60m)**

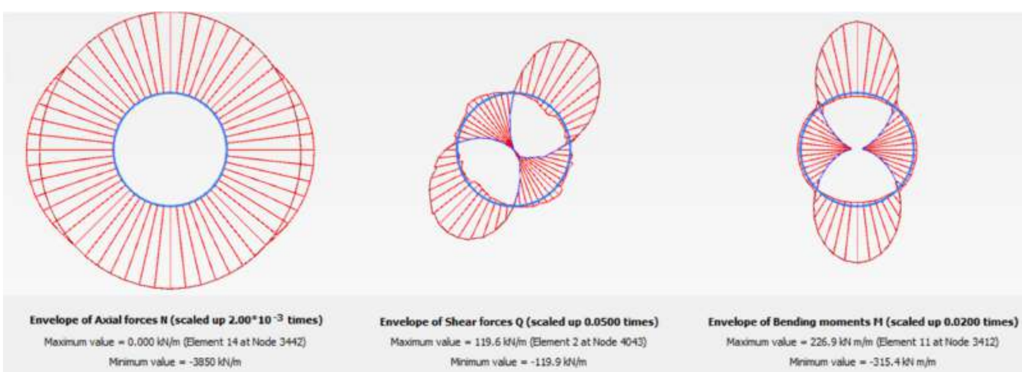



**Figure 46: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 65m depth, GWL=-60m)**

## 5.1.11. Profile #1A, Tunnel depth 75m, GWL= -20m


**Figure 47: Excavation induced Settlement (#1A, 75m depth, GWL=-20m)**

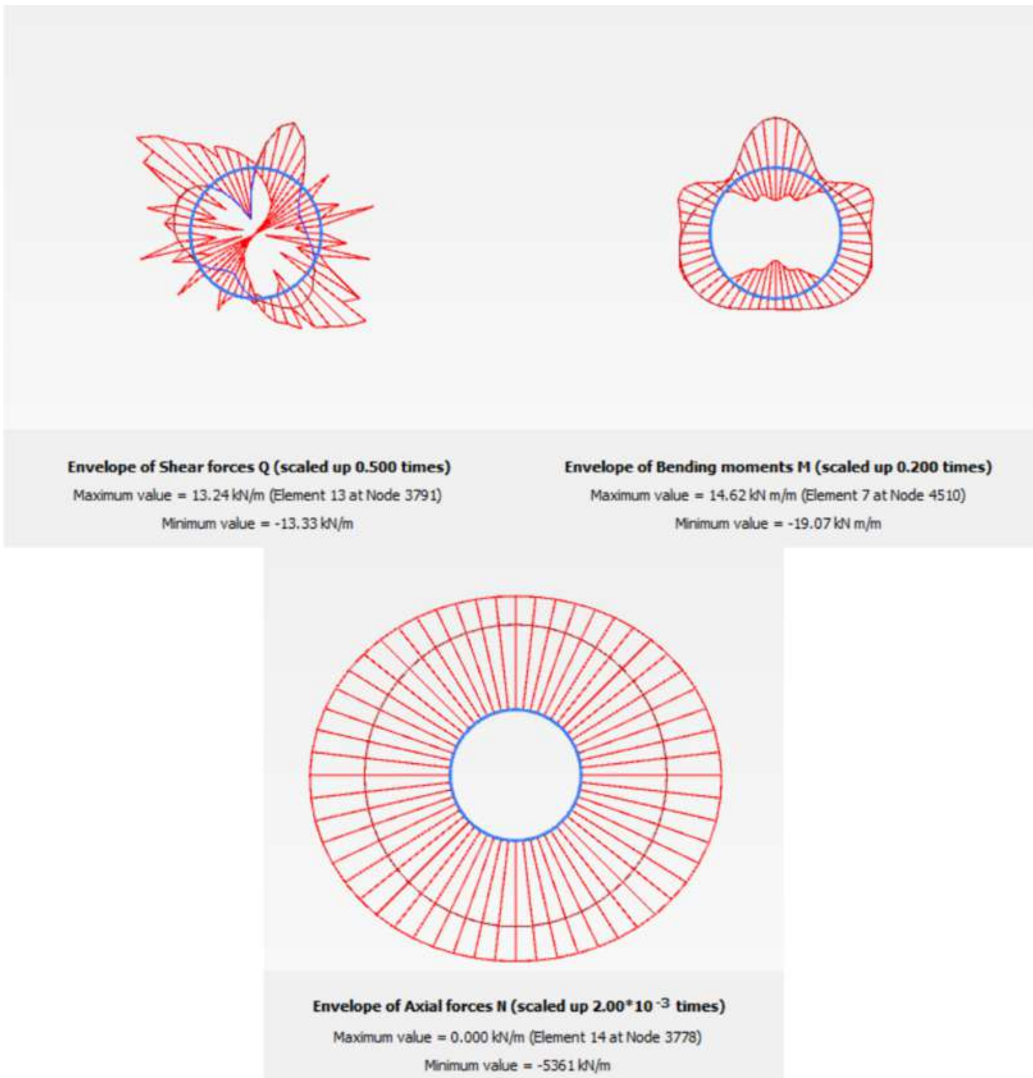



**Figure 48: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 75m depth, GWL=-20m)**

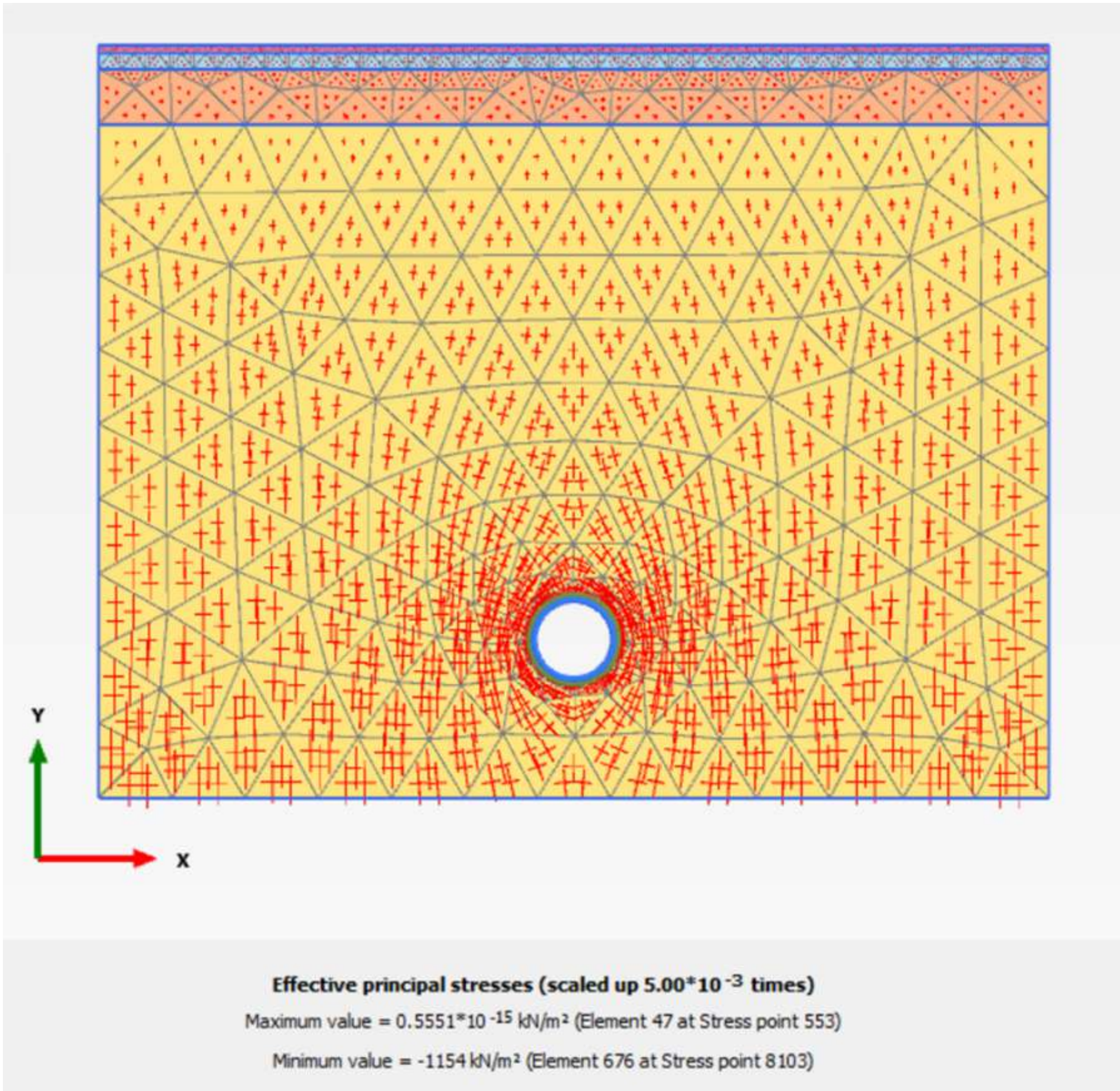



**Figure 49: Effective Principal Stress (#1A, 75m depth, GWL=-20m)**

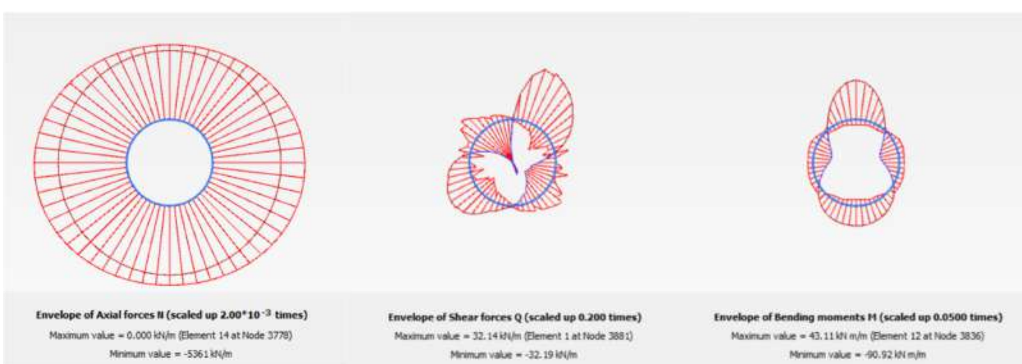



**Figure 50: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 75m depth, GWL=-20m)**

## 5.1.12. Profile #1A, Tunnel depth 75m, GWL= -60m


**Figure 51: Excavation induced Settlement (#1A, 75m depth, GWL=-60m)**

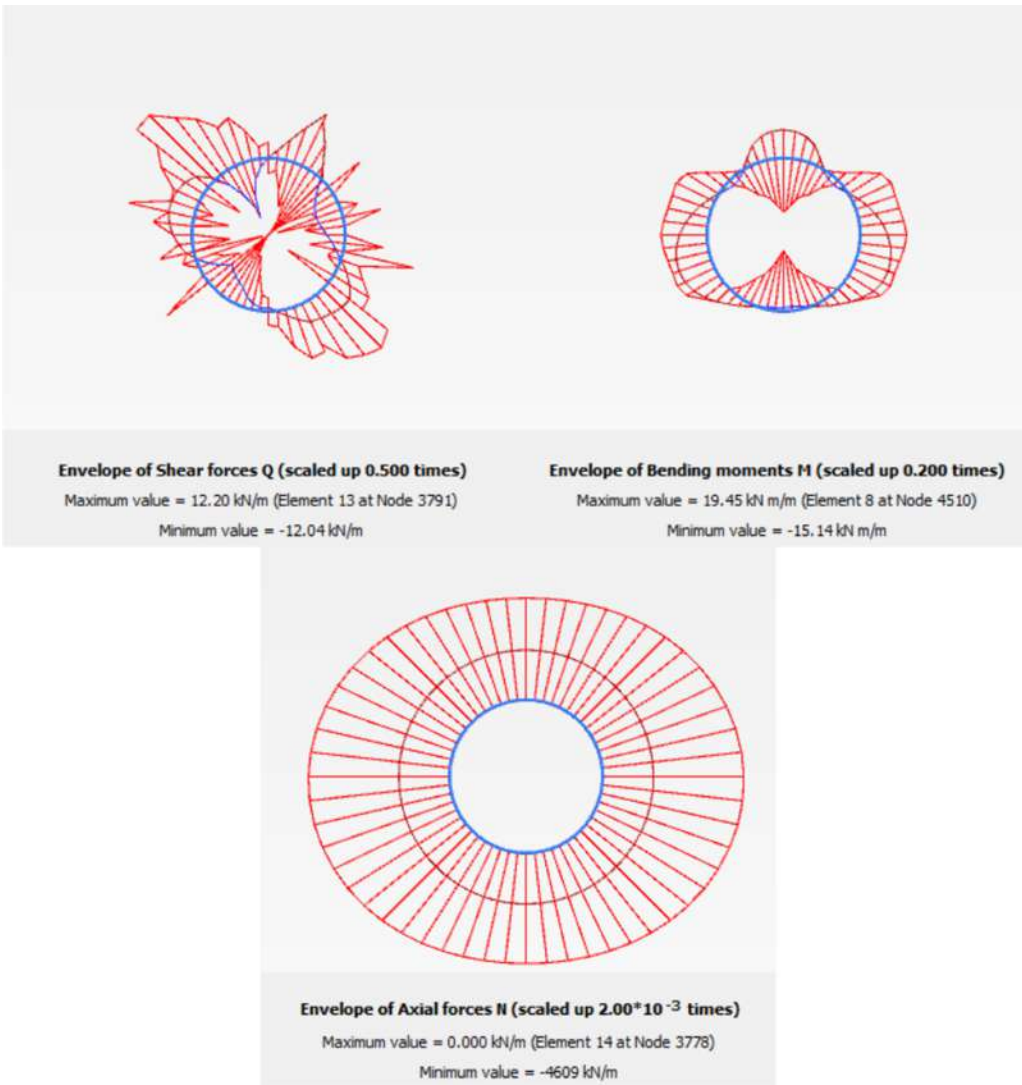



**Figure 52: Axial force, Shear force & Bending Moment on Tunnel Lining (#1A, 75m depth, GWL=-60m)**

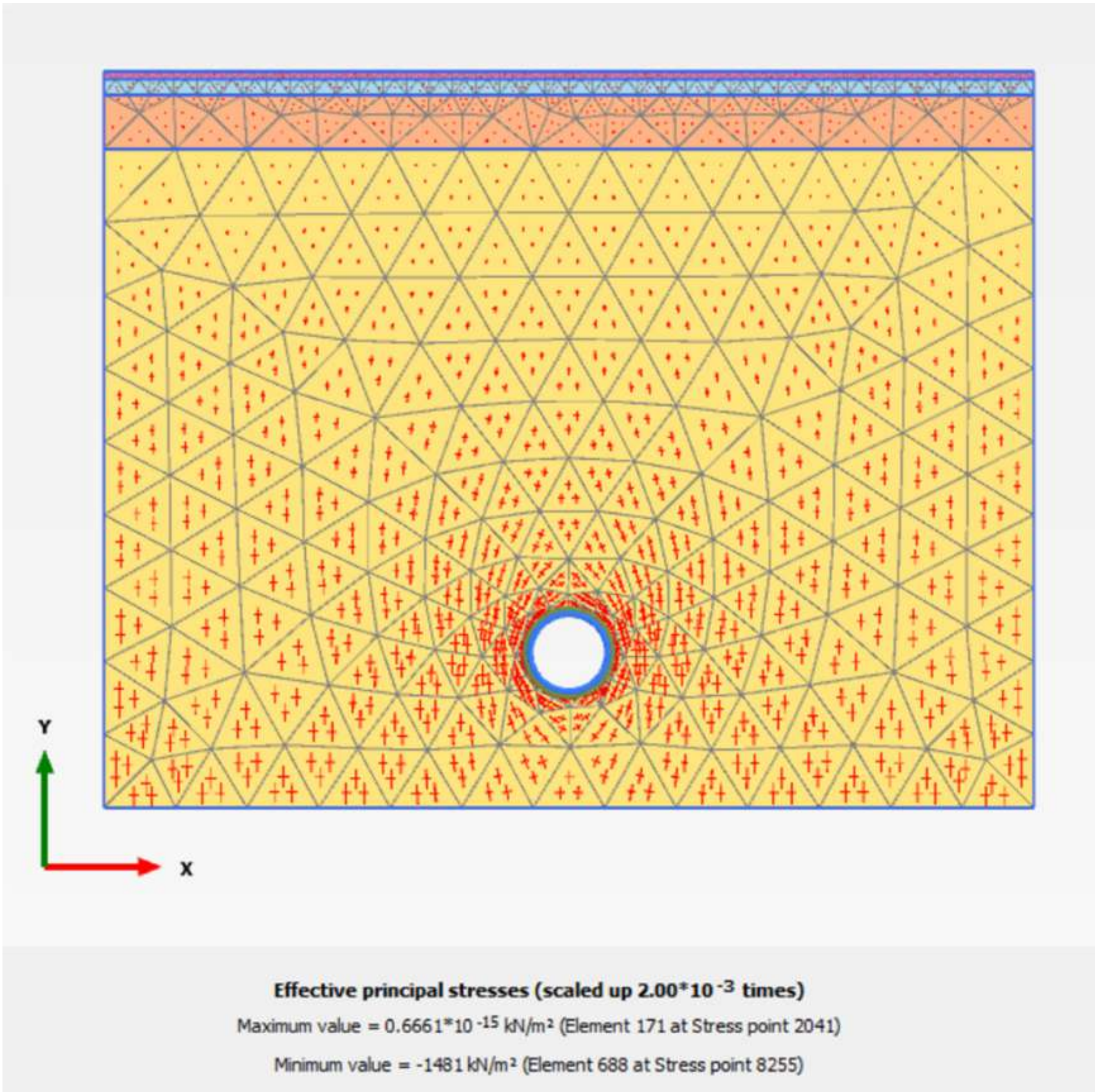



**Figure 53: Effective Principal Stress (#1A, 75m depth, GWL=-60m)**

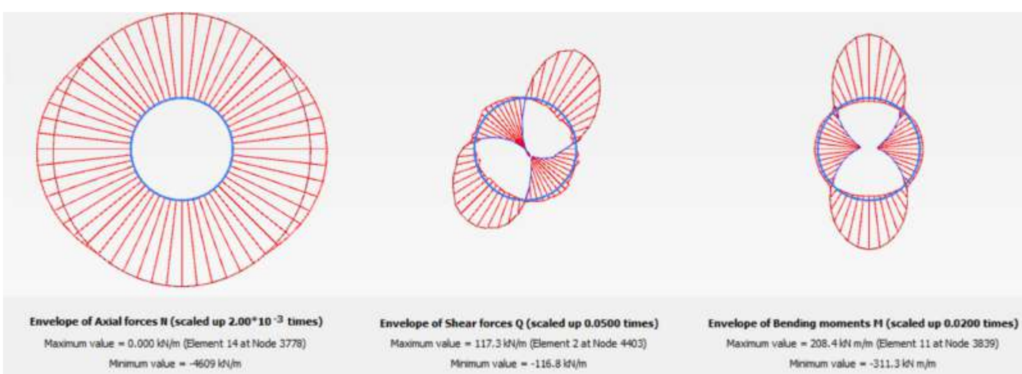



**Figure 54: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1A, 75m depth, GWL=-60m)**

## 5.1.13. Profile #1B, Tunnel depth 30m, GWL= -20m


**Figure 55: Excavation induced Settlement (#1B, 30m depth, GWL=-20m)**

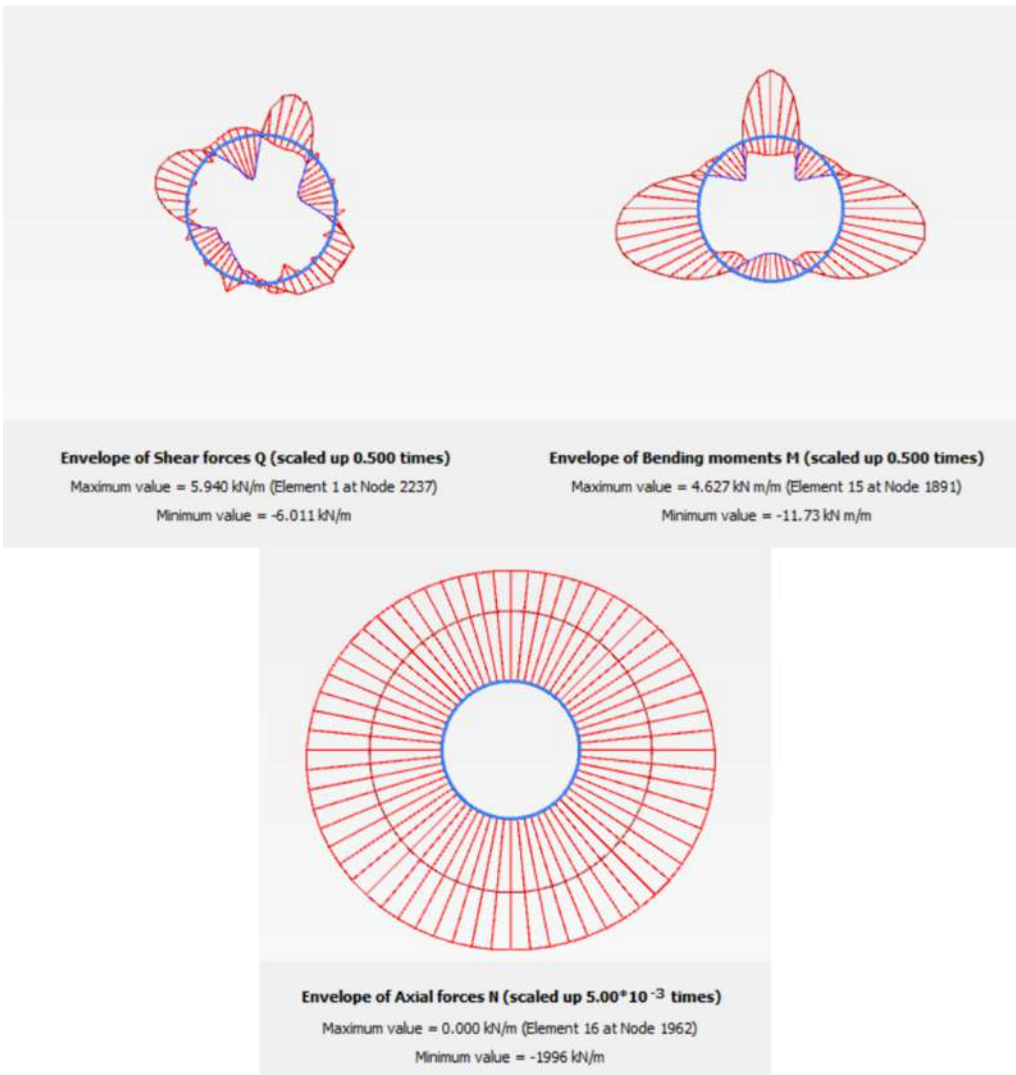



**Figure 56: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 30m depth, GWL=-20m)**

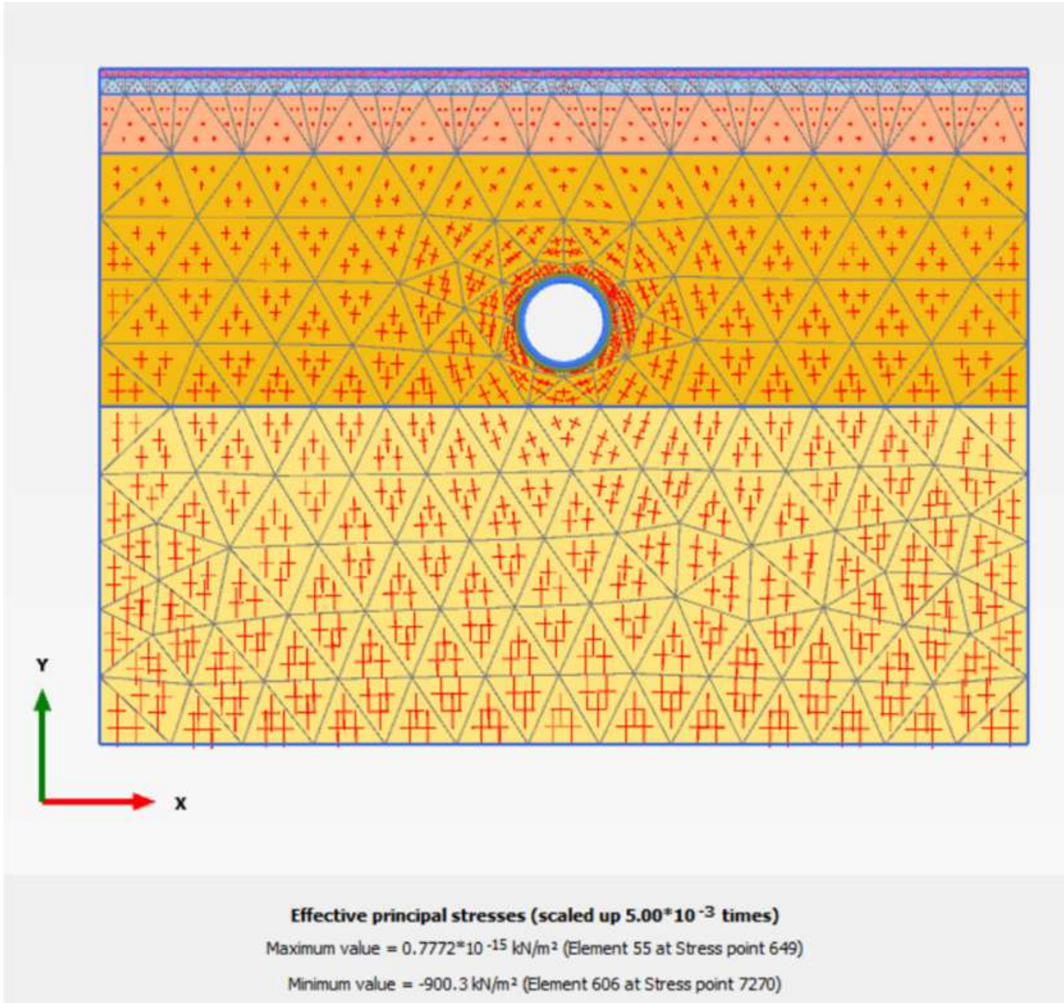



**Figure 57: Effective Principal Stress (#1B, 30m depth, GWL=-20m)**

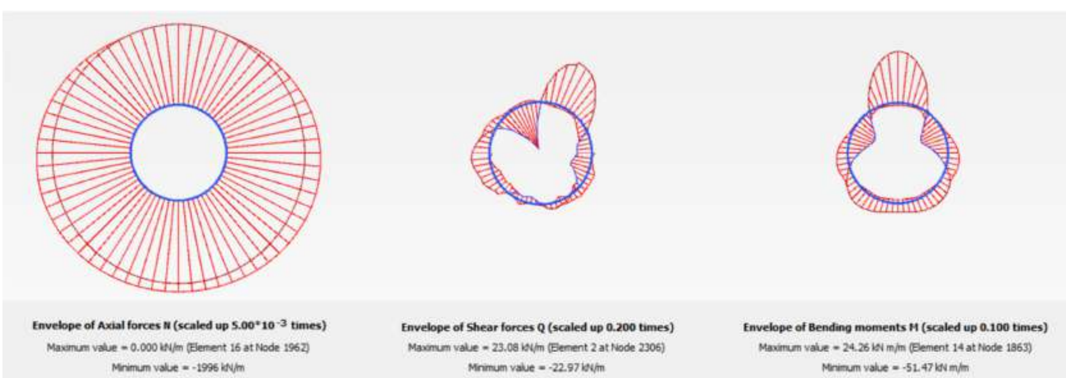



**Figure 58: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 30m depth, GWL=-20m)**

## 5.1.14. Profile #1B, Tunnel depth 30m, GWL= -60m


**Figure 59: Excavation induced Settlement (#1B, 30m depth, GWL=-60m)**

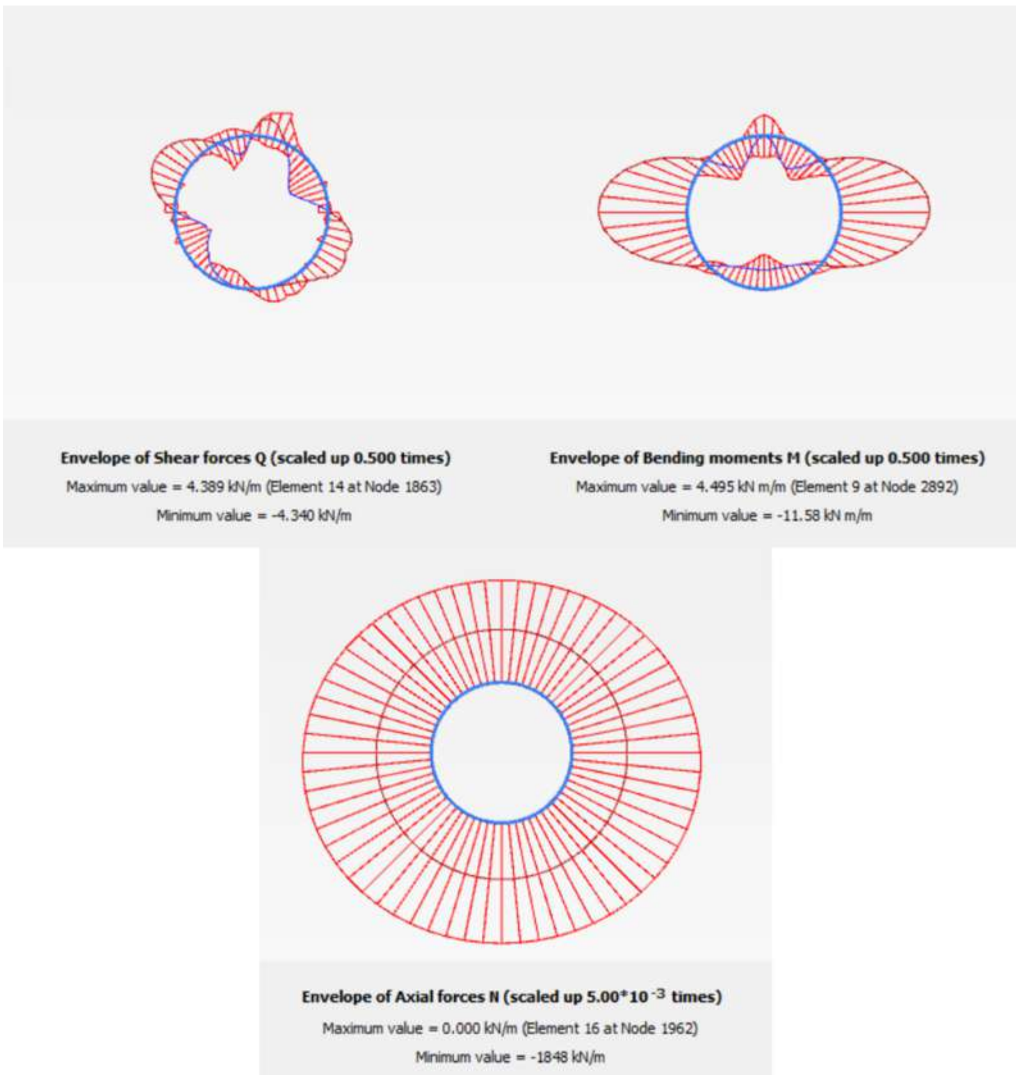



**Figure 60: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 30m depth, GWL=-60m)**

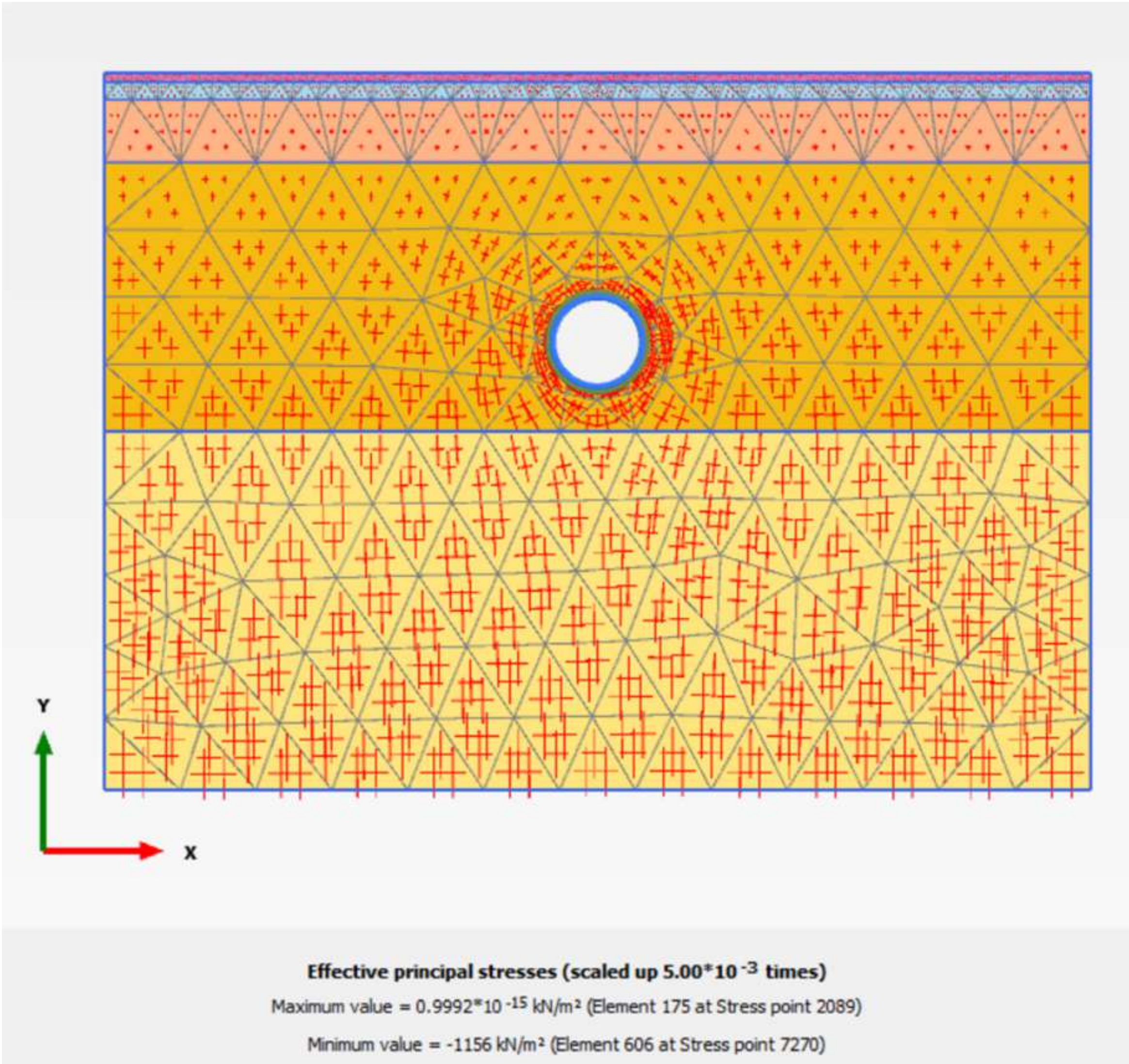



**Figure 61: Effective Principal Stress (#1B, 30m depth, GWL=-60m)**

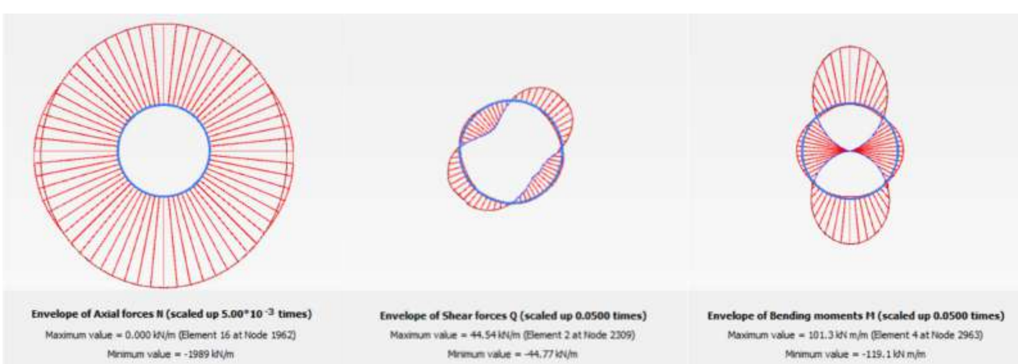



**Figure 62: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 30m depth, GWL=-60m)**

## 5.1.15. Profile #1B, Tunnel depth 40m, GWL= -20m


**Figure 63: Excavation induced Settlement (#1B, 40m depth, GWL=-20m)**

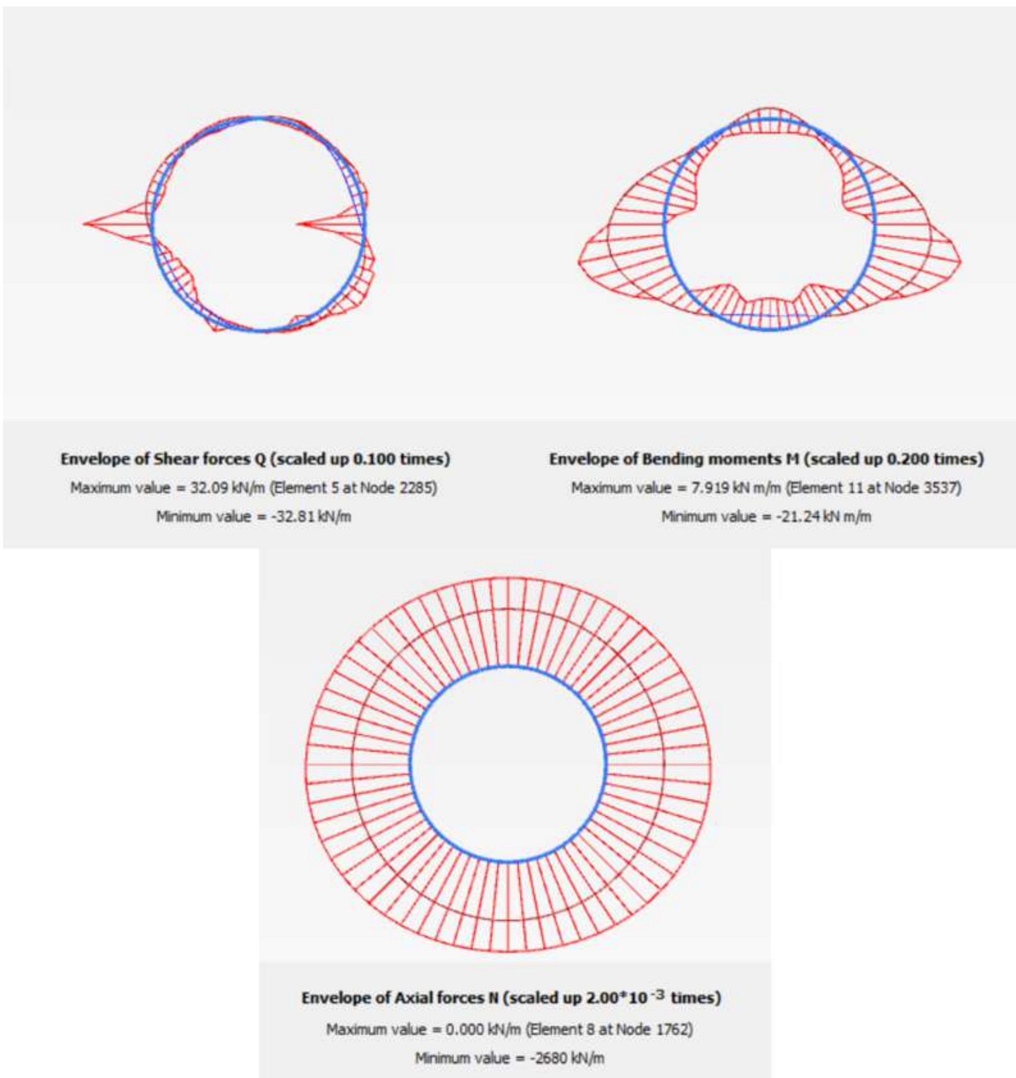



**Figure 64: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 40m depth, GWL=-20m)**

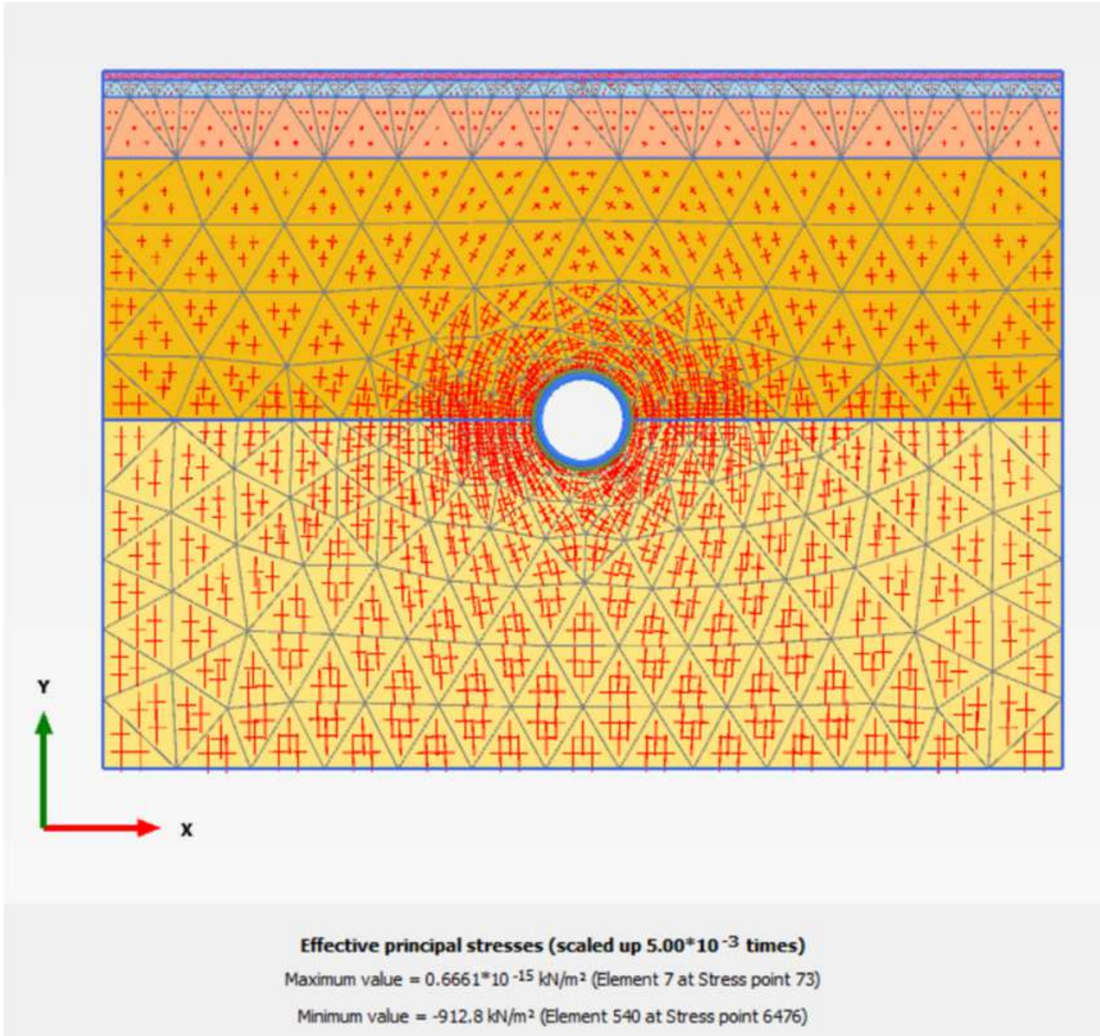



**Figure 65: Effective Principal Stress (#1B, 40m depth, GWL=-20m)**

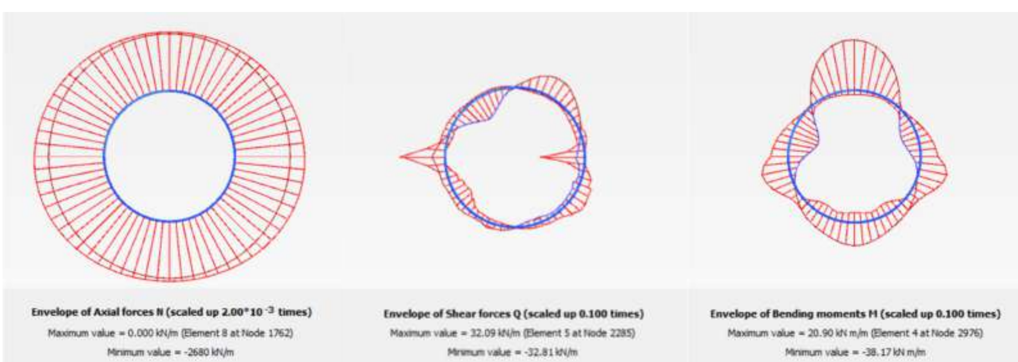



**Figure 66: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 40m depth, GWL=-20m)**

## 5.1.16. Profile #1B, Tunnel depth 40m, GWL= - 60m


**Figure 67: Excavation induced Settlement (#1B, 40m depth, GWL=-60m)**

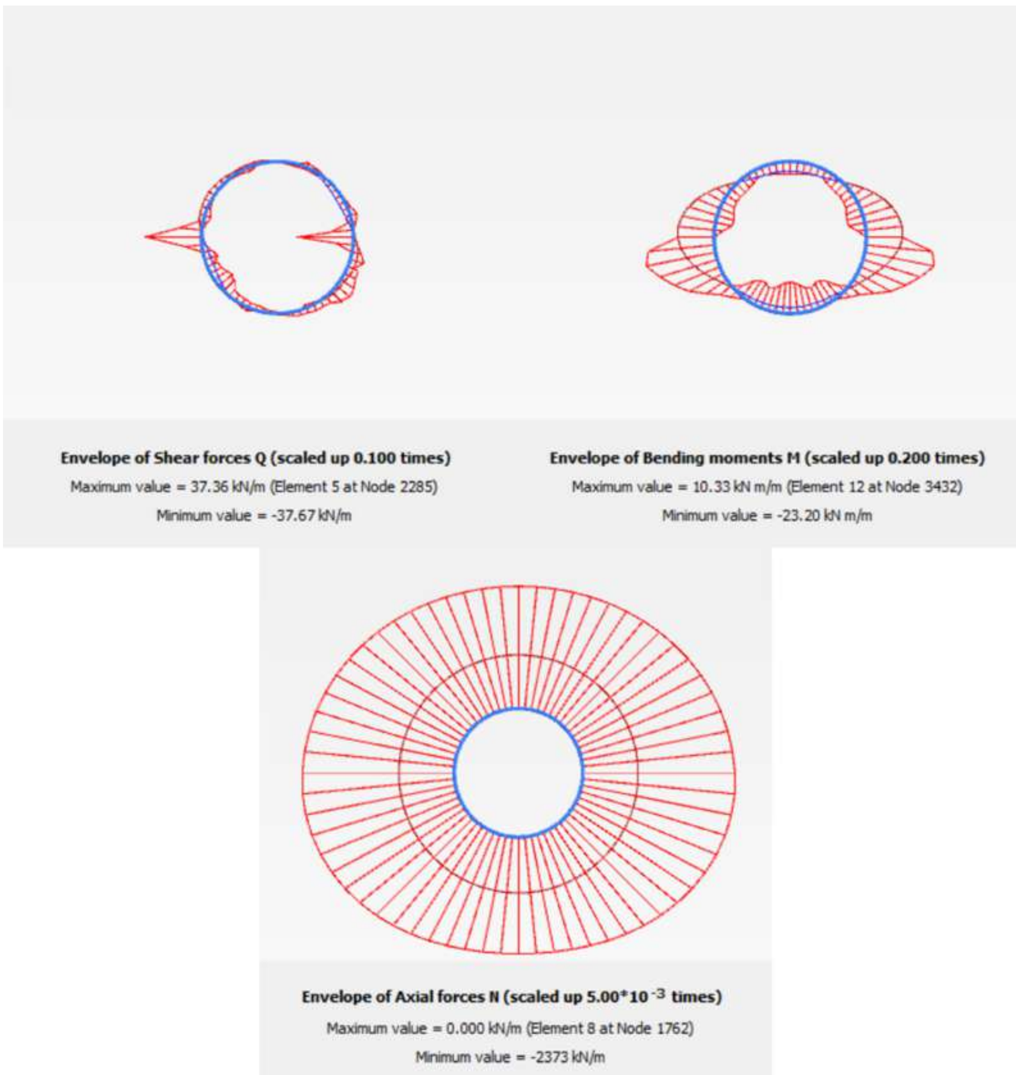



**Figure 68: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 40m depth, GWL=-60m)**

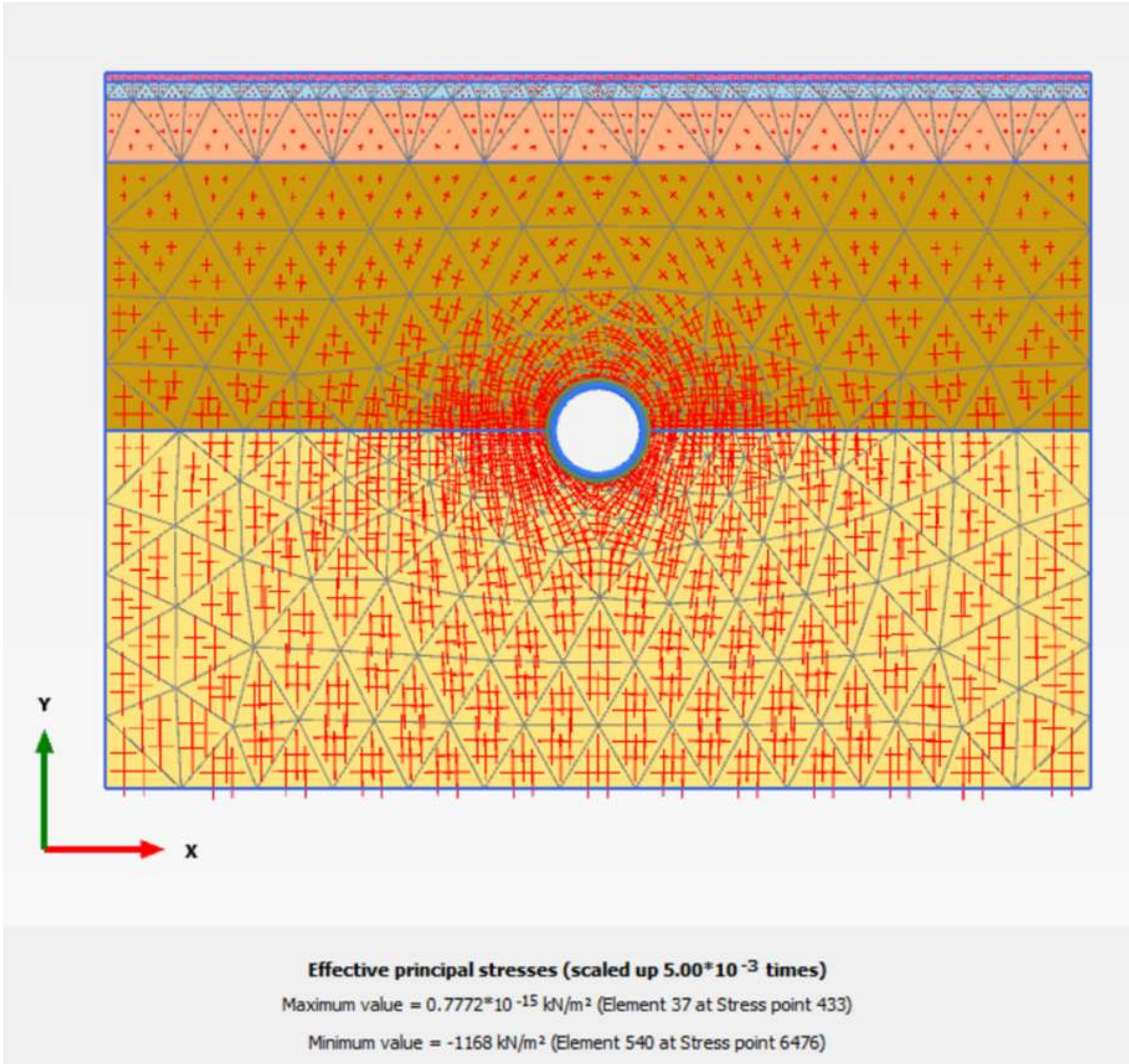



**Figure 69: Effective Principal Stress (#1B, 40m depth, GWL=-60m)**

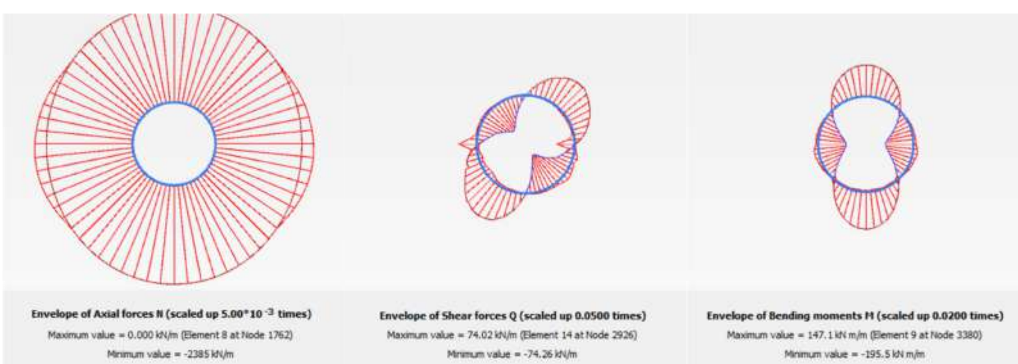



**Figure 70: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 40m depth, GWL=-60m)**

## 5.1.17. Profile #1B, Tunnel depth 50m, GWL= -20m


**Figure 71: Excavation induced Settlement (#1B, 50m depth, GWL=-20m)**

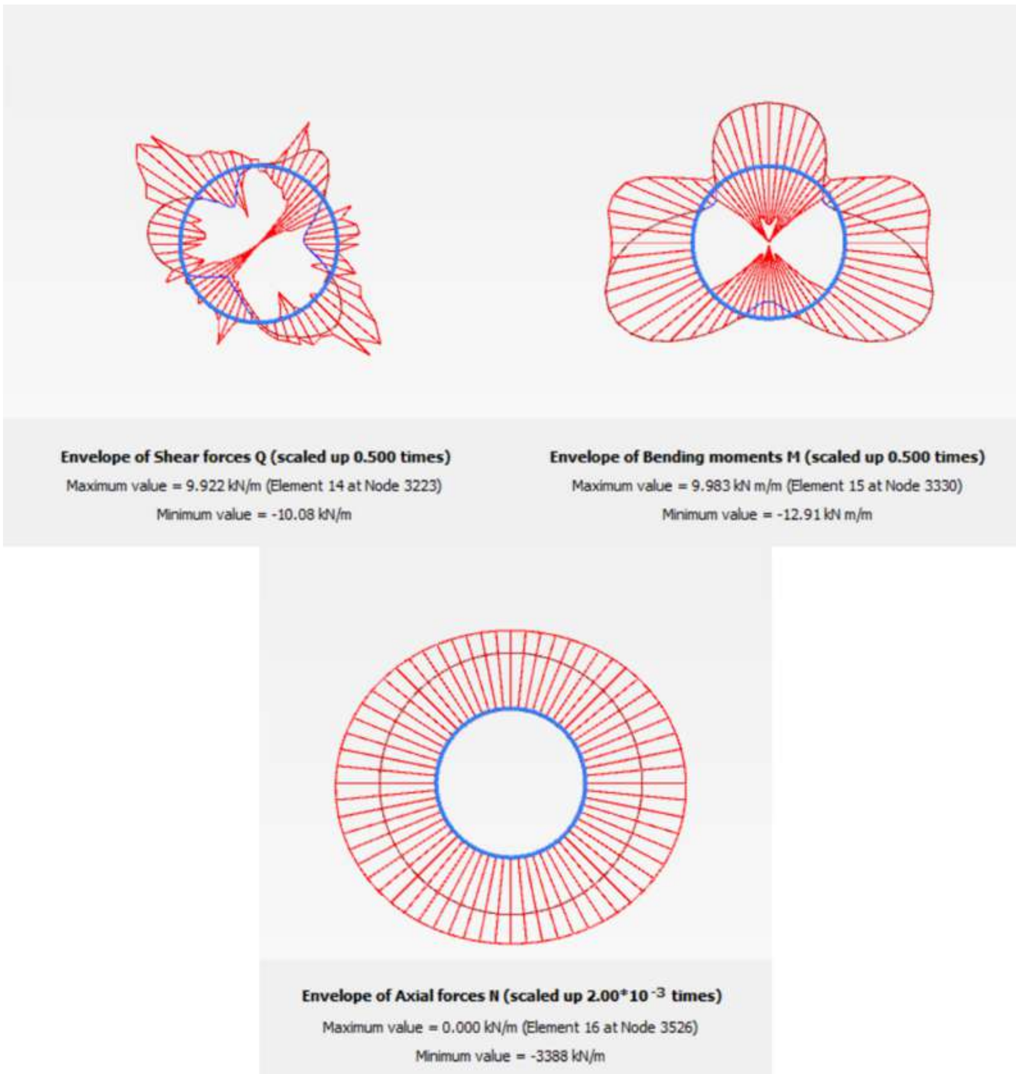



**Figure 72: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 50m depth, GWL=-20m)**

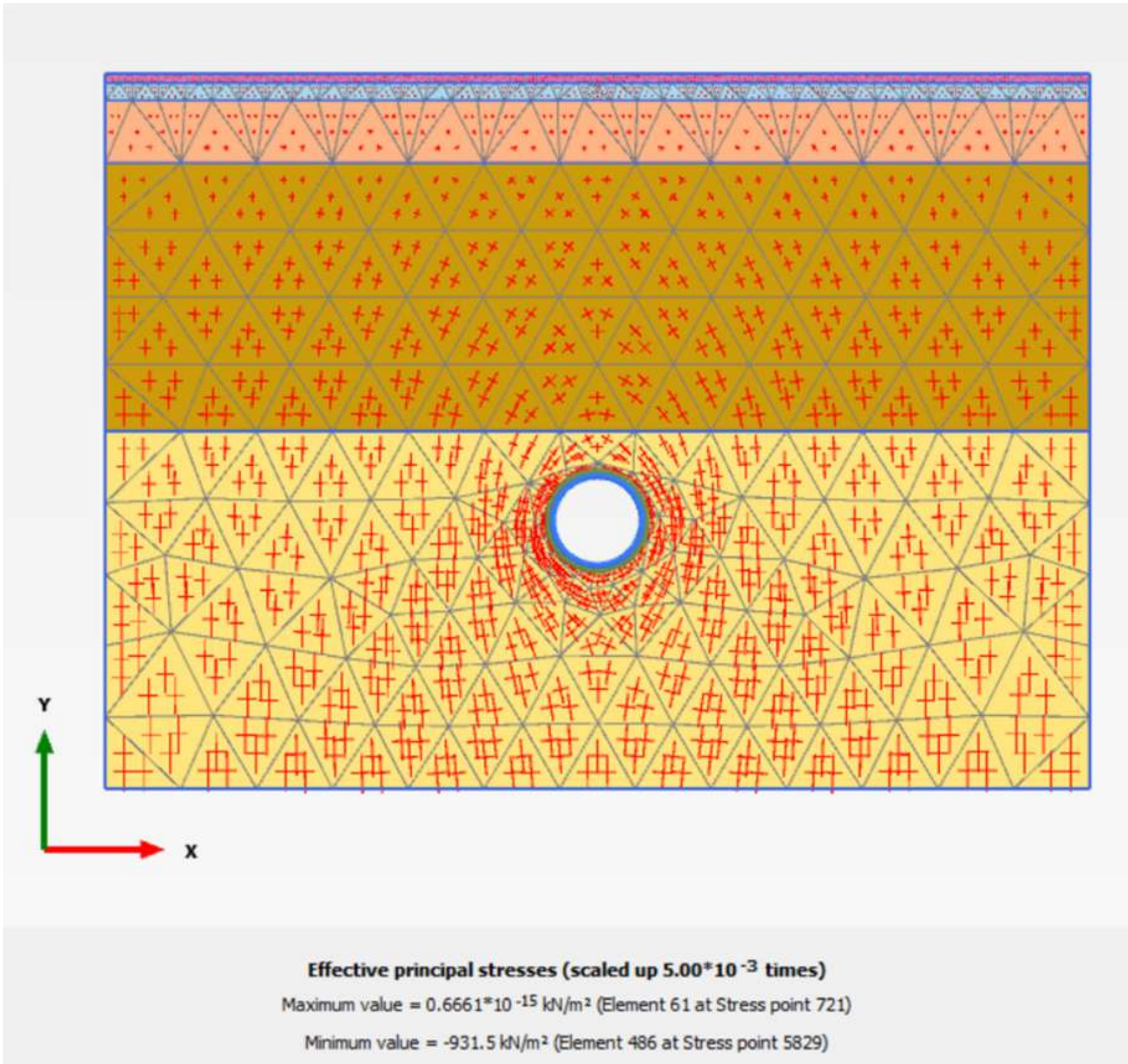



**Figure 73: Effective Principal Stress (#1B, 50m depth, GWL=-20m)**

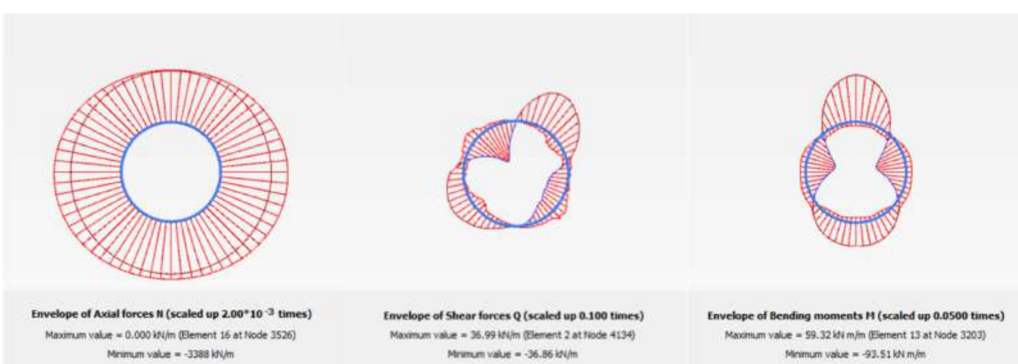



**Figure 74: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 50m depth, GWL=-20m)**

## 5.1.18. Profile #1B, Tunnel depth 50m, GWL= -60m


**Figure 75: Excavation induced Settlement (#1B, 50m depth, GWL=-60m)**

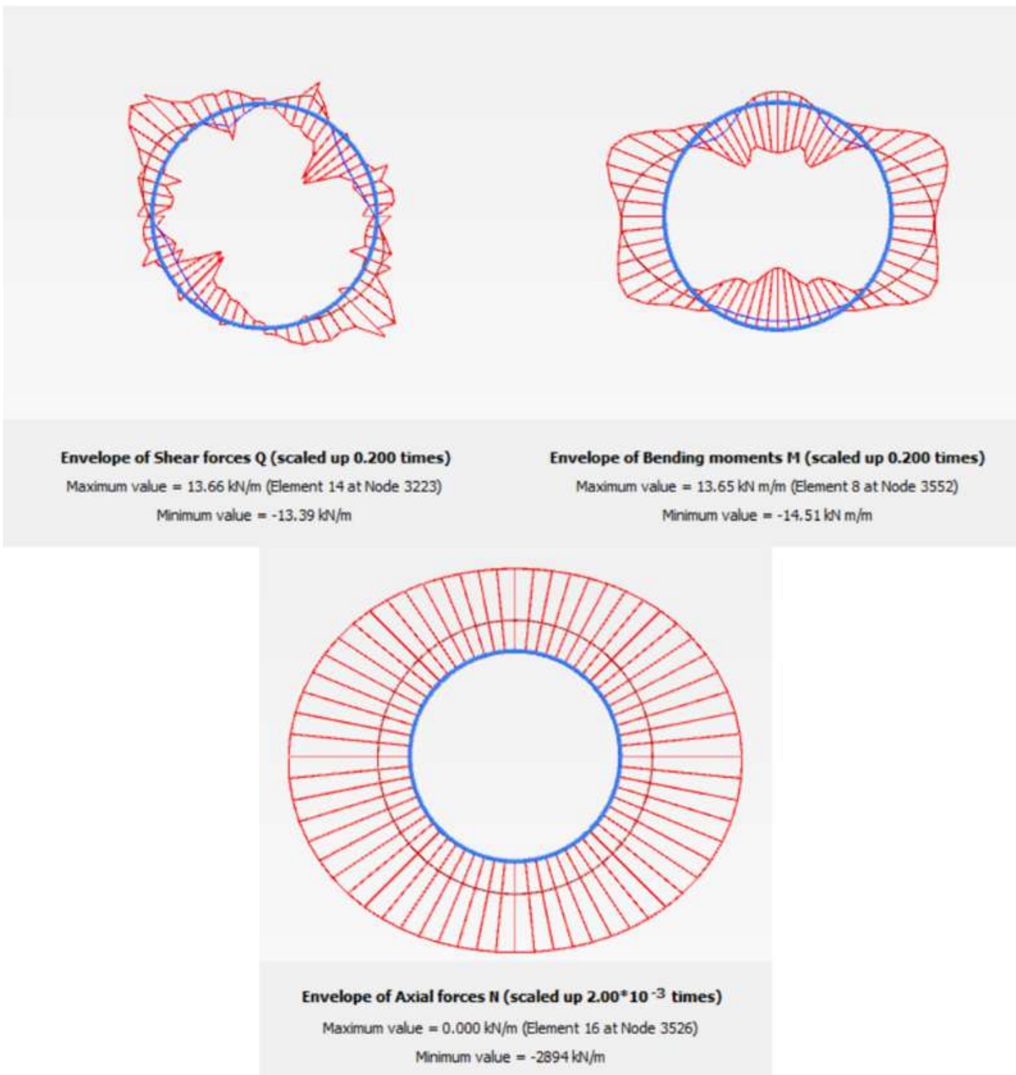



**Figure 76: Axial force, Shear force & Bending Moment on Tunnel Lining (#1B, 50m depth, GWL=-60m)**

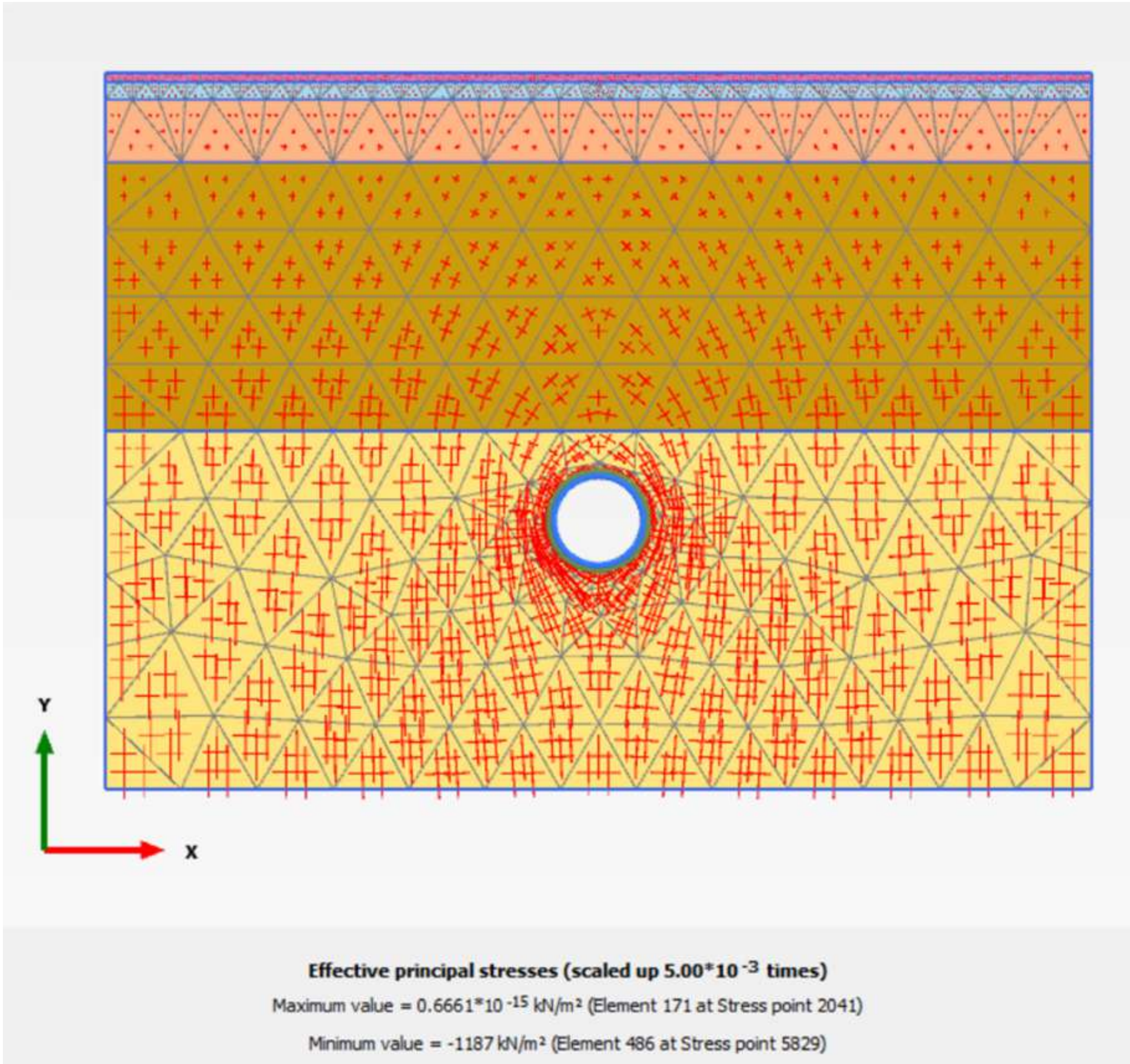



**Figure 77: Effective Principal Stress (#1B, 50m depth, GWL=-60m)**

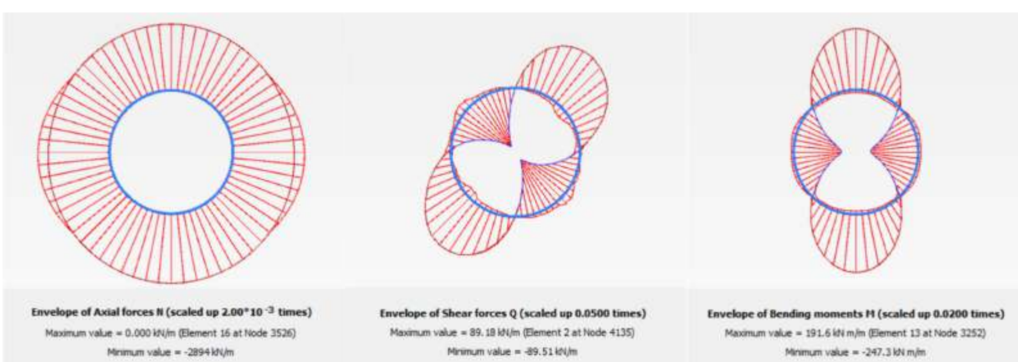



**Figure 78: Axial force, Shear force & Bending Moment after rising of Groundwater level (#1B, 50m depth, GWL=-60m)**

### 5.1.19. Profile #2A, Tunnel depth 25m, GWL= -20m

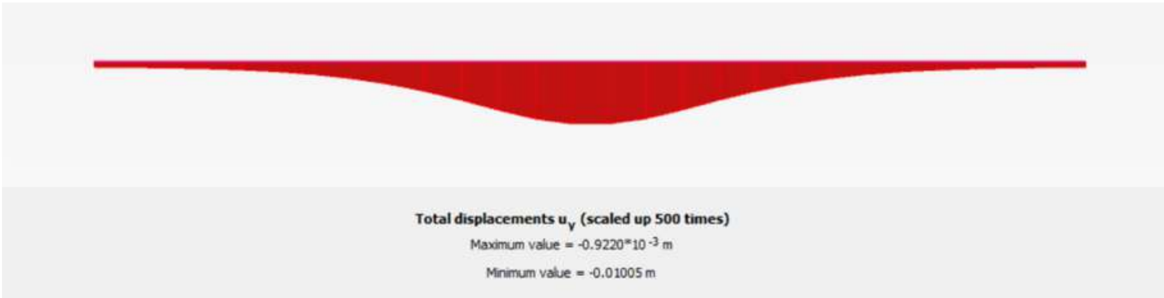



**Figure 79: Excavation induced Settlement (#2A, 25m depth, GWL=-20m)**

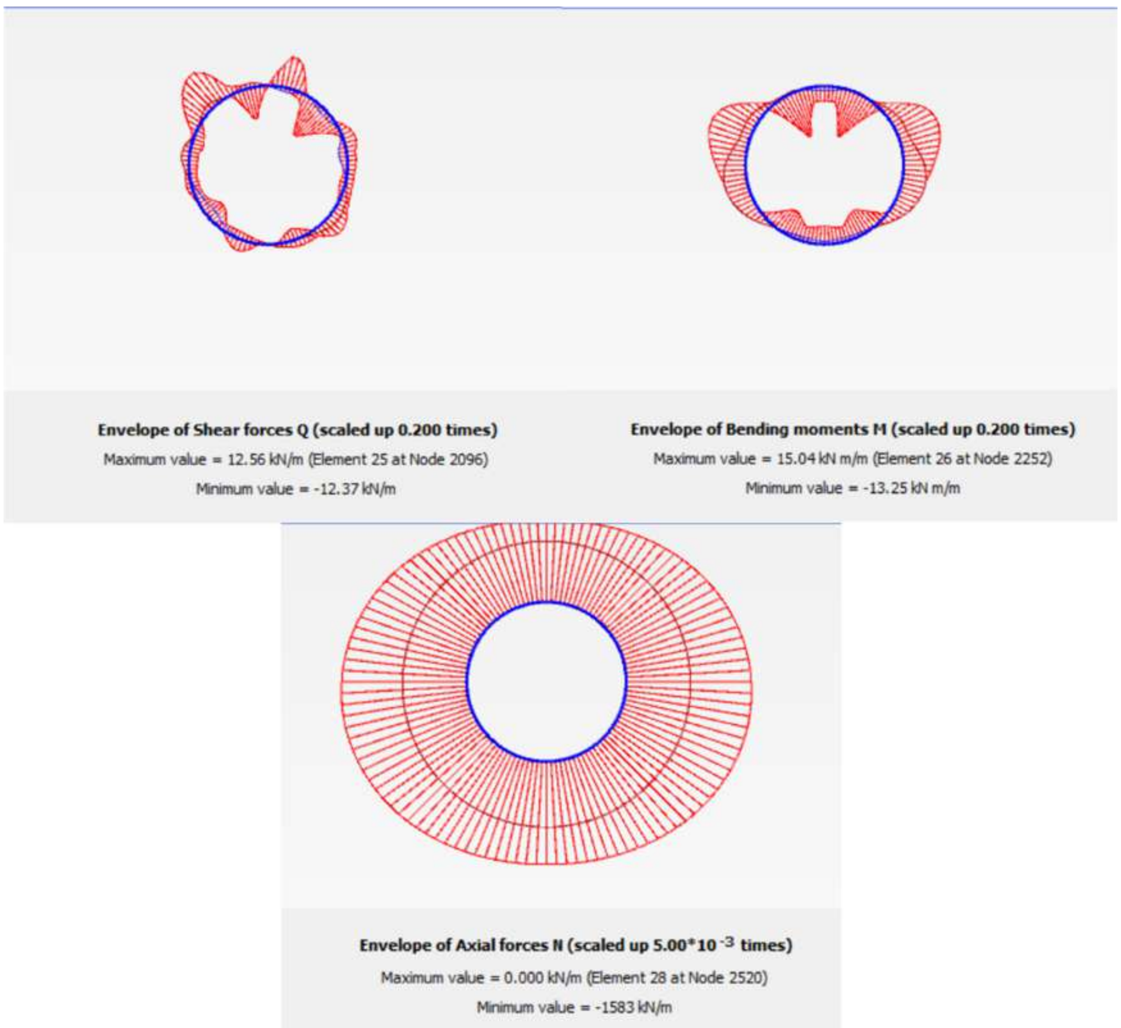



**Figure 80: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 25m depth, GWL=-20m)**

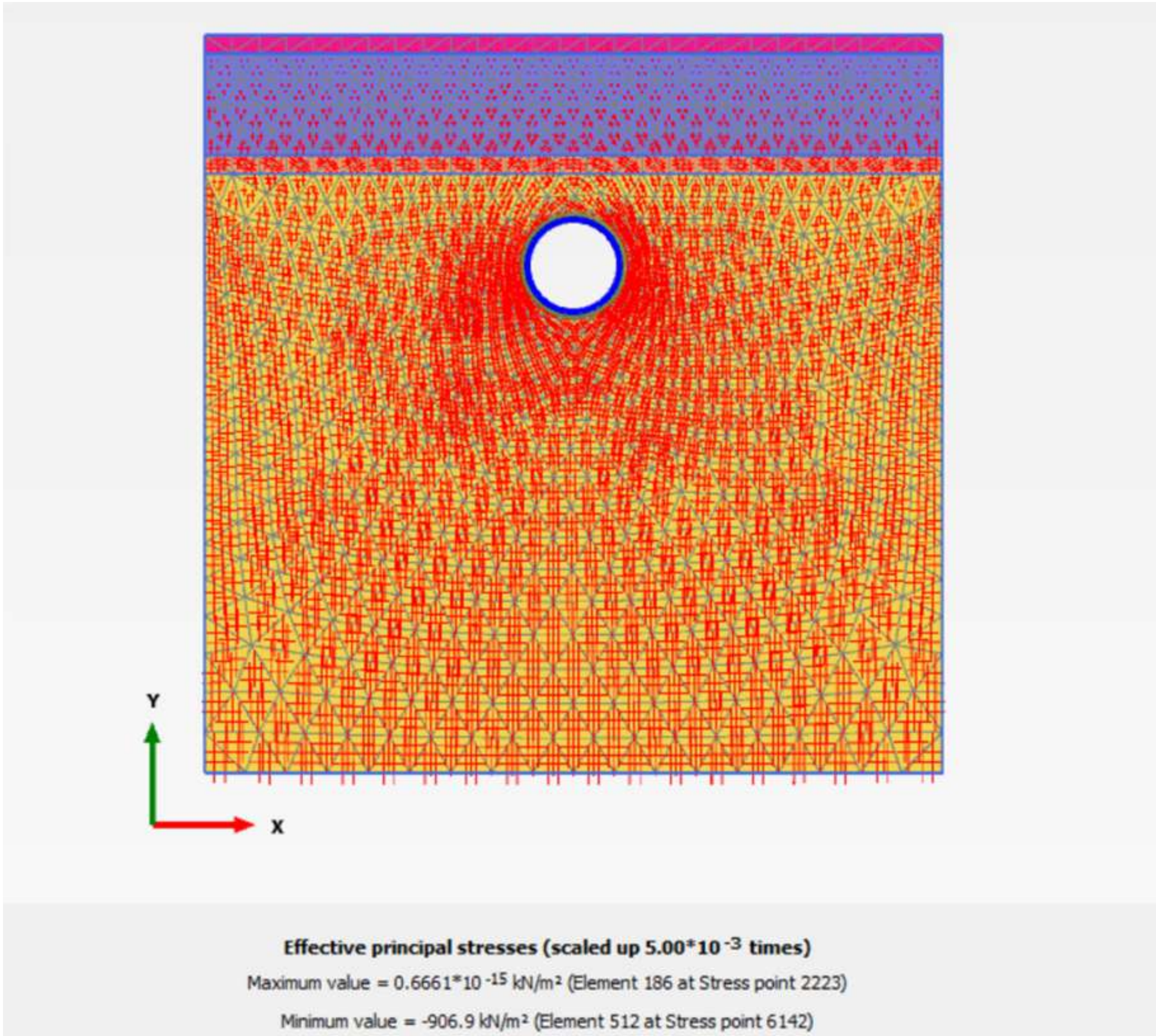



**Figure 81: Effective Principal Stress (#2A, 25m depth, GWL=-20m)**

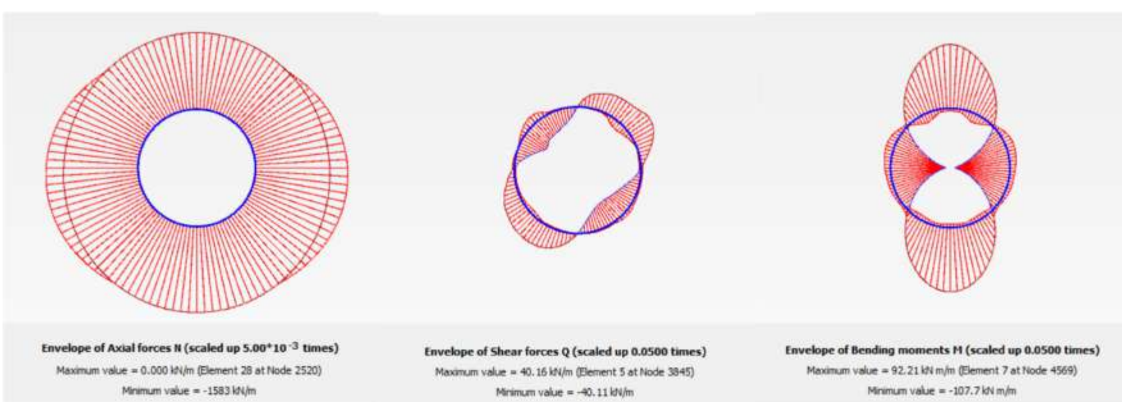



**Figure 82: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 25m depth, GWL=-20m)**

## 5.1.20. Profile #2A, Tunnel depth 25m, GWL= -60m

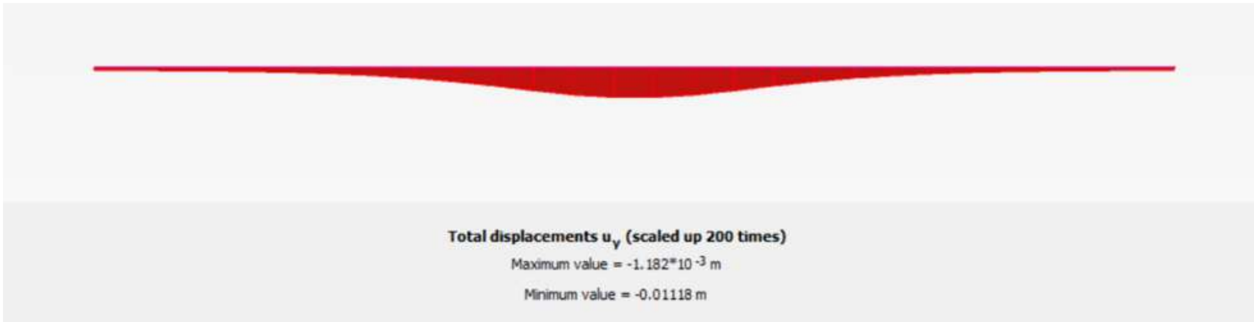



**Figure 83: Excavation induced Settlement (#2A, 25m depth, GWL= -60m)**

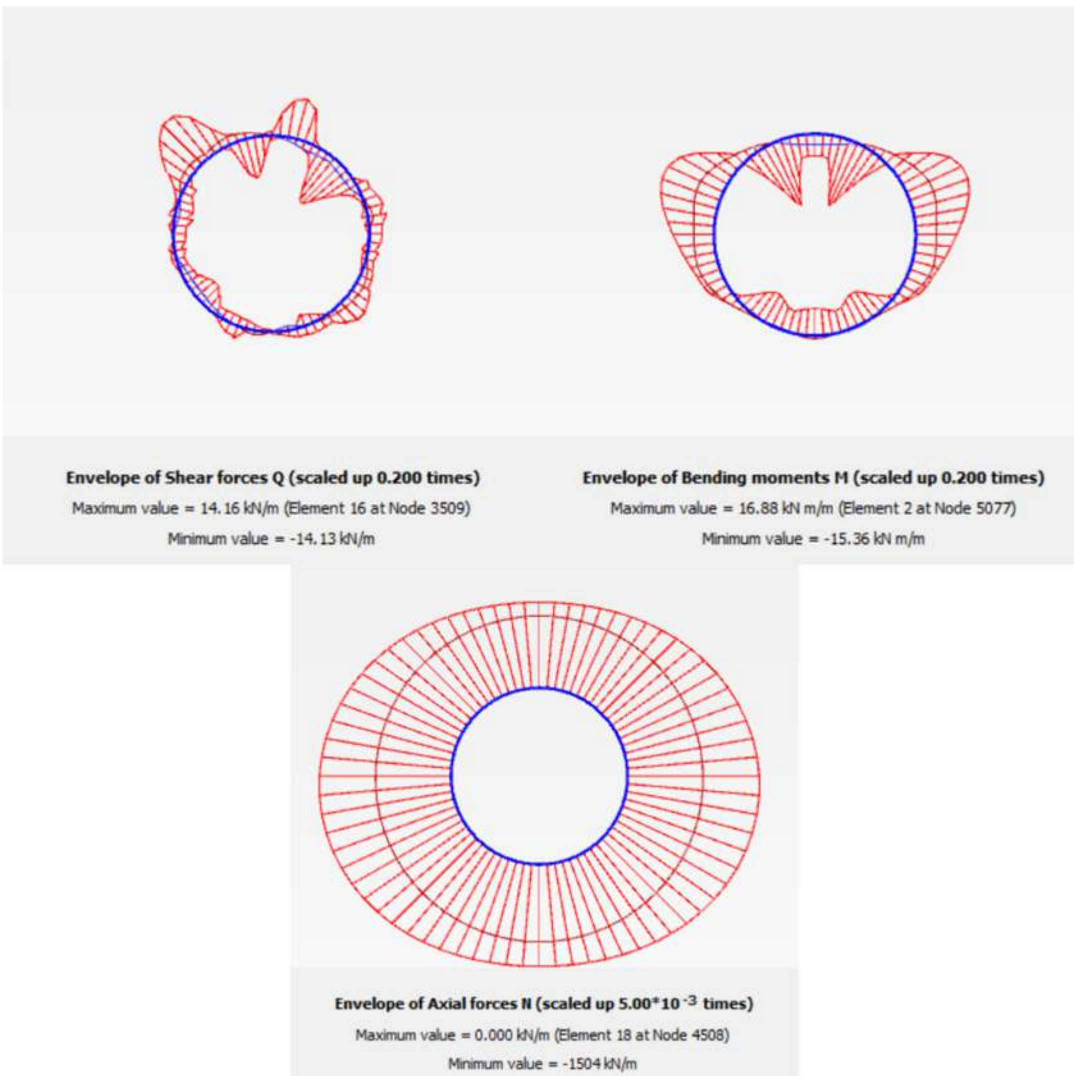



**Figure 84: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 25m depth, GWL= -60m)**

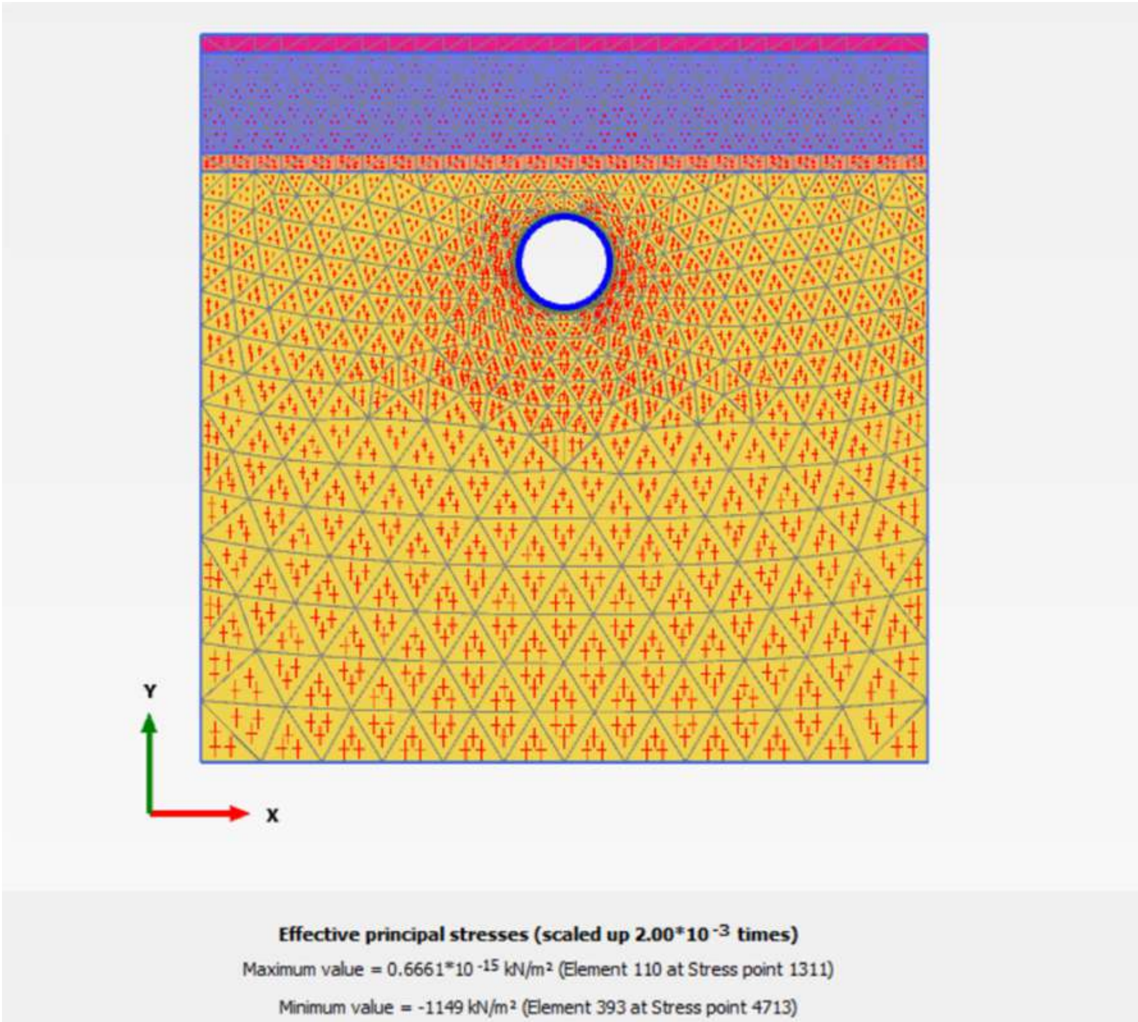



**Figure 85: Effective Principal Stress (#2A, 25m depth, GWL= -60m)**

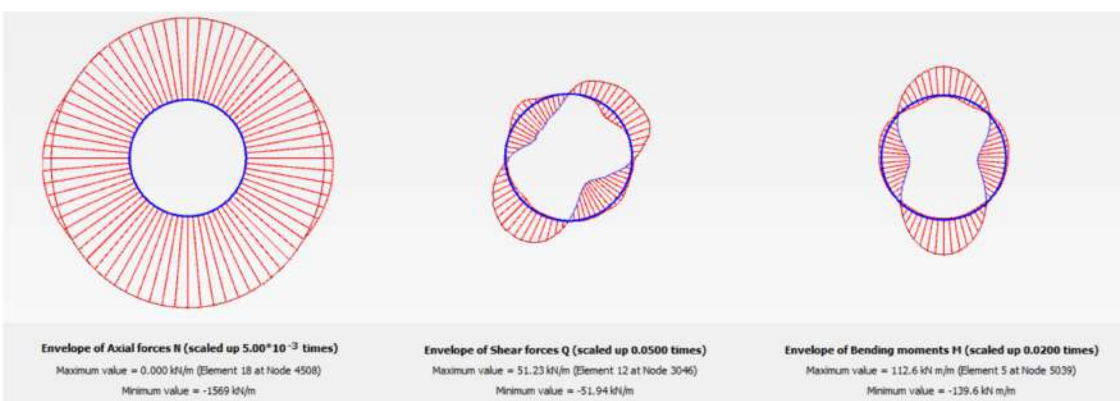
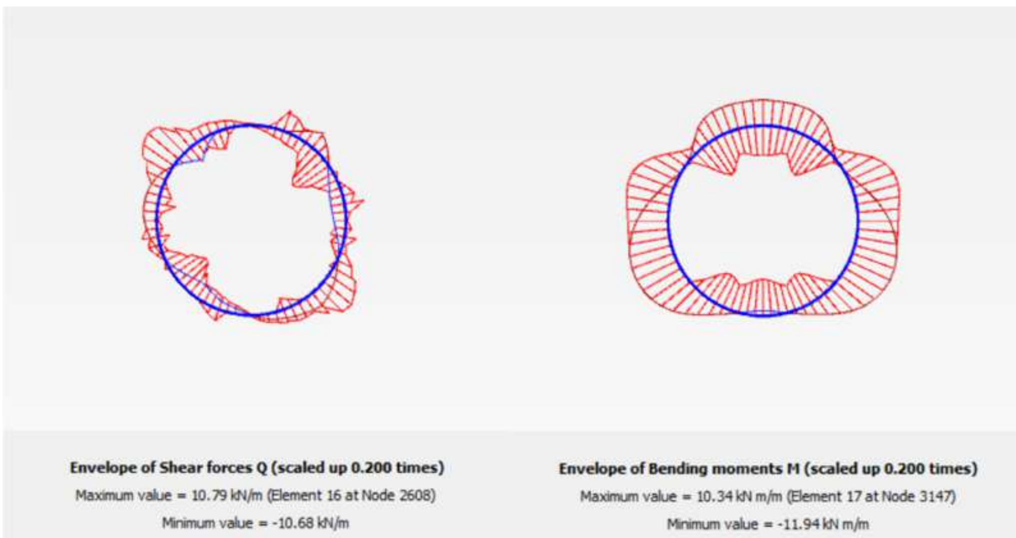



**Figure 86: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 25m depth, GWL= -60m)**

### 5.1.21. Profile #2A, Tunnel depth 50m, GWL= -20m


Figure 87: Excavation induced Settlement (#2A, 50m depth, GWL= -20m)



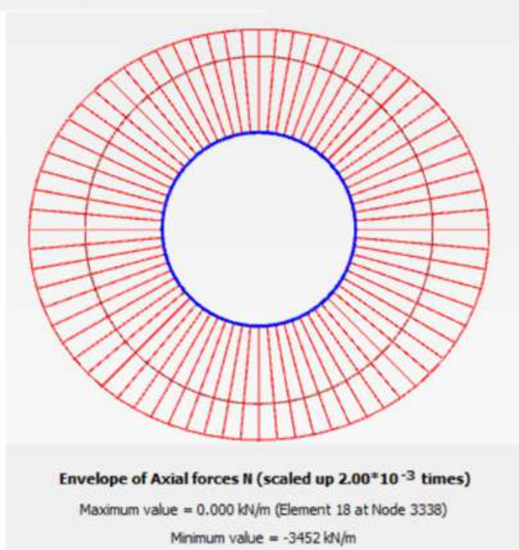




Figure 88: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 50m depth, GWL= -20m)

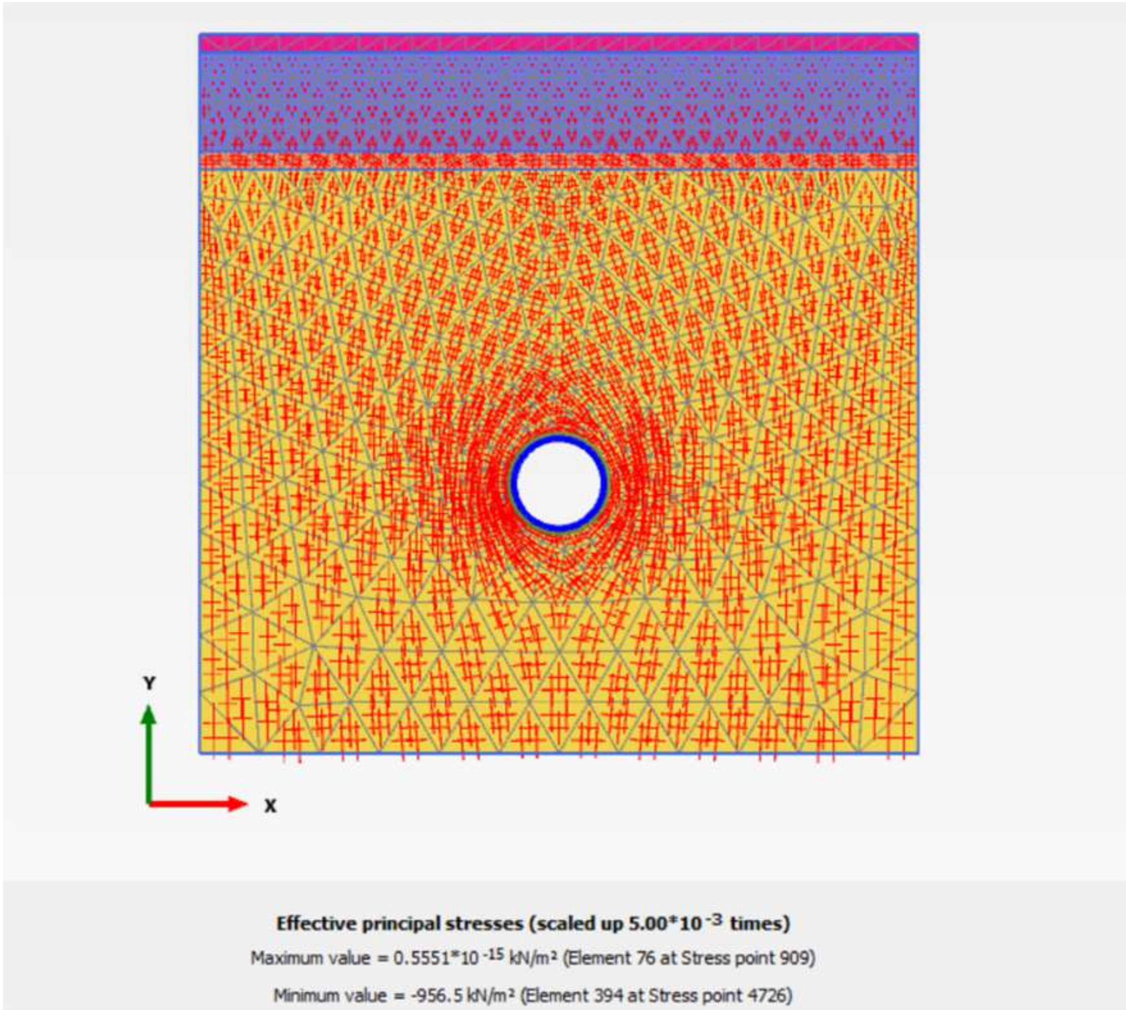



**Figure 89: Effective Principal Stress (#2A, 50m depth, GWL= -20m)**

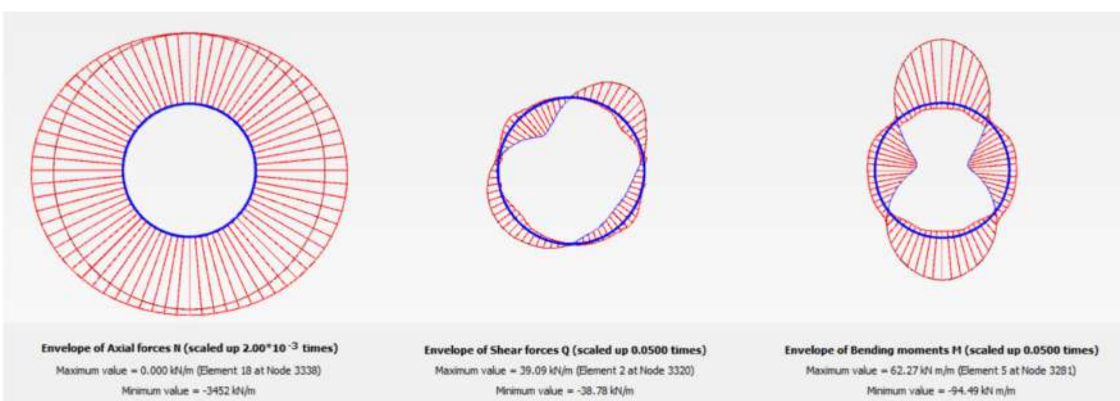



**Figure 90: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 50m depth, GWL= -20m)**

## 5.1.22. Profile #2A, Tunnel depth 50m, GWL= -60m


**Figure 91: Excavation induced Settlement (#2A, 50m depth, GWL= -60m)**

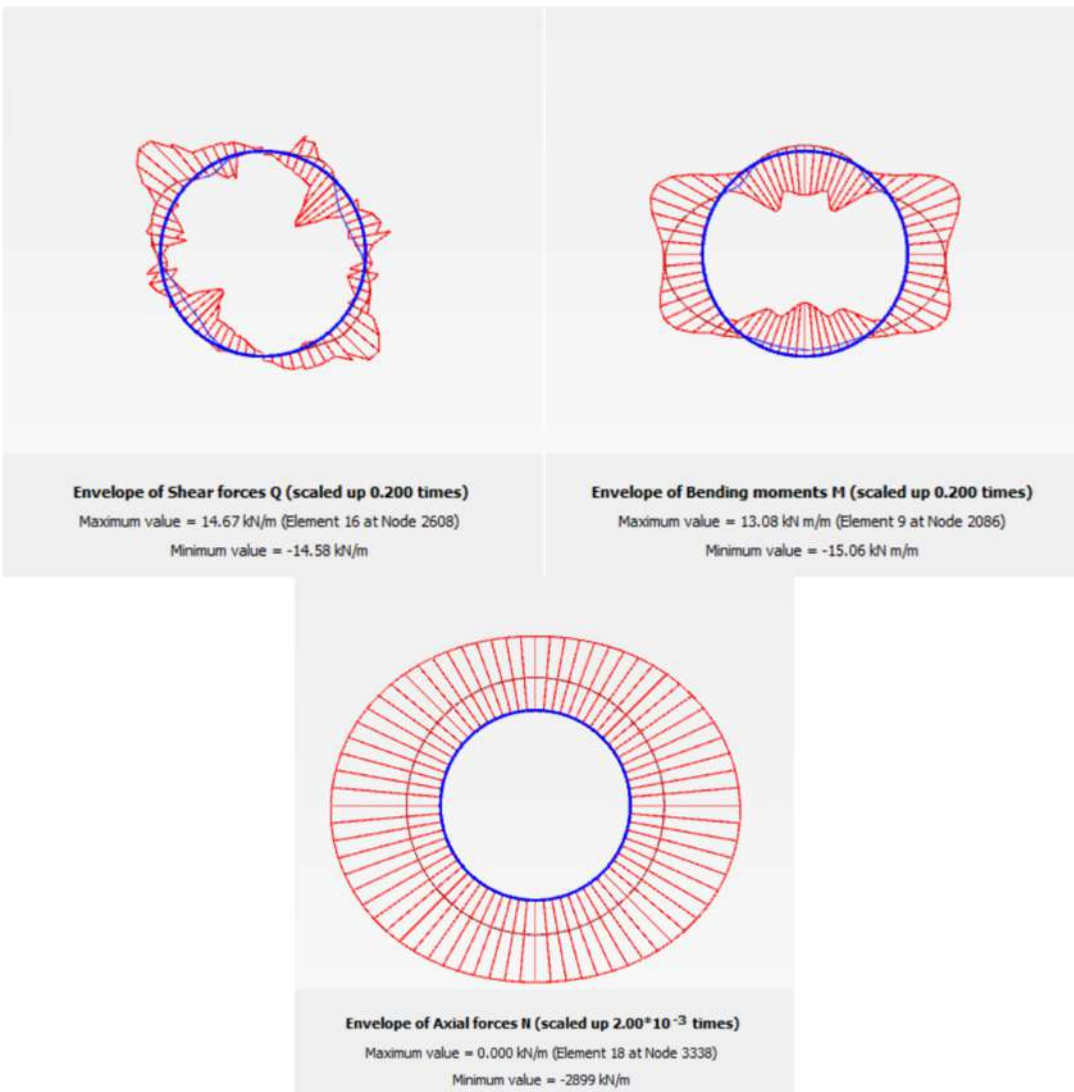



**Figure 92: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 50m depth, GWL= -60m)**

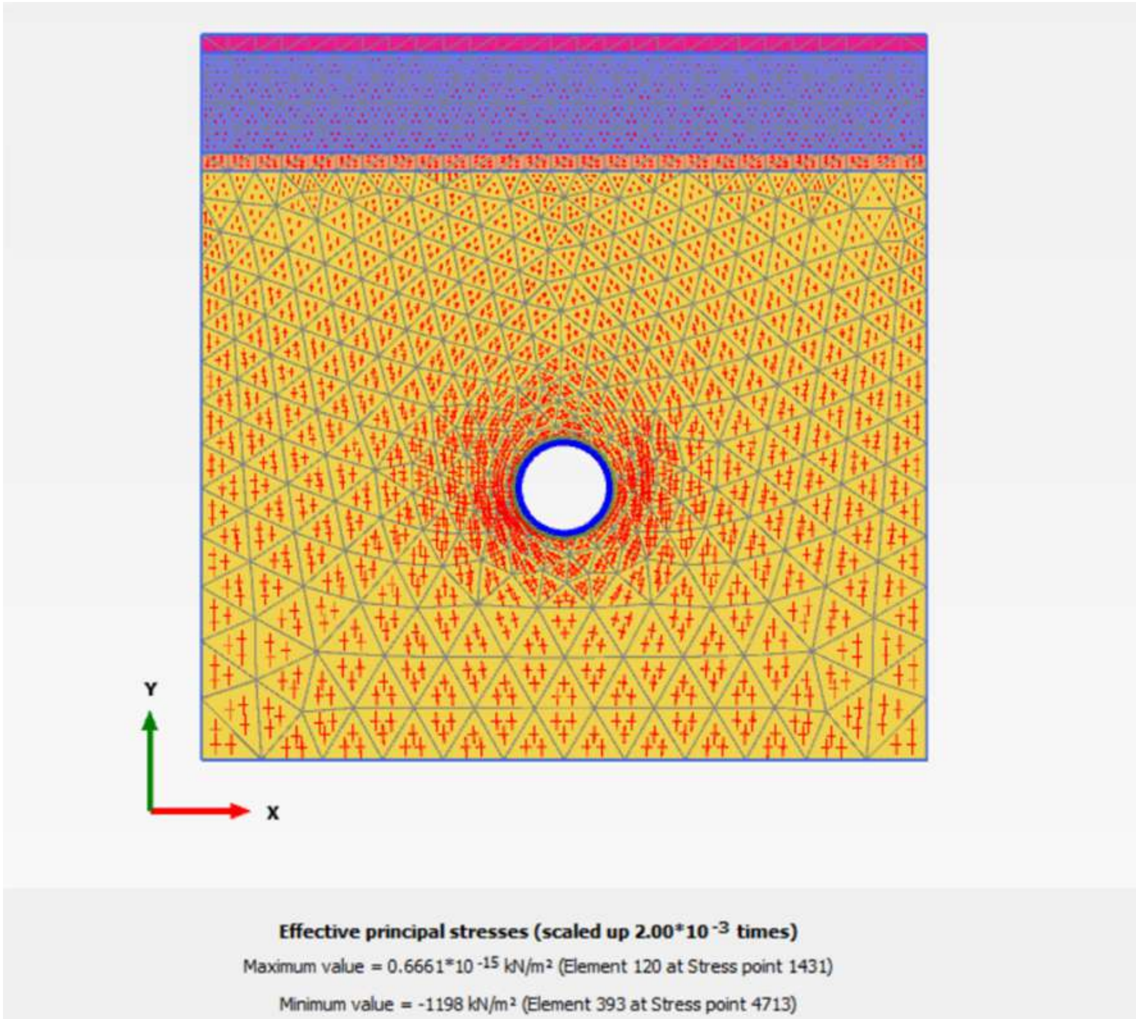



**Figure 93: Effective Principal Stress (#2A, 50m depth, GWL= -60m)**

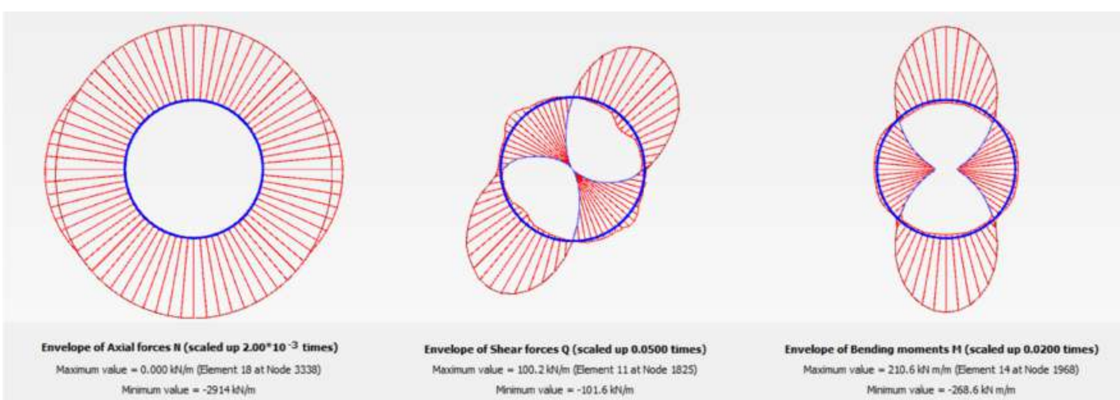



**Figure 94: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 50m depth, GWL= -60m)**

## 5.1.23. Profile #2A, Tunnel depth 75m, GWL= -20m


**Figure 95: Excavation induced Settlement (#2A, 75m depth, GWL= -20m)**

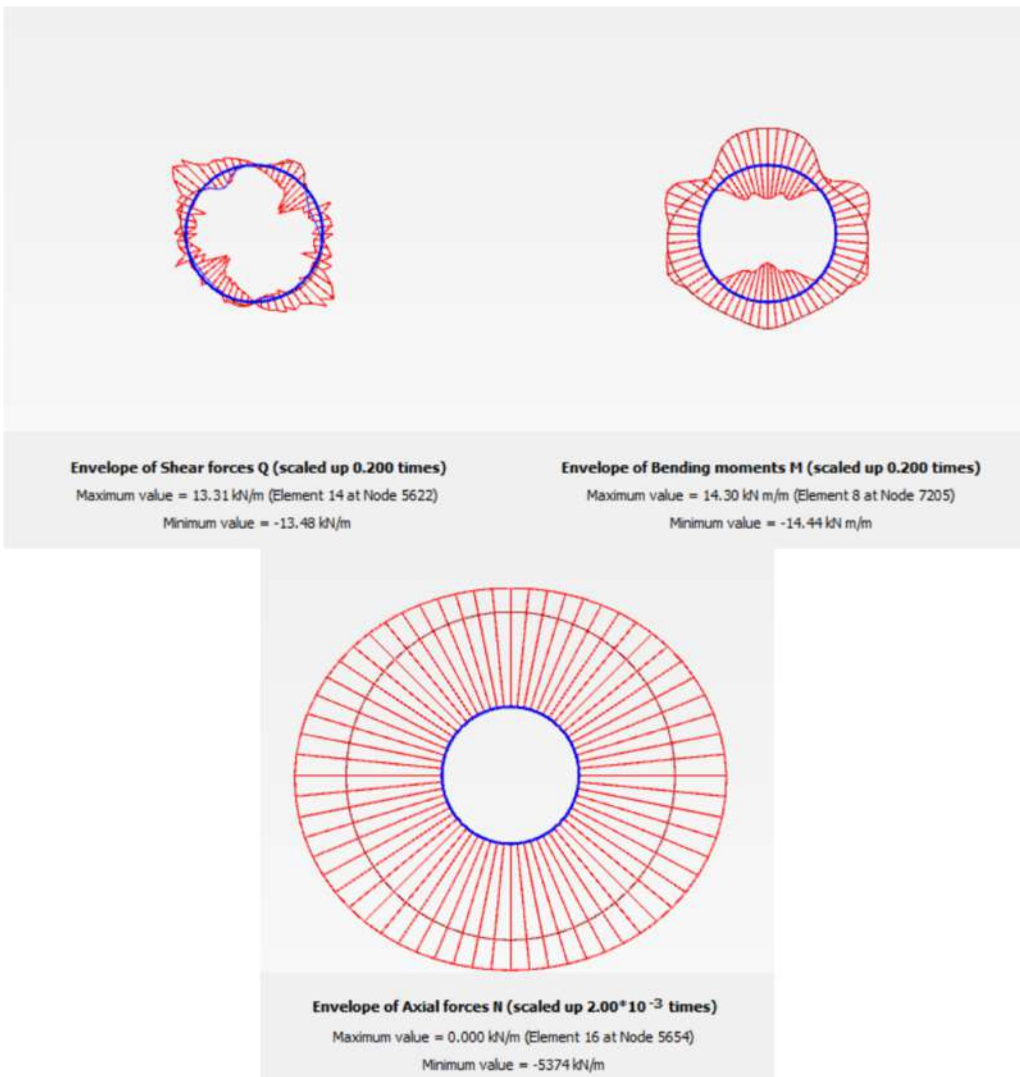



**Figure 96: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 75m depth, GWL= -20m)**

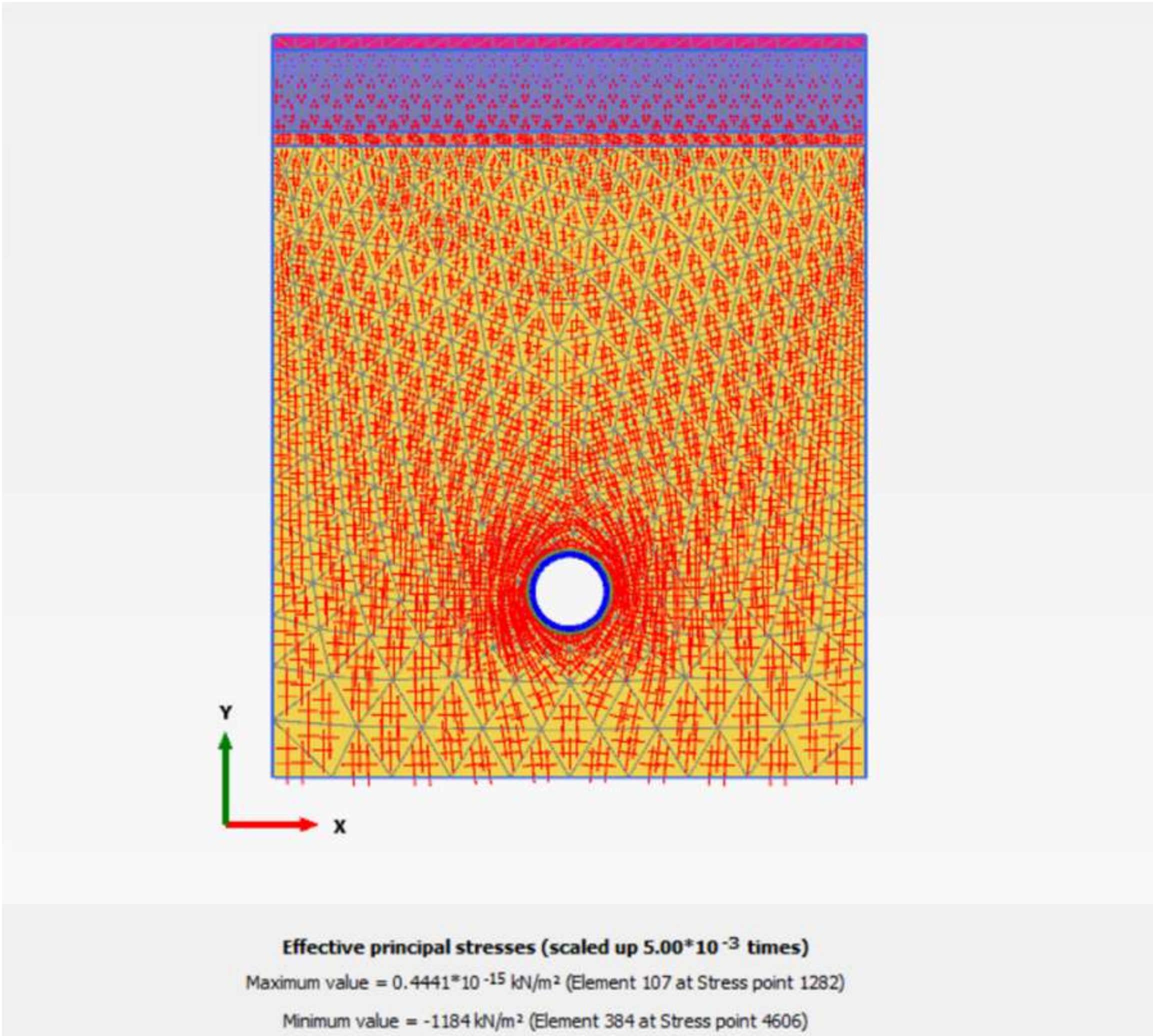



**Figure 97: Effective Principal Stress (#2A, 75m depth, GWL= -20m)**

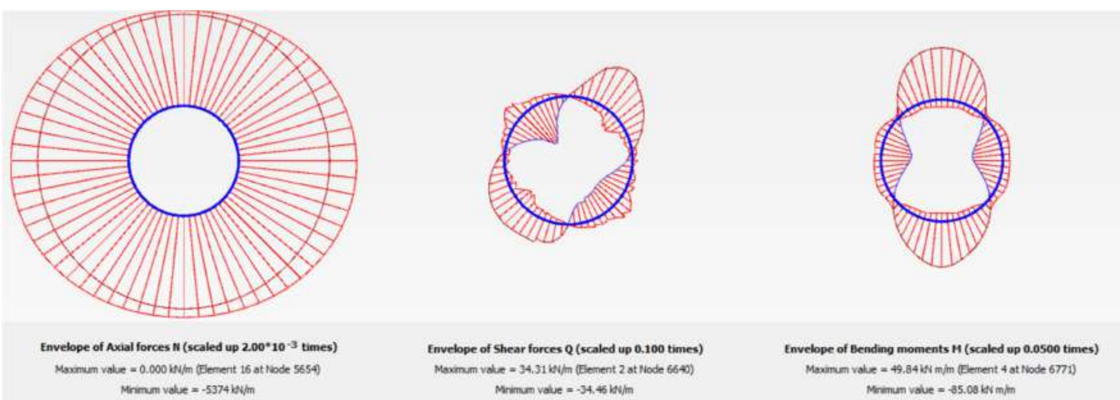



**Figure 98: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 75m depth, GWL= -20m)**

## 5.1.24. Profile #2A, Tunnel depth 75m, GWL= -60m


**Figure 99: Excavation induced Settlement (#2A, 75m depth, GWL= -60m)**

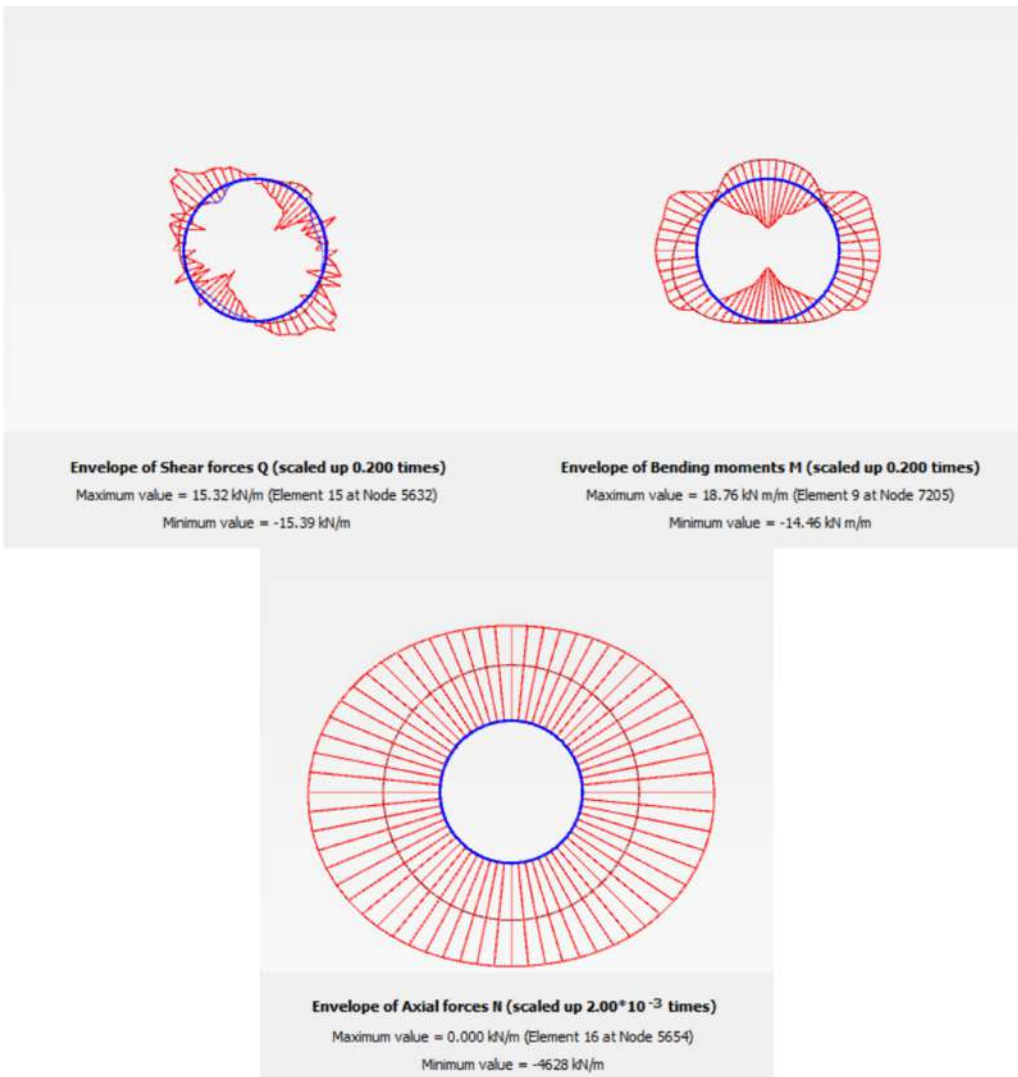



**Figure 100: Axial force, Shear force & Bending Moment on Tunnel Lining (#2A, 75m depth, GWL= -60m)**

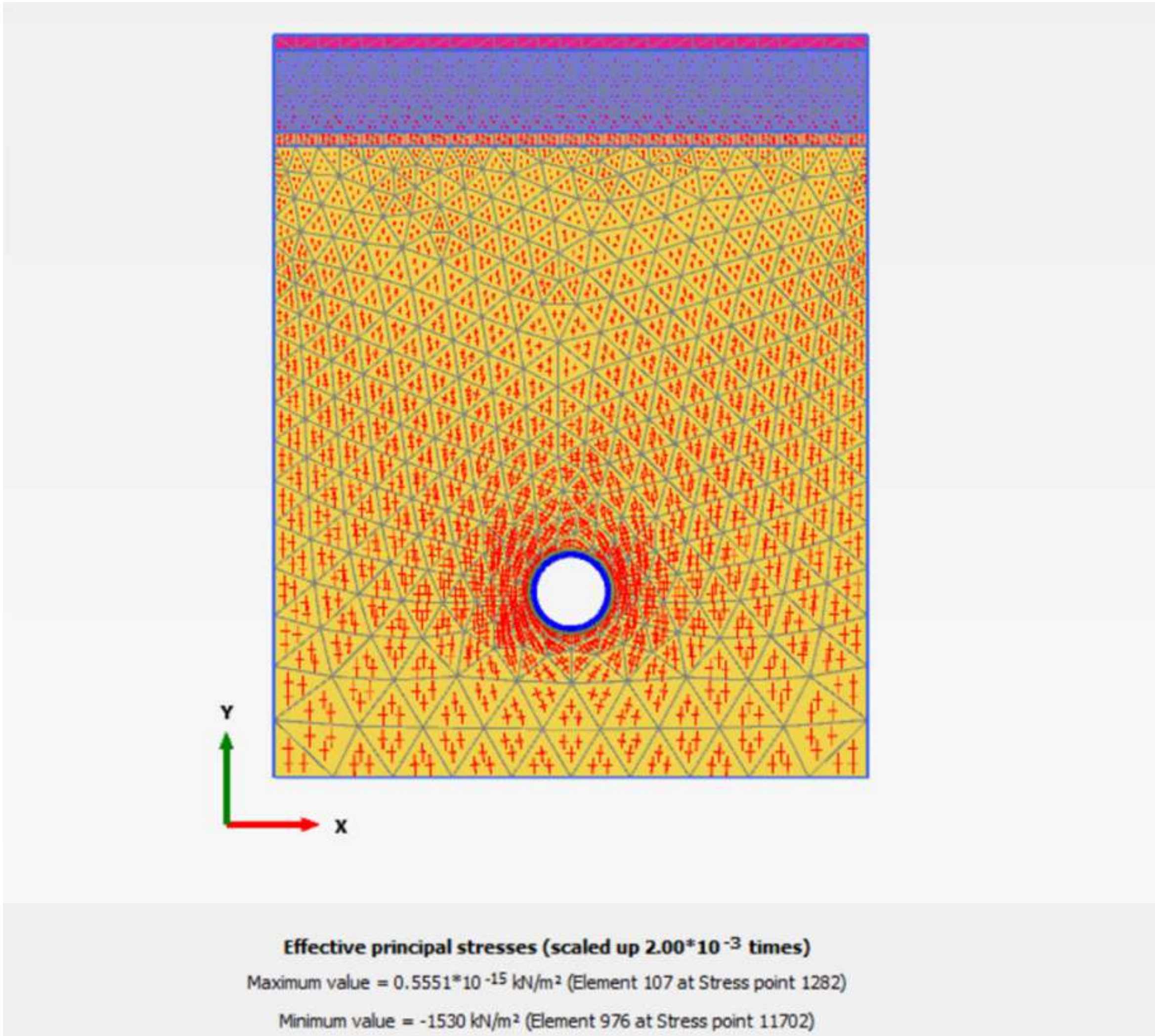



**Figure 101: Effective Principal Stress (#2A, 75m depth, GWL= -60m)**

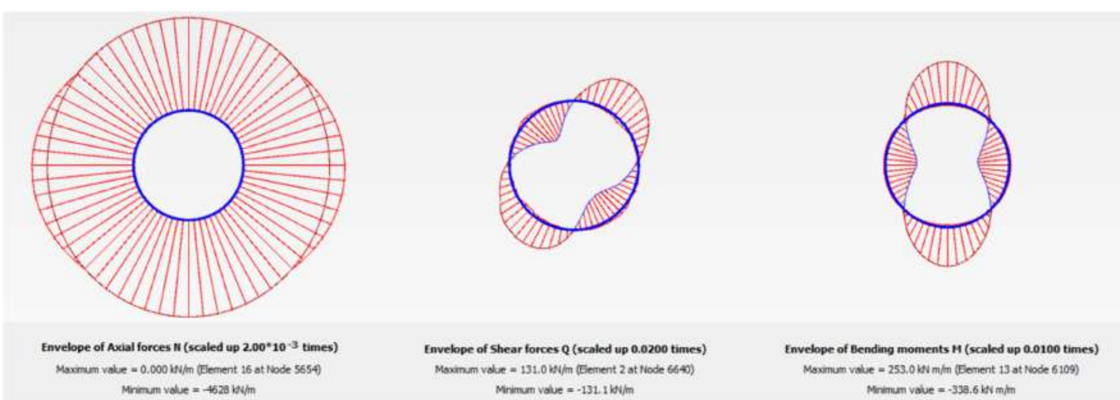



**Figure 102: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2A, 75m depth, GWL= -60m)**

## 5.1.25. Profile #2B, Tunnel depth 35m, GWL= -20m

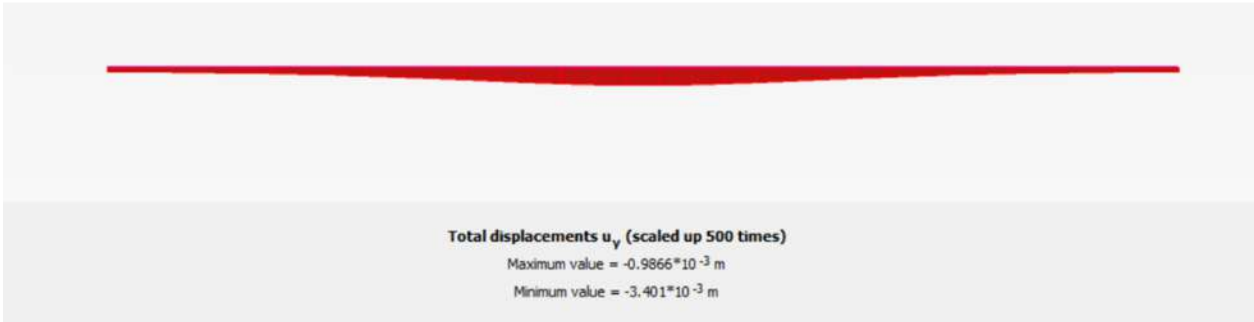



**Figure 103: Excavation induced Settlement (#2B, 35m depth, GWL= -20m)**

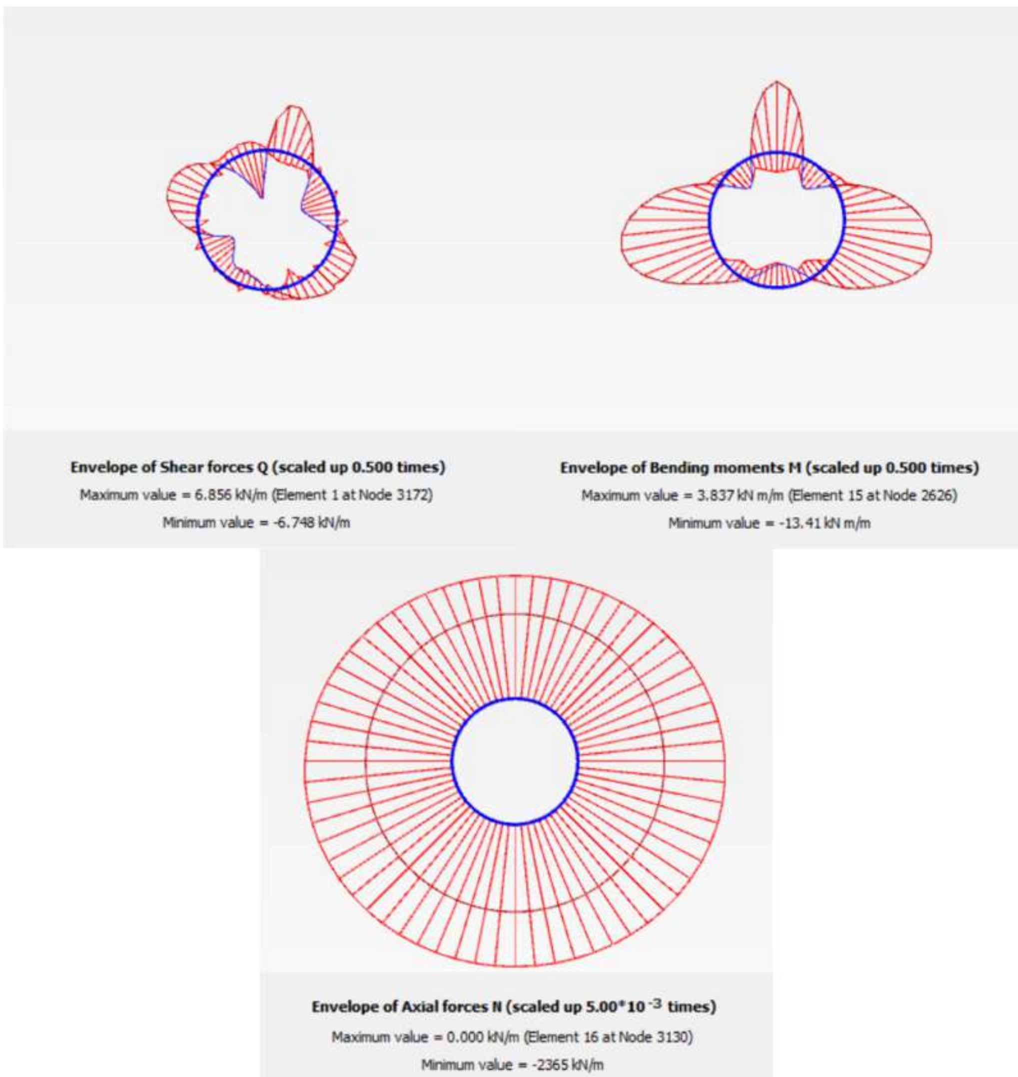



**Figure 104: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 35m depth, GWL= -20m)**

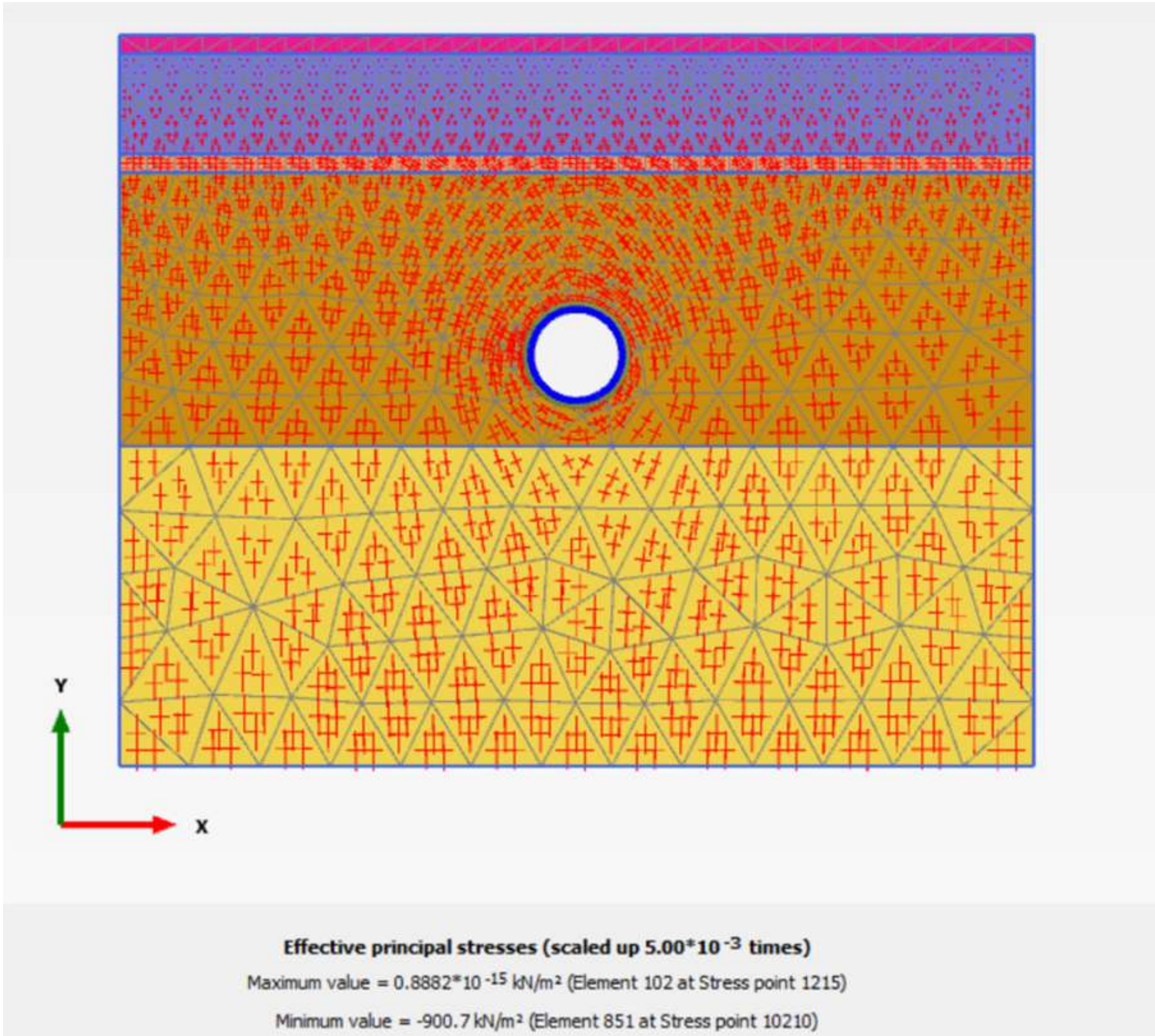



**Figure 105: Effective Principal Stress (#2B, 35m depth, GWL= -20m)**


**Figure 106: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 35m depth, GWL= -20m)**

## 5.1.26. Profile #2B, Tunnel depth 35m, GWL= -60m

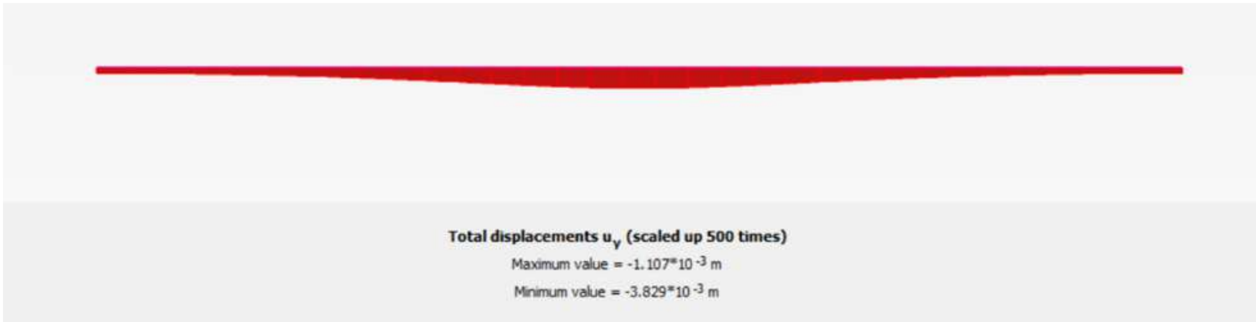



**Figure 107: Excavation induced Settlement (#2B, 35m depth, GWL= -60m)**

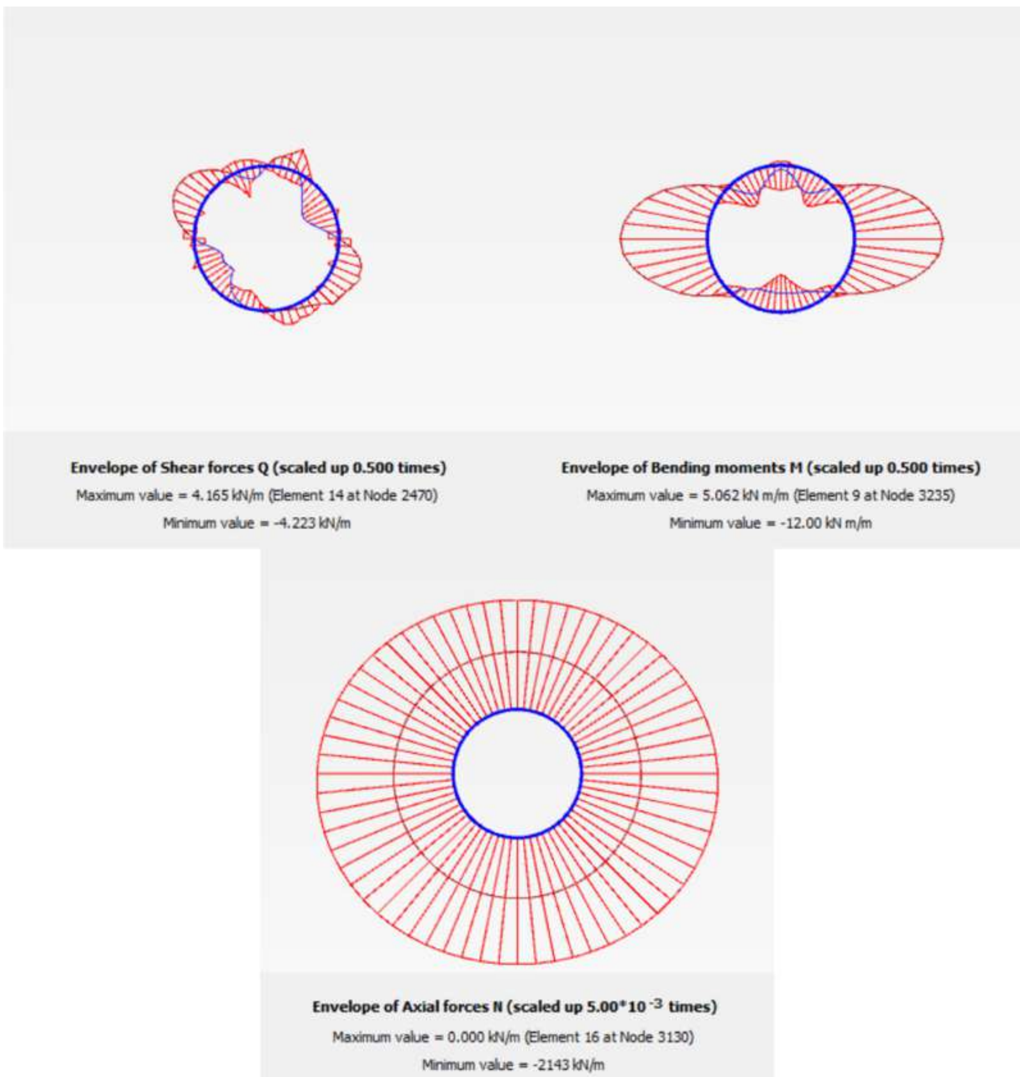



**Figure 108: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 35m depth, GWL= -60m)**

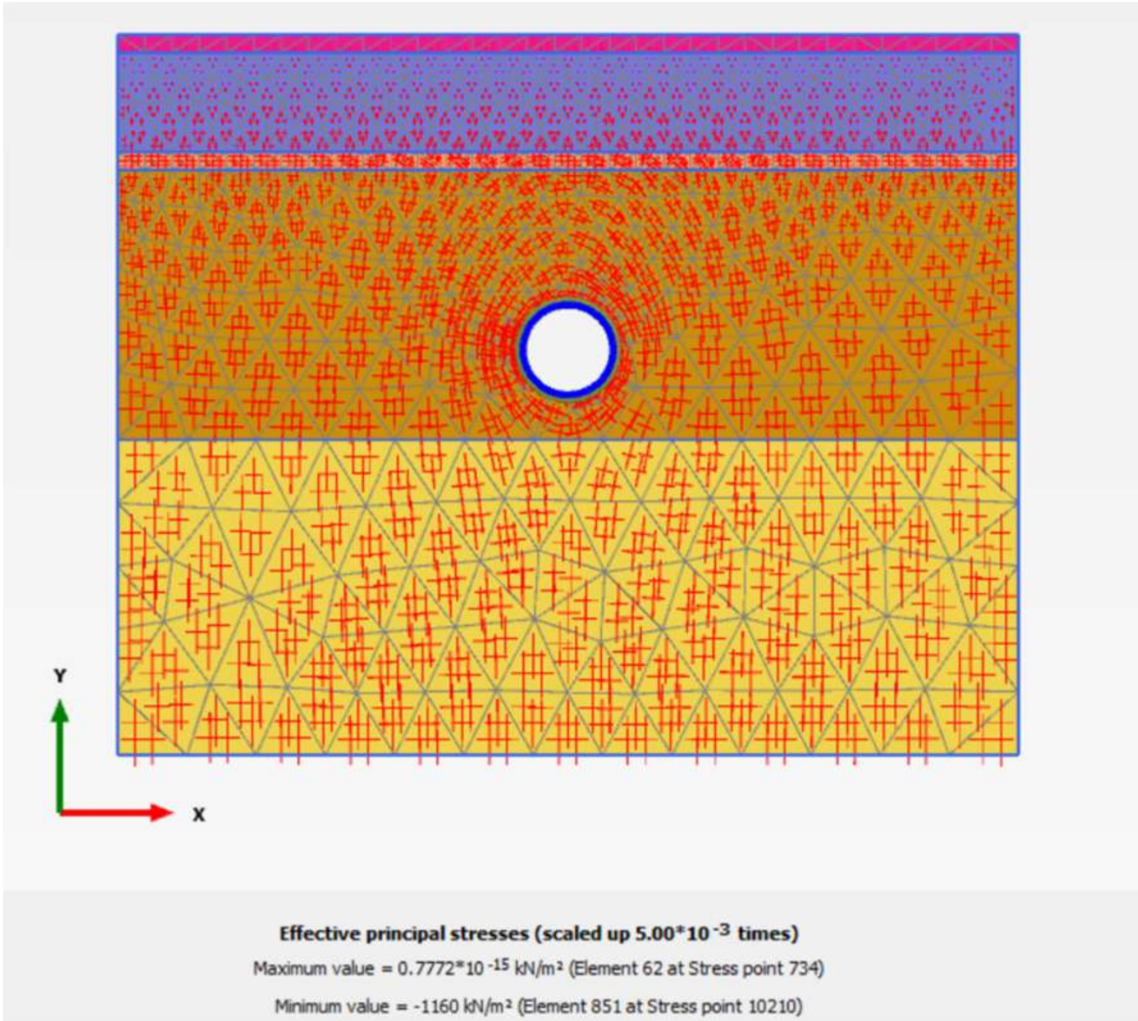



**Figure 109: Effective Principal Stress (#2B, 35m depth, GWL= -60m)**

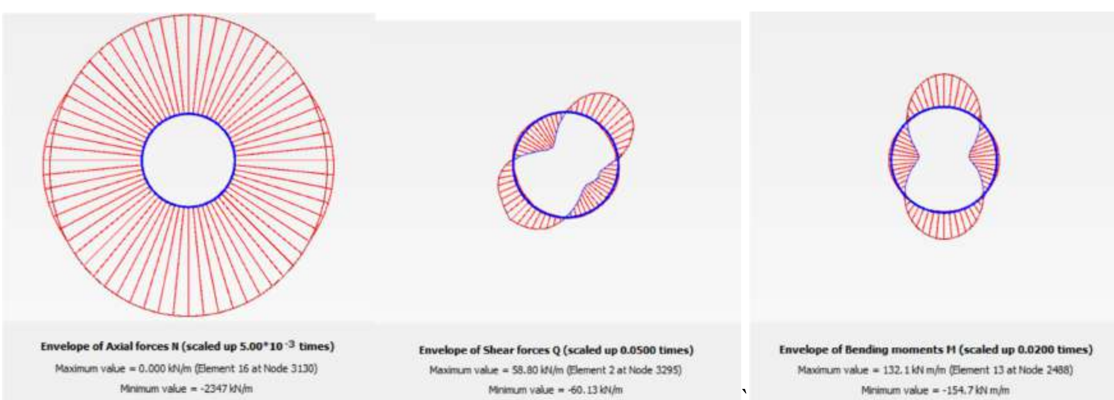



**Figure 110: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 35m depth, GWL= -60m)**

## 5.1.27. Profile #2B, Tunnel depth 45m, GWL= -20m


**Figure 111: Excavation induced Settlement (#2B, 45m depth, GWL= -20m)**

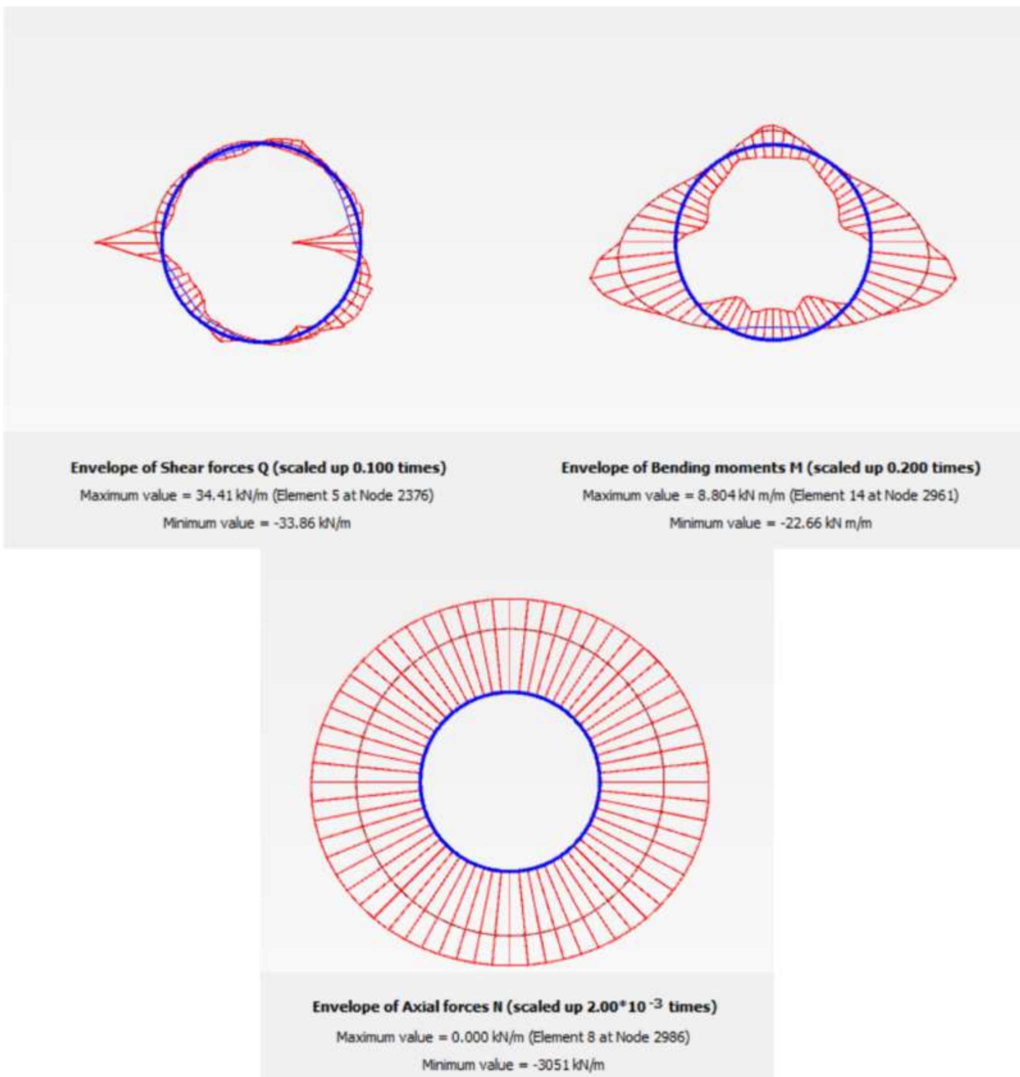



**Figure 112: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 45m depth, GWL= -20m)**

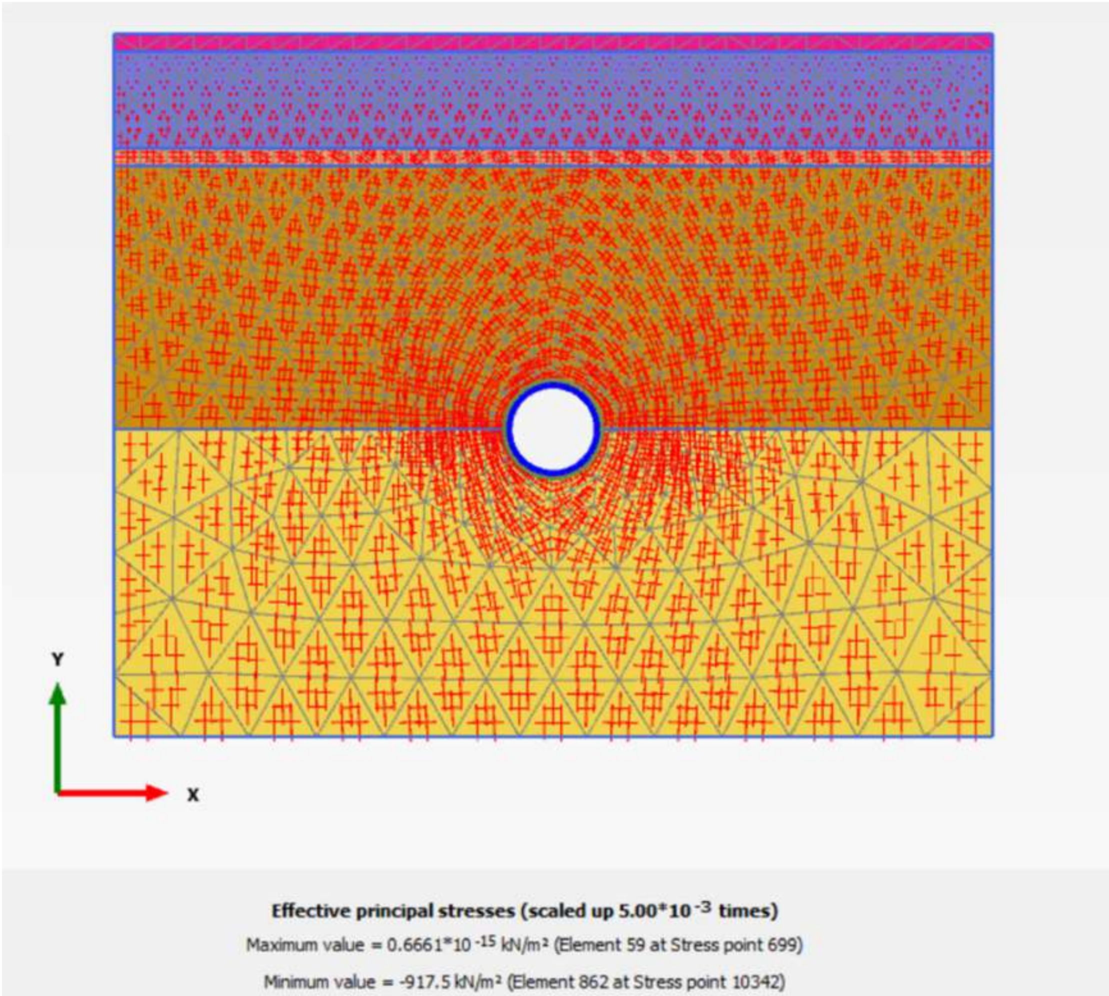



**Figure 113: Effective Principal Stress (#2B, 45m depth, GWL= -20m)**

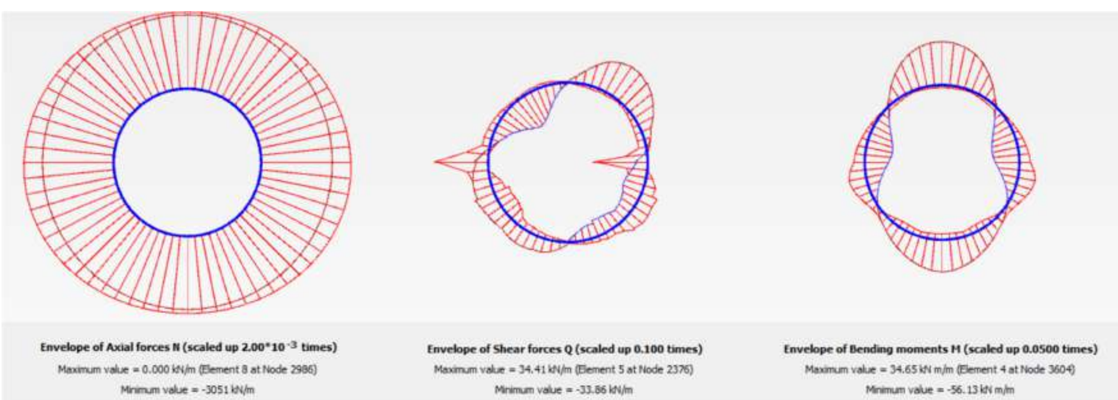



**Figure 114: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 45m depth, GWL= -20m)**

## 5.1.28. Profile #2B, Tunnel depth 45m, GWL= -60m

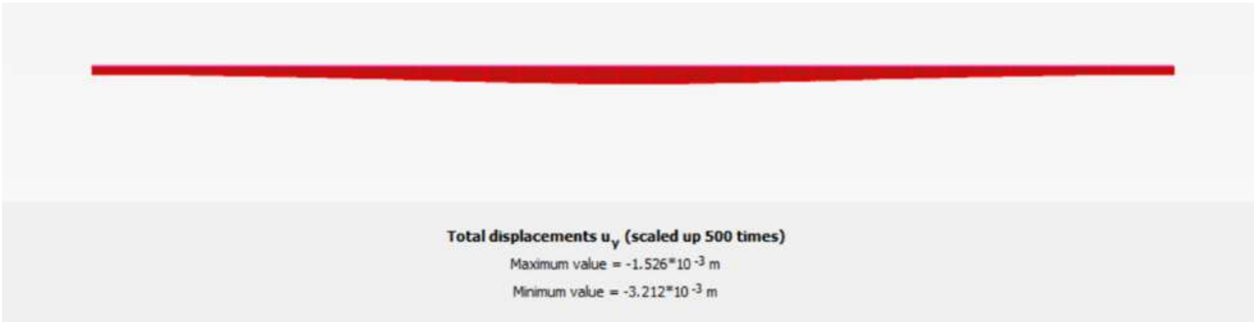



**Figure 115: Excavation induced Settlement (#2B, 45m depth, GWL= -60m)**

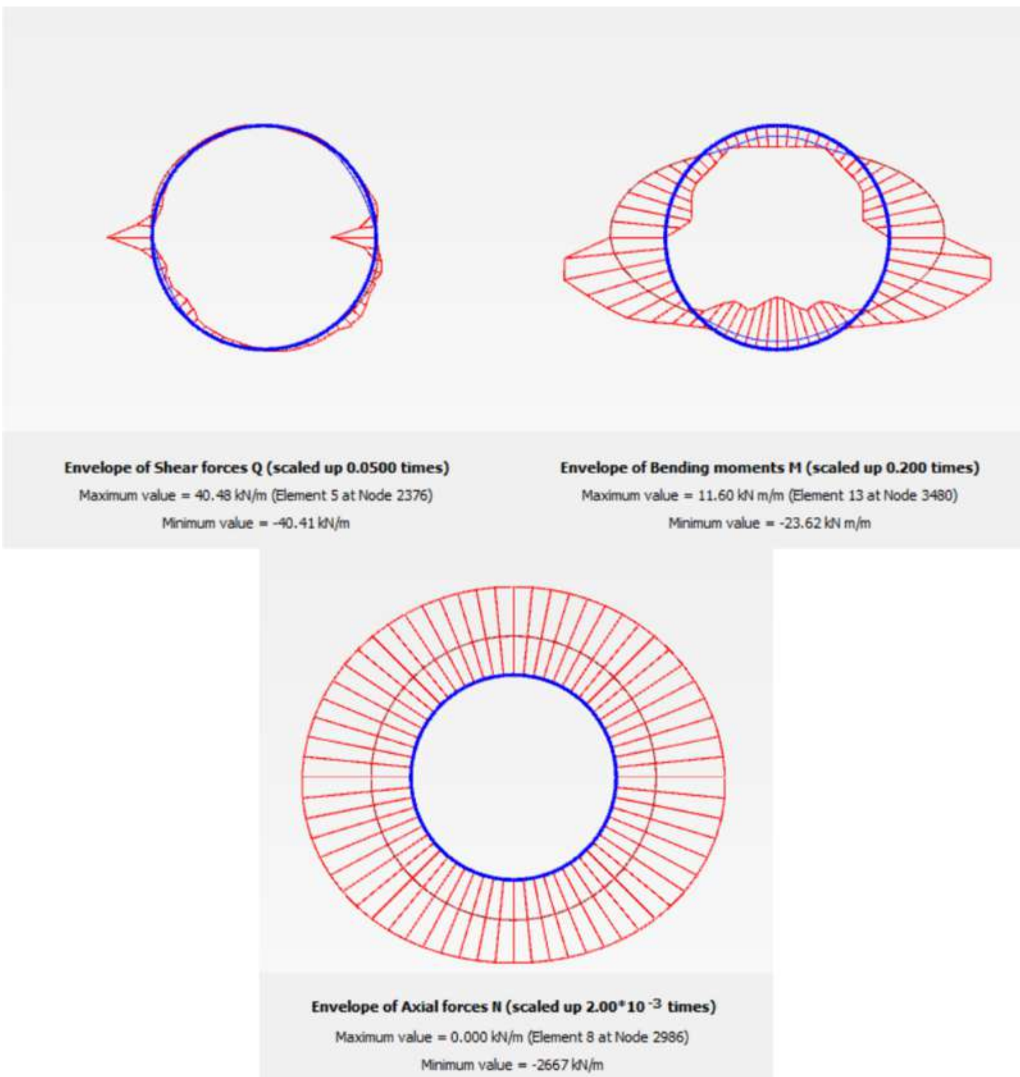



**Figure 116: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 45m depth, GWL= -60m)**

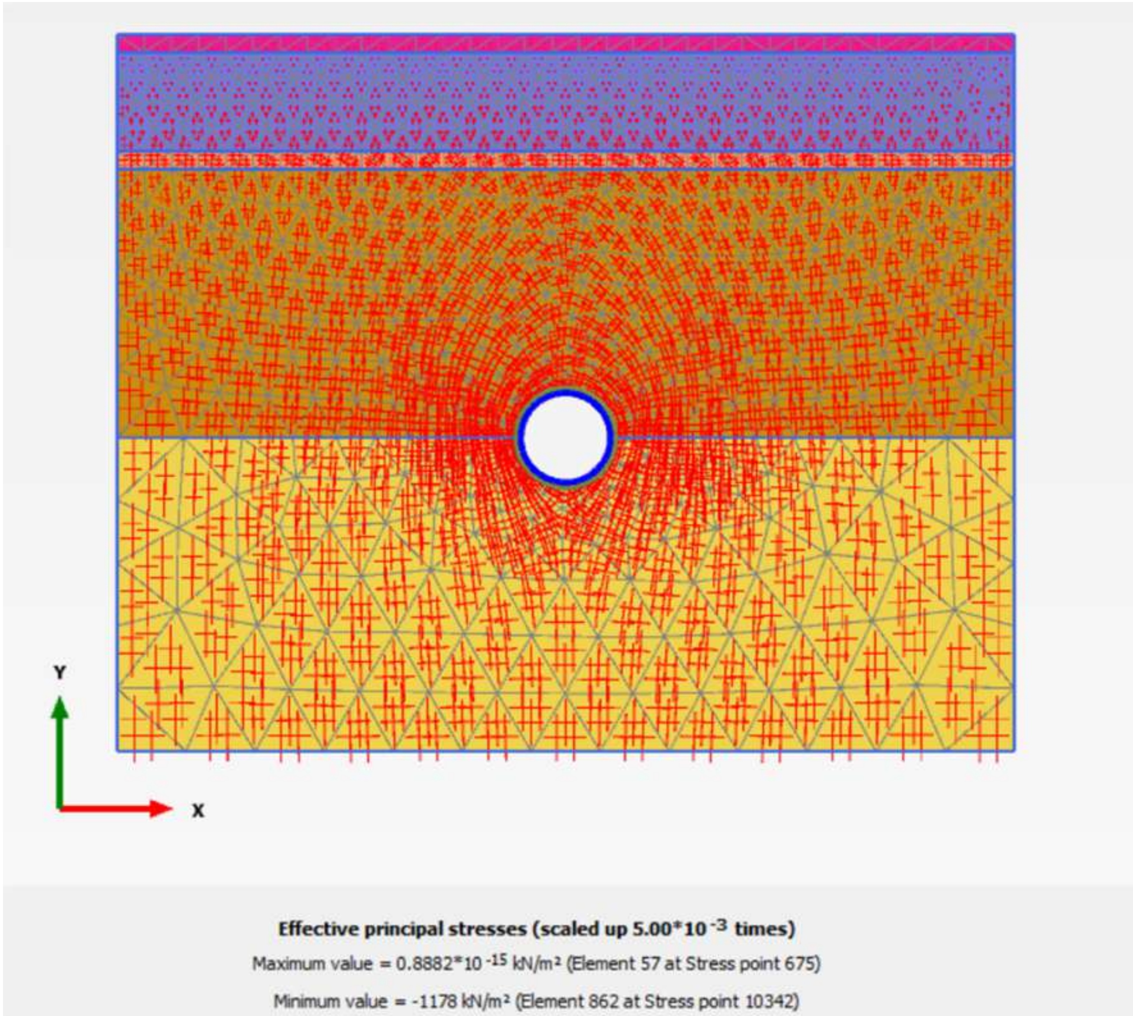



**Figure 117: Effective Principal Stress (#2B, 45m depth, GWL= -60m)**

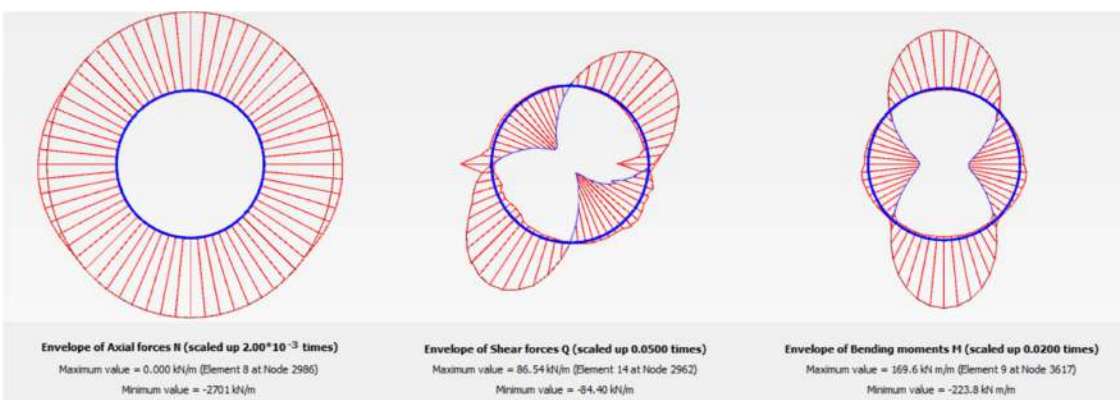



**Figure 118: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 45m depth, GWL= -60m)**

## 5.1.29. Profile #2B, Tunnel depth 55m, GWL= -20m


**Figure 119: Excavation induced Settlement (#2B, 55m depth, GWL= -20m)**

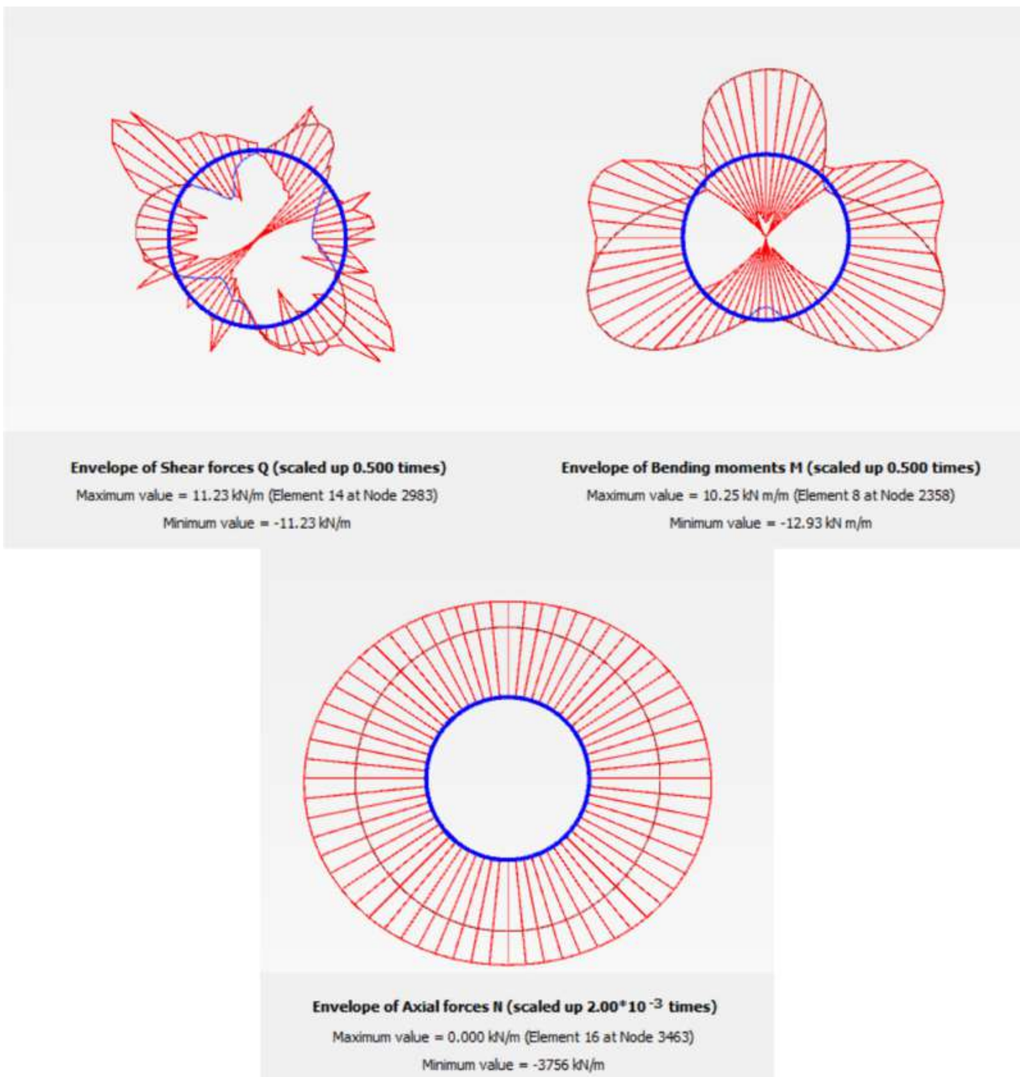



**Figure 120: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 55m depth, GWL= -20m)**

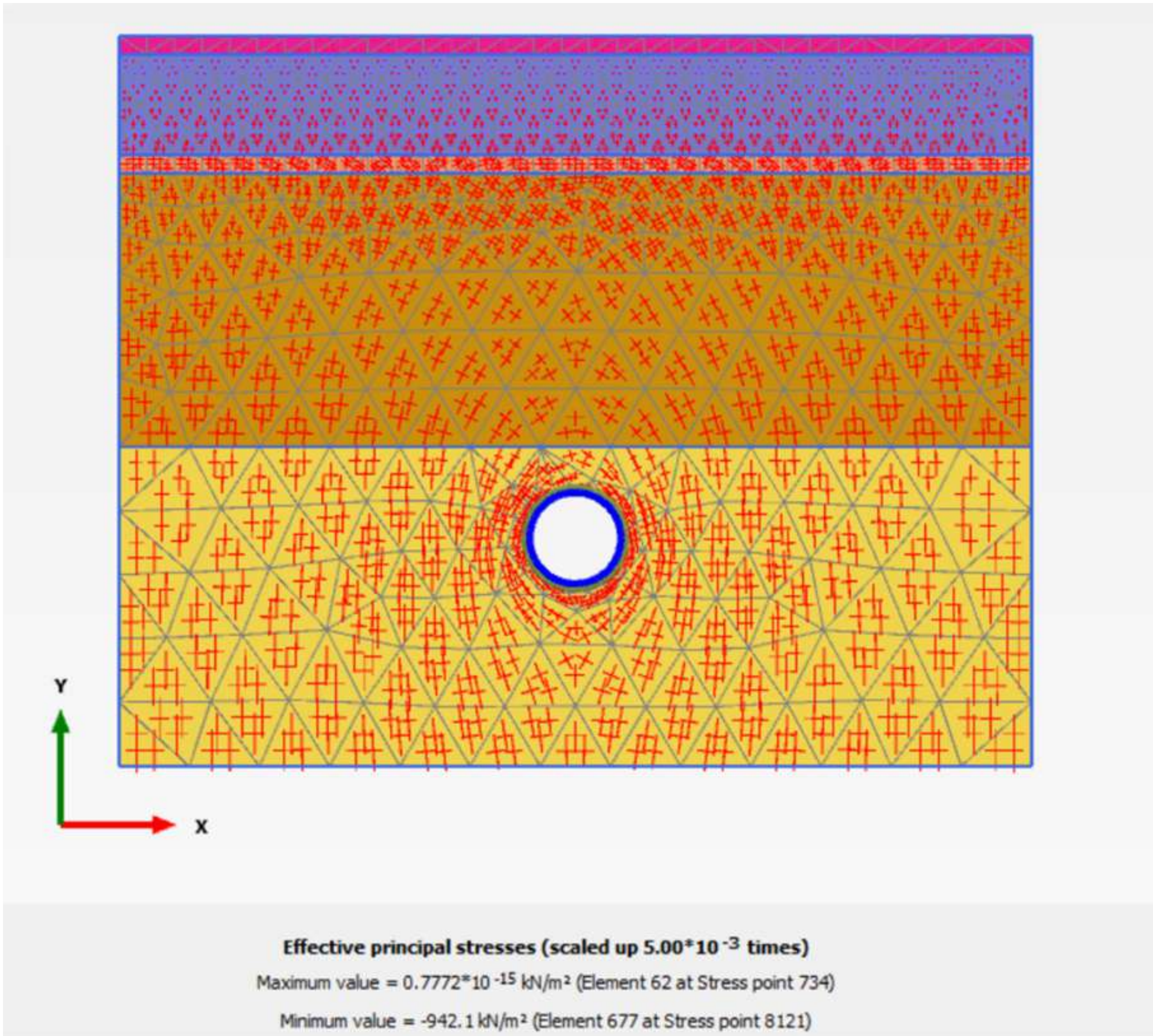



**Figure 121: Effective Principal Stress (#2B, 55m depth, GWL= -20m)**

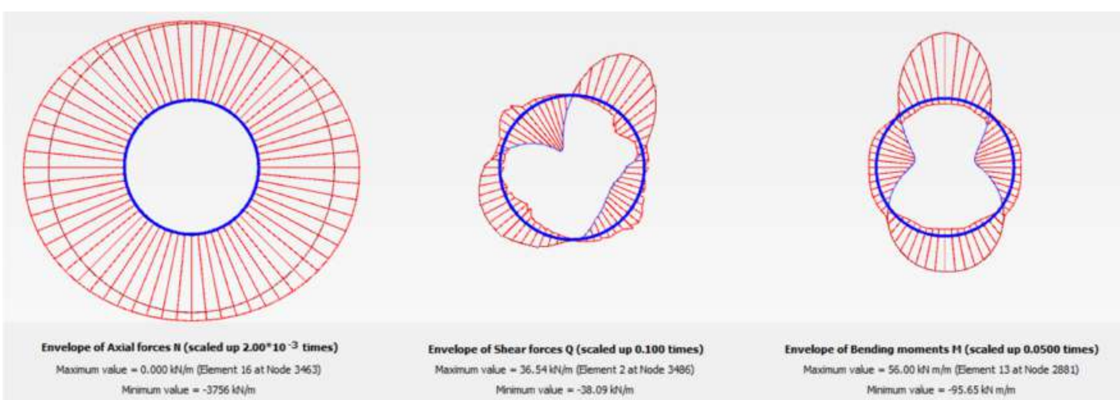



**Figure 122: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 55m depth, GWL= -20m)**

# 5.1.30. Profile #2B, Tunnel depth 55m, GWL= -60m

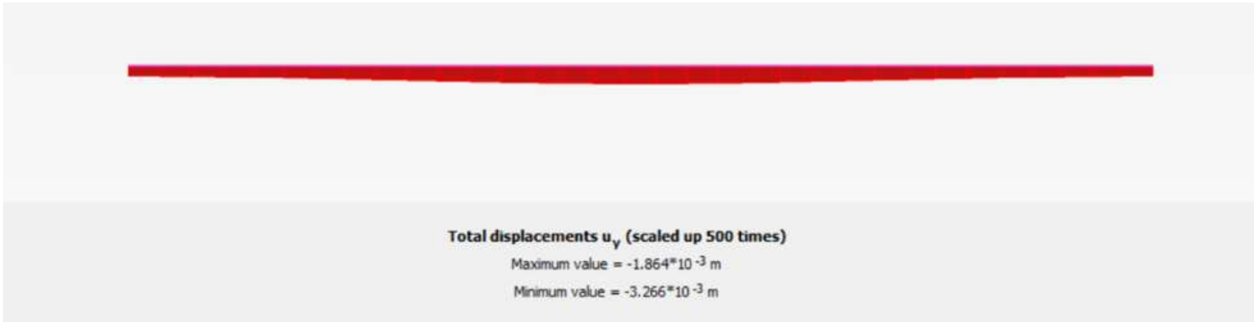



**Figure 123: Excavation induced Settlement (#2B, 55m depth, GWL= -60m)**

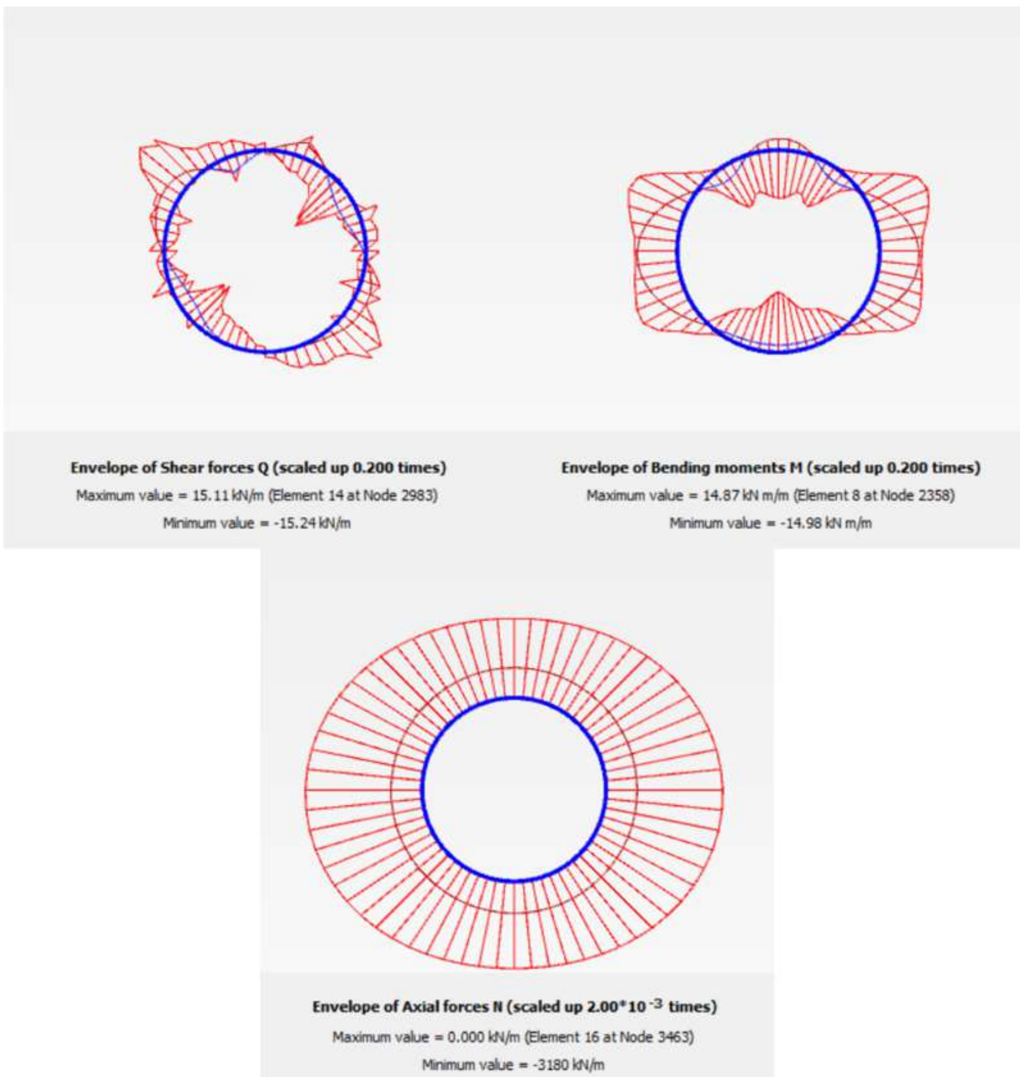



**Figure 124: Axial force, Shear force & Bending Moment on Tunnel Lining (#2B, 55m depth, GWL= -60m)**

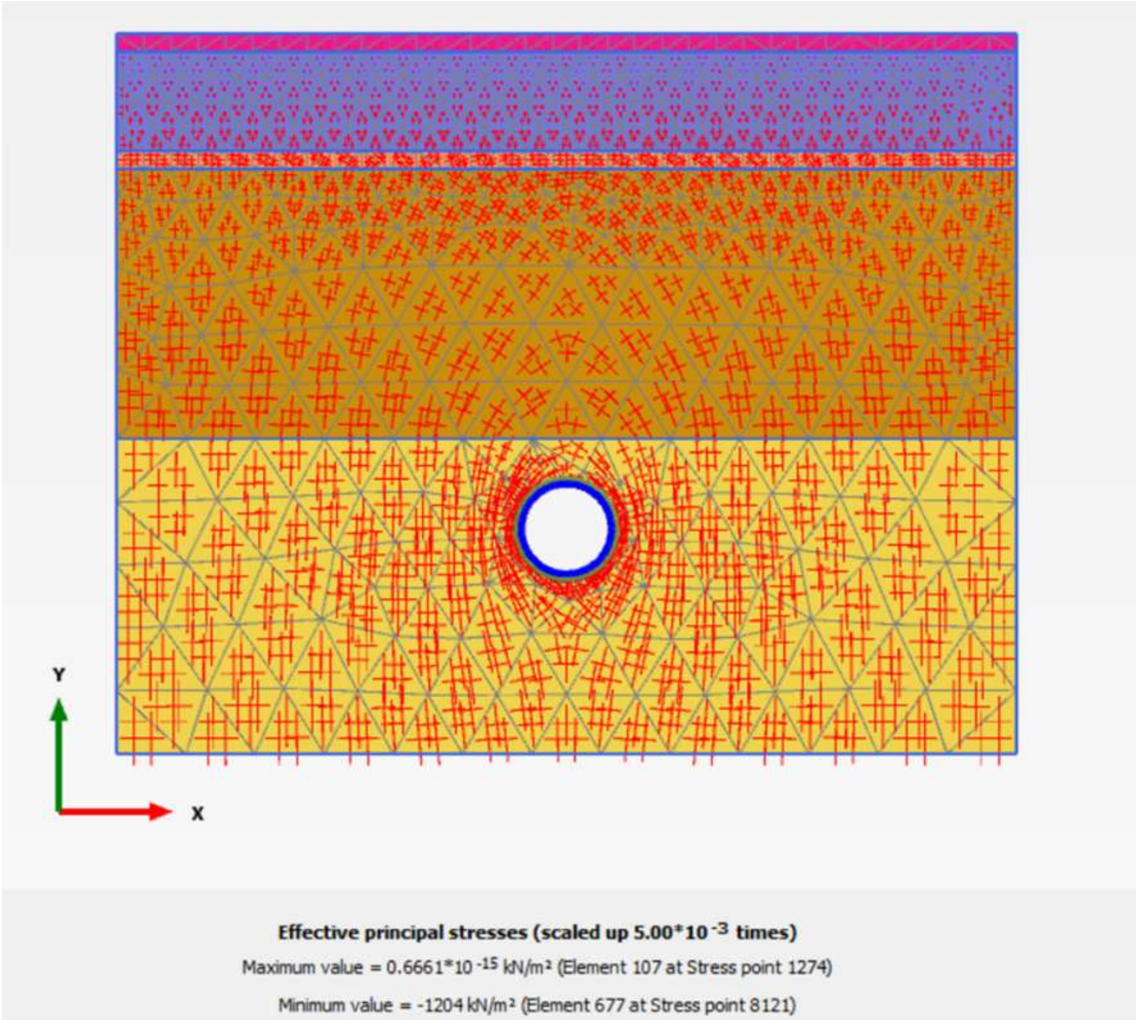



**Figure 125: Effective Principal Stress (#2B, 55m depth, GWL= -60m)**

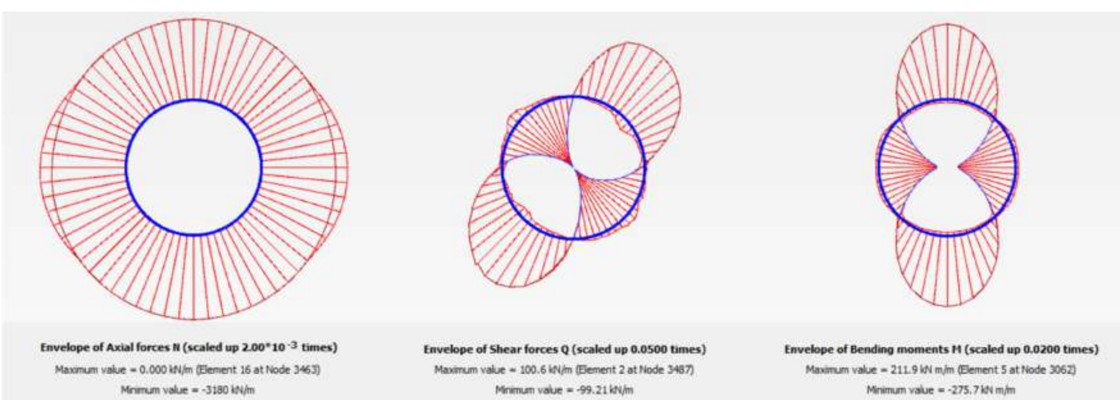



**Figure 126: Axial force, Shear force & Bending Moment after rising of Groundwater level (#2B, 55m depth, GWL= -60m)**

## 5.1.31. Profile #3A, Tunnel depth 45m, GWL= -4m

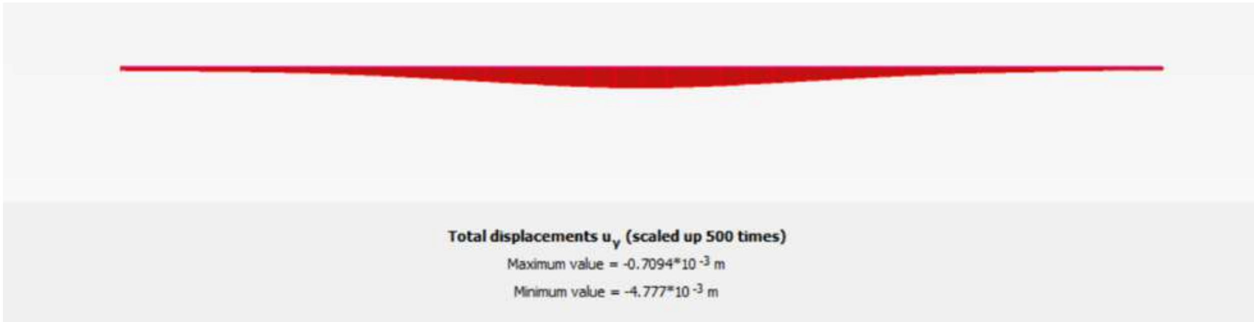



**Figure 127: Excavation induced Settlement (#3A, 45m depth, GWL= -4m)**

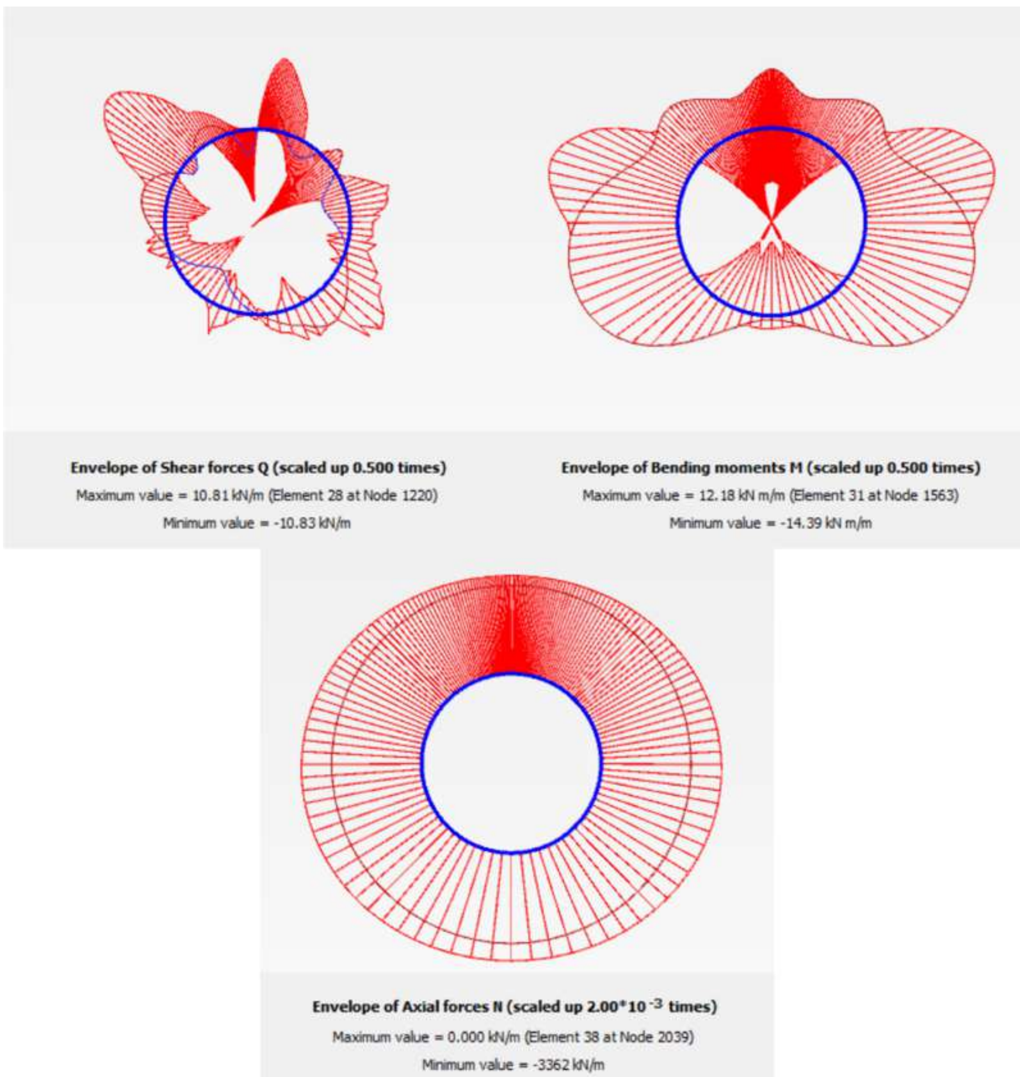



**Figure 128: Axial force, Shear force & Bending Moment on Tunnel Lining (#3A, 45m depth, GWL= -4m)**

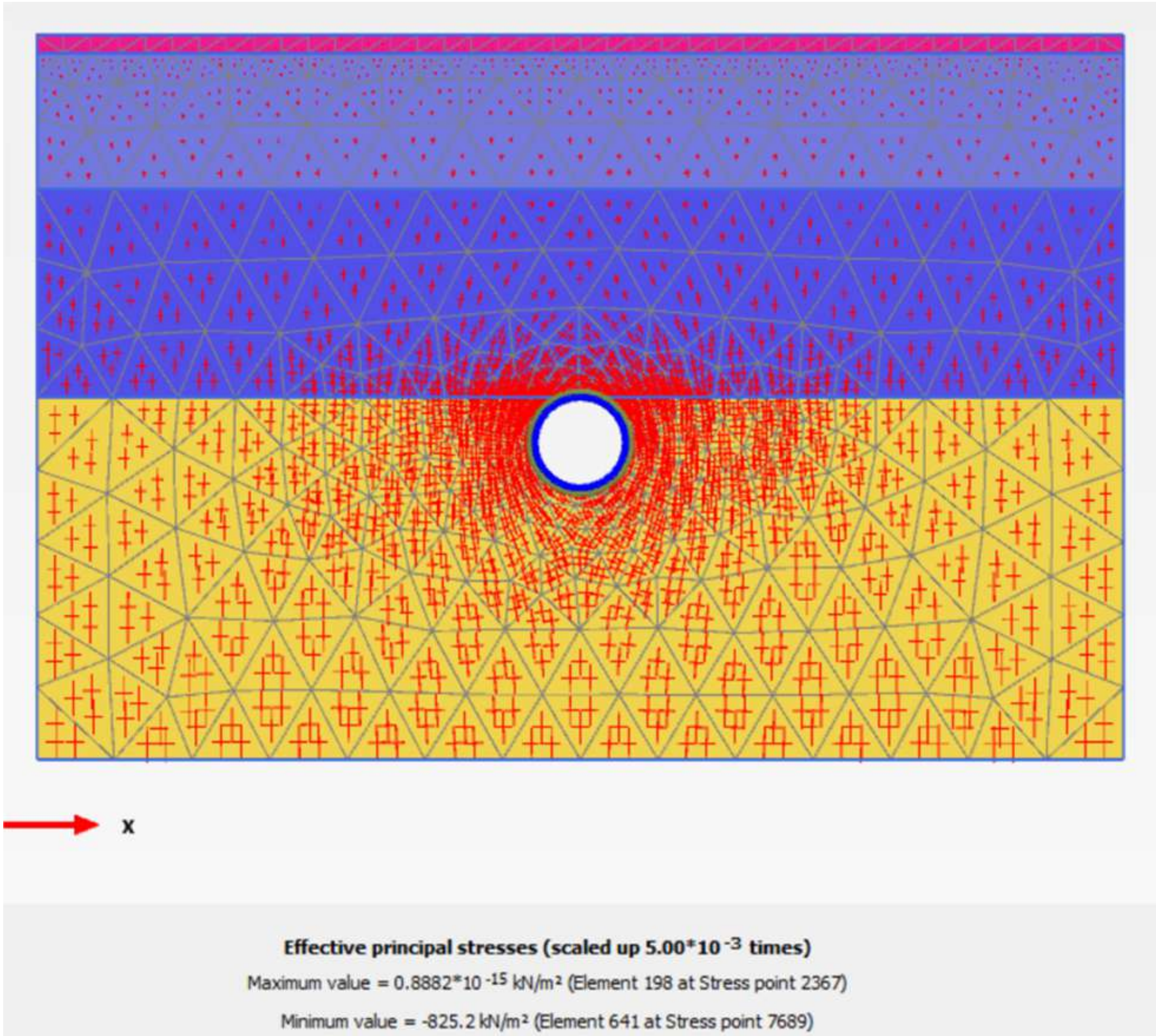



**Figure 129: Effective Principal Stress (#3A, 45m depth, GWL= -4m)**

## 5.1.32. Profile #3A, Tunnel depth 60m, GWL= -4m


**Figure 130: Excavation induced Settlement (#3A, 60m depth, GWL= -4m)**

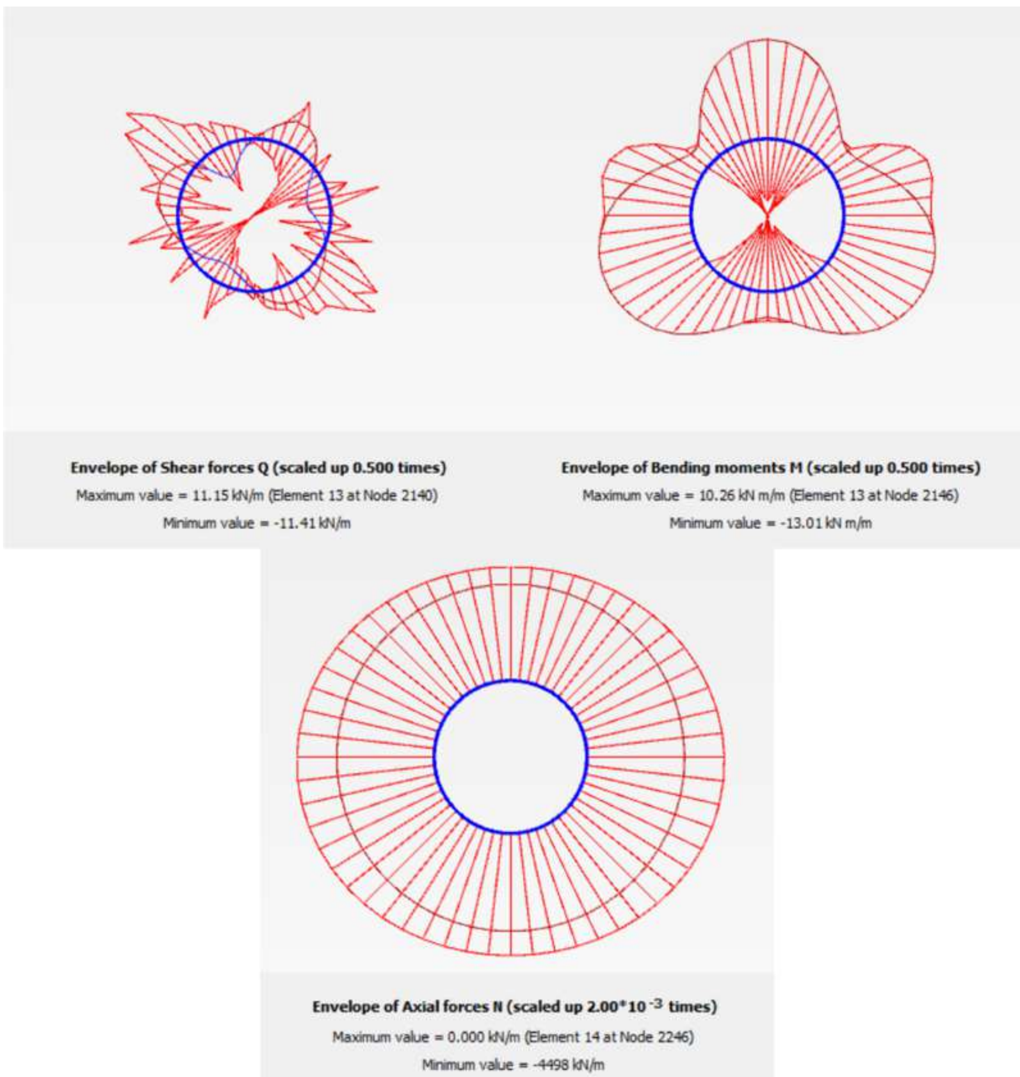



**Figure 131: Axial force, Shear force & Bending Moment on Tunnel Lining (#3A, 60m depth, GWL= -4m)**

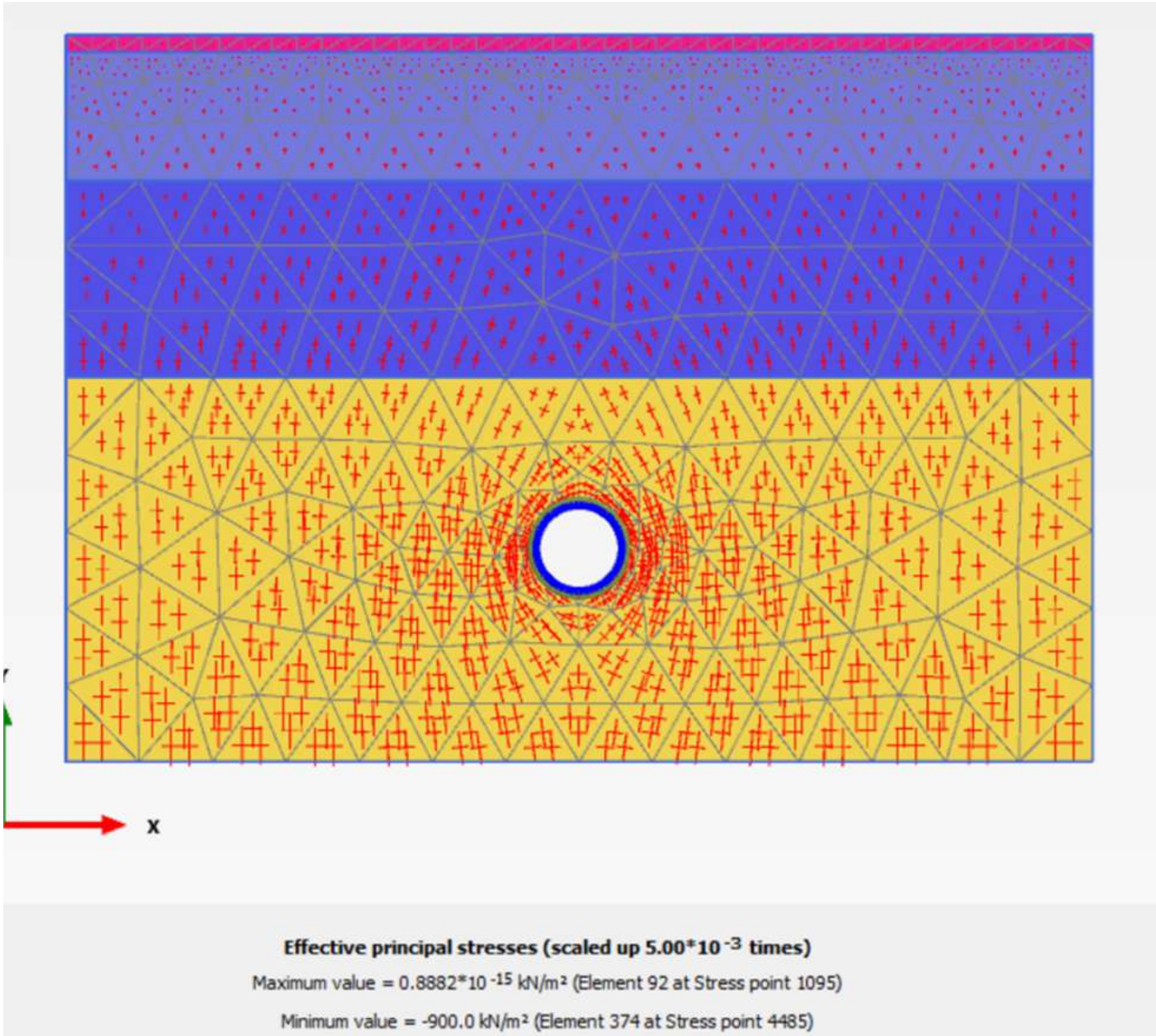



**Figure 132: Effective Principal Stress (#3A, 60m depth, GWL= -4m)**

## 5.1.33. Profile #3A, Tunnel depth 75m, GWL= -4m


**Figure 133: Excavation induced Settlement (#3A, 75m depth, GWL= -4m)**

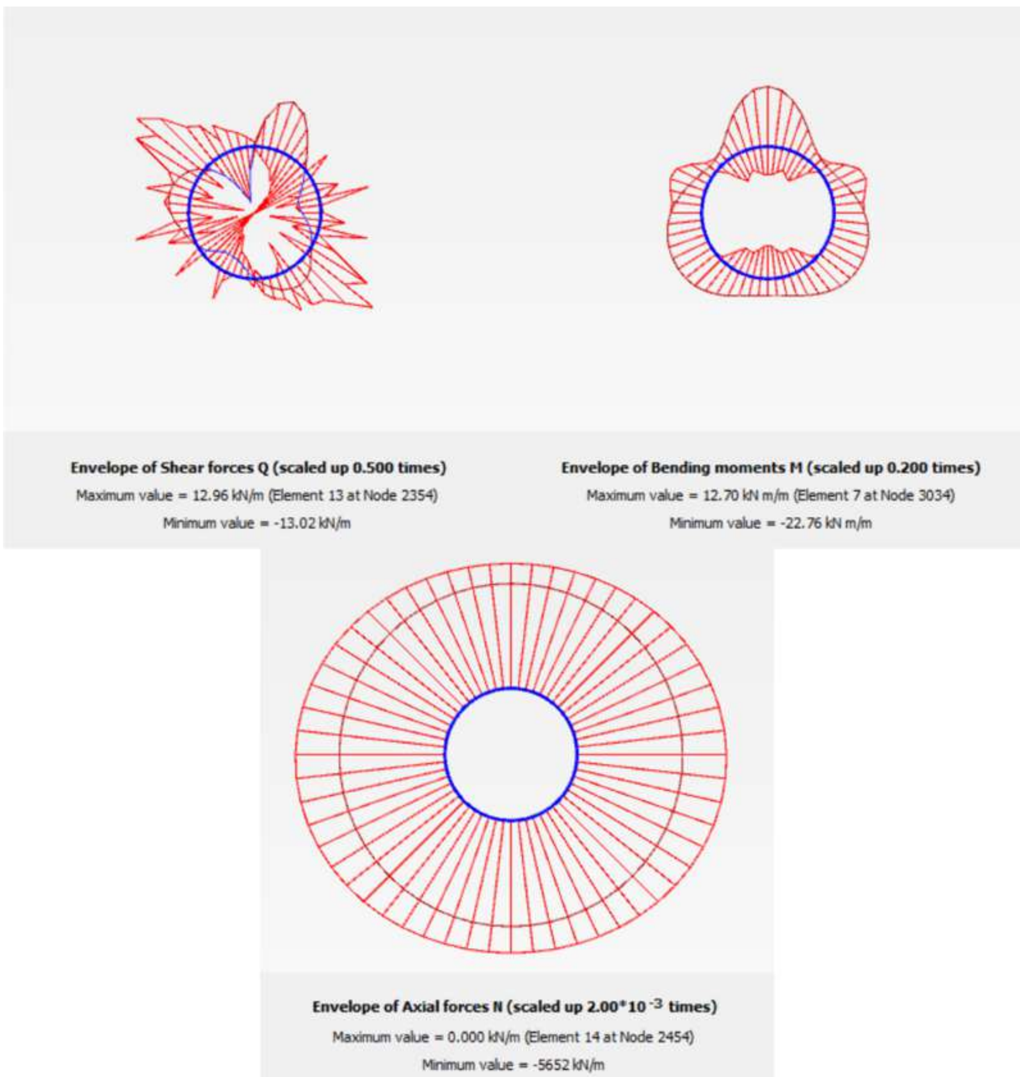



**Figure 134: Axial force, Shear force & Bending Moment on Tunnel Lining (#3A, 75m depth, GWL= -4m)**

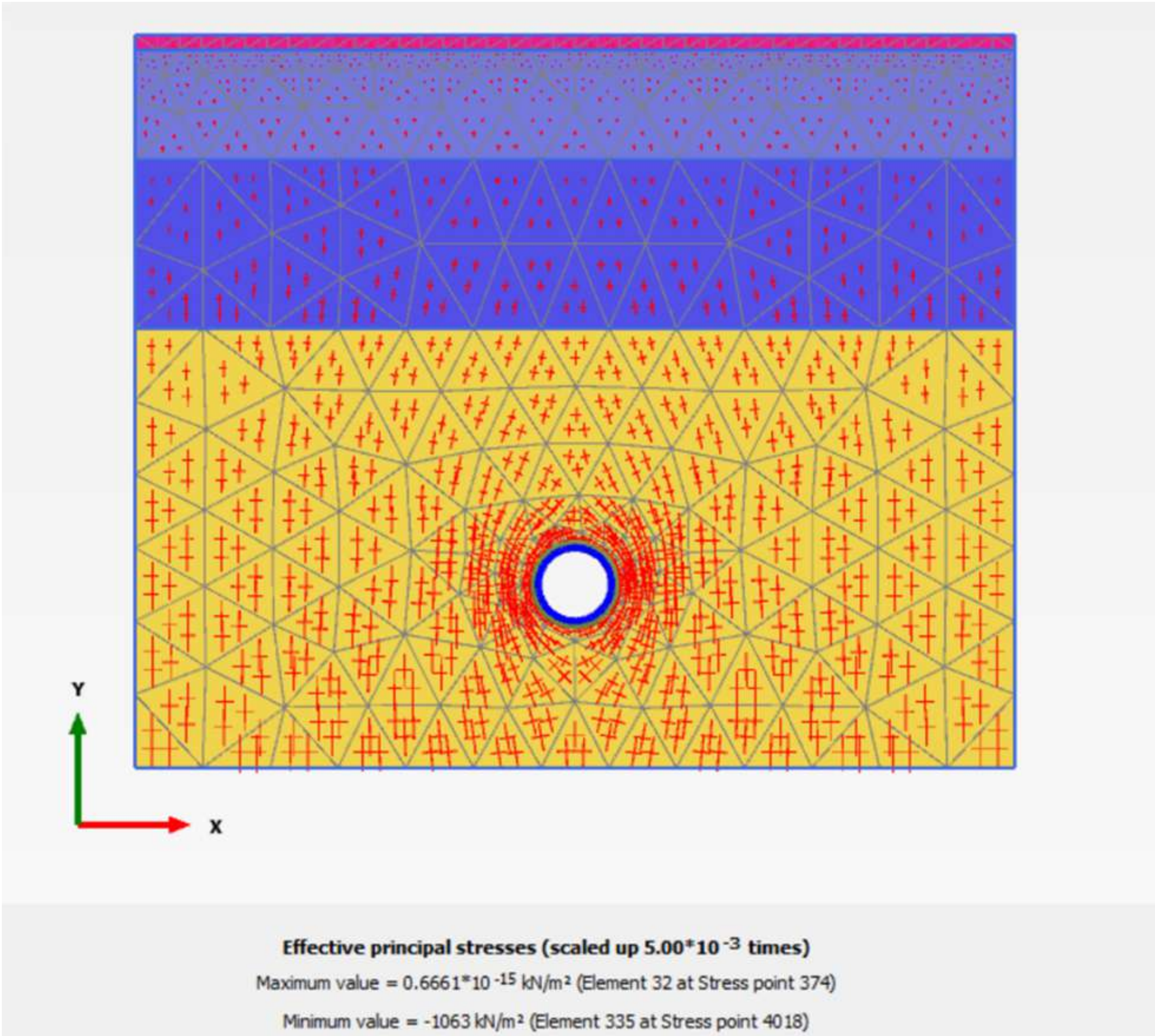



**Figure 135: Effective Principal Stress (#3A, 75m depth, GWL= -4m)**

## 5.1.34. Profile #3B, Tunnel depth 35m, GWL= +11m

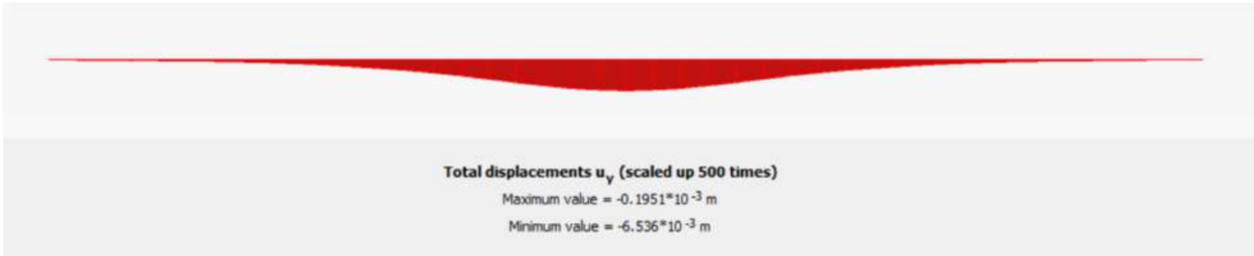



**Figure 136: Excavation induced Settlement (#3B, 35m depth, GWL= +11m)**

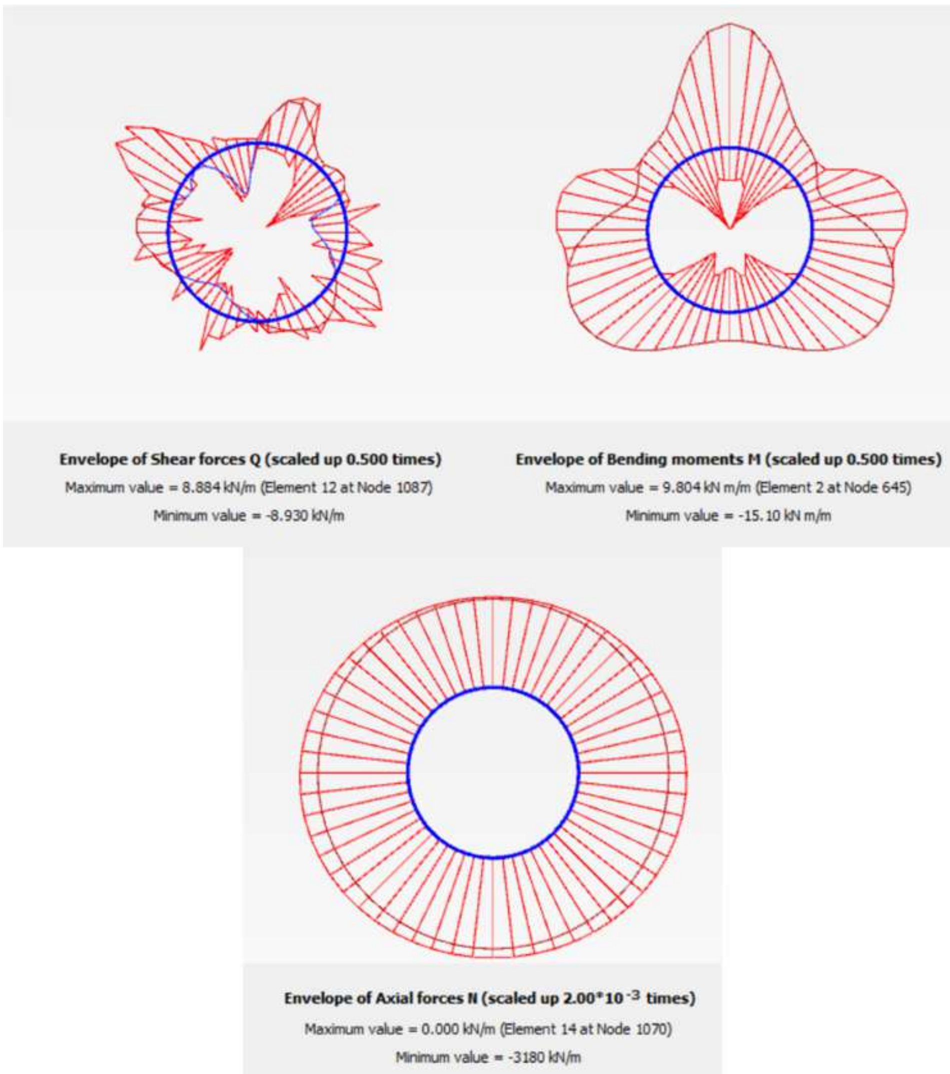



**Figure 137: Axial force, Shear force & Bending Moment on Tunnel Lining (#3B, 35m depth, GWL= +11m)**

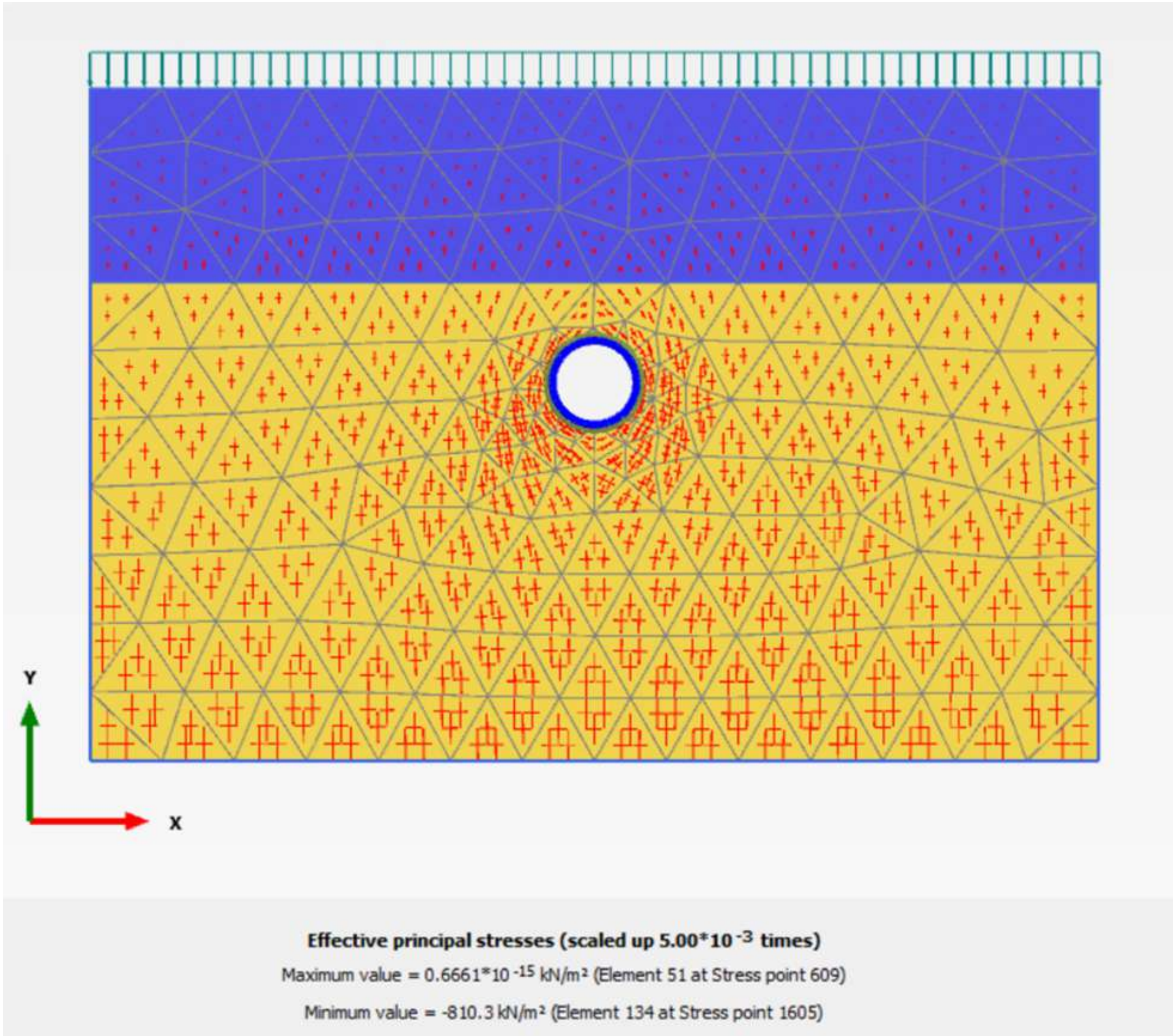



**Figure 138: Effective Principal Stress (#3B, 35m depth, GWL= +11m)**

## 5.1.35. Profile #3B, Tunnel depth 45m, GWL= +11m

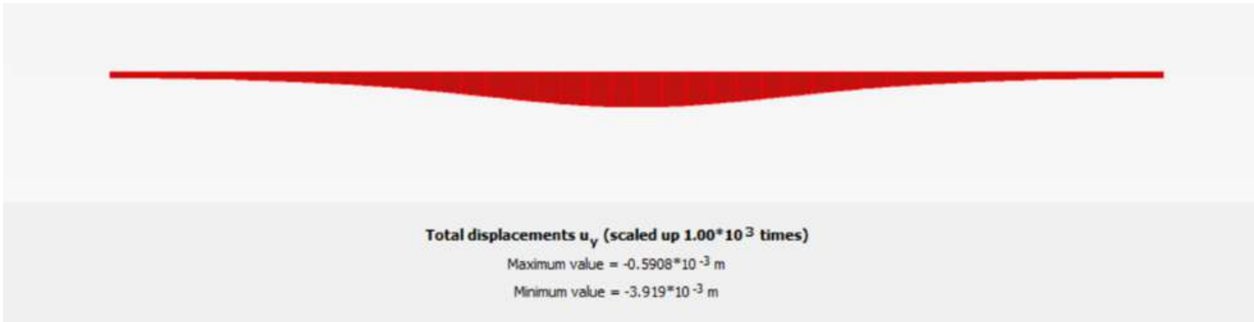



**Figure 139: Excavation induced Settlement (#3B, 45m depth, GWL= +11m)**

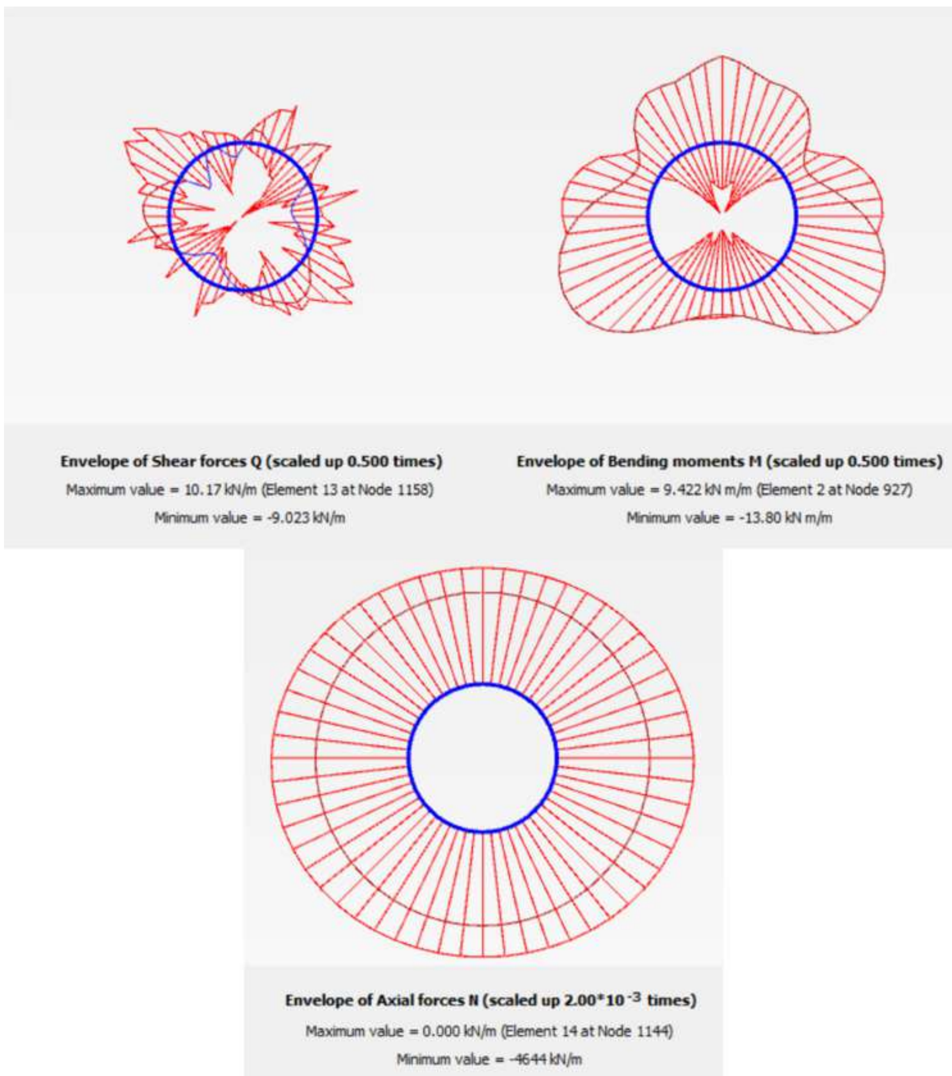



**Figure 140: Axial force, Shear force & Bending Moment on Tunnel Lining (#3B, 45m depth, GWL= +11m)**

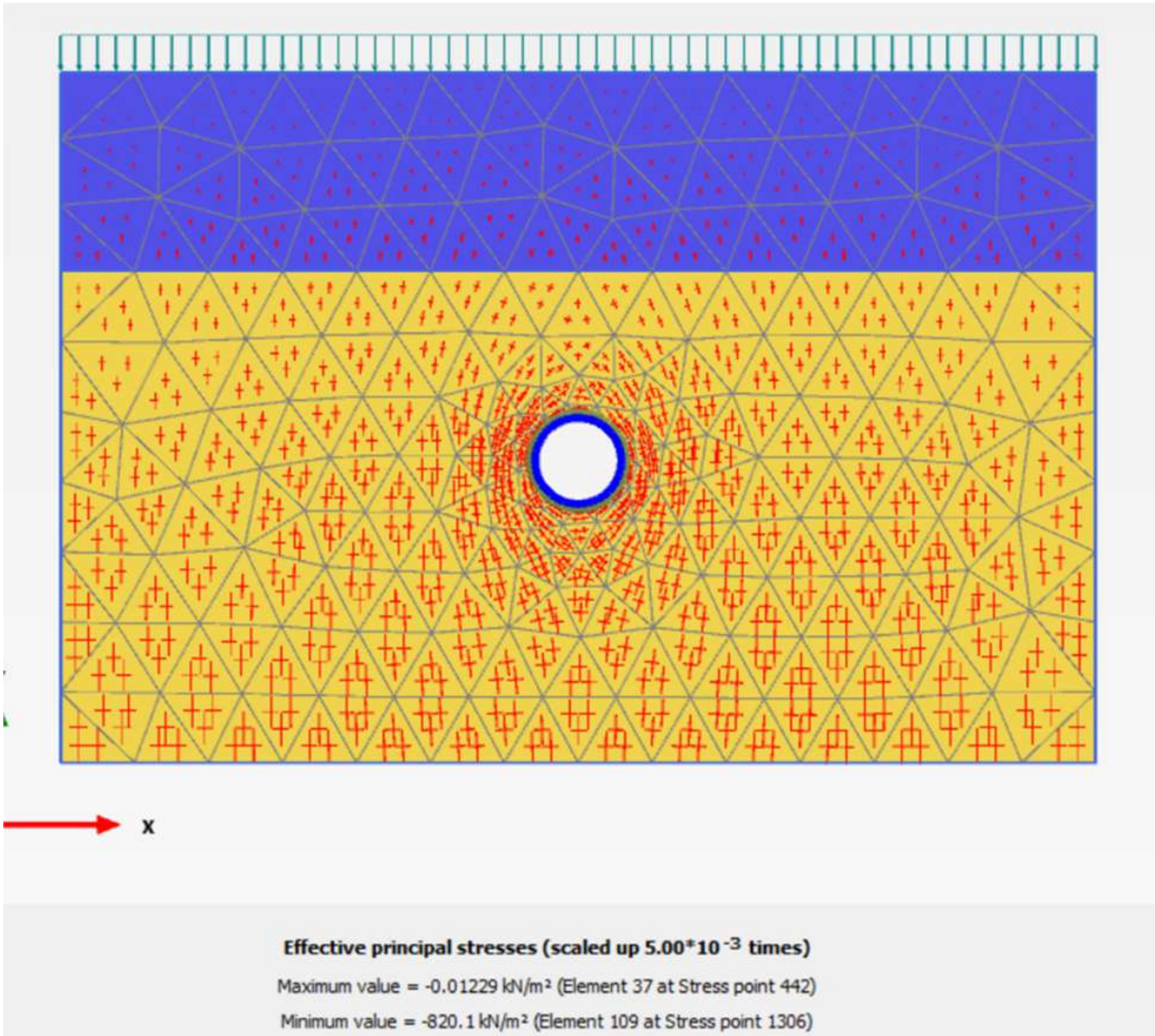



**Figure 141: Effective Principal Stress (#3B, 45m depth, GWL= +11m)**

## 5.1.36. Profile #3B, Tunnel depth 60m, GWL= +11m


**Figure 142: Excavation induced Settlement (#3B, 60m depth, GWL= +11m)**

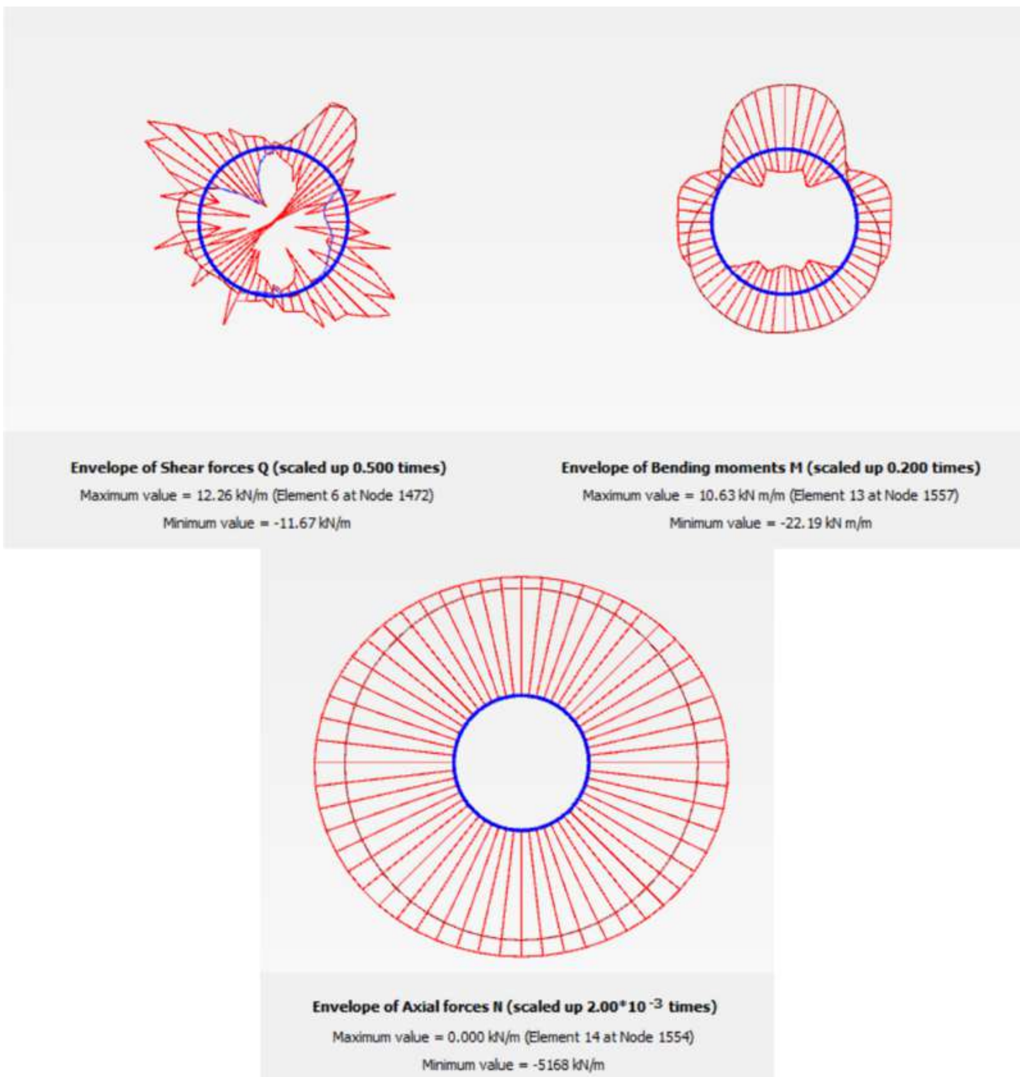



**Figure 143: Axial force, Shear force & Bending Moment on Tunnel Lining (#3B, 60m depth, GWL= +11m)**

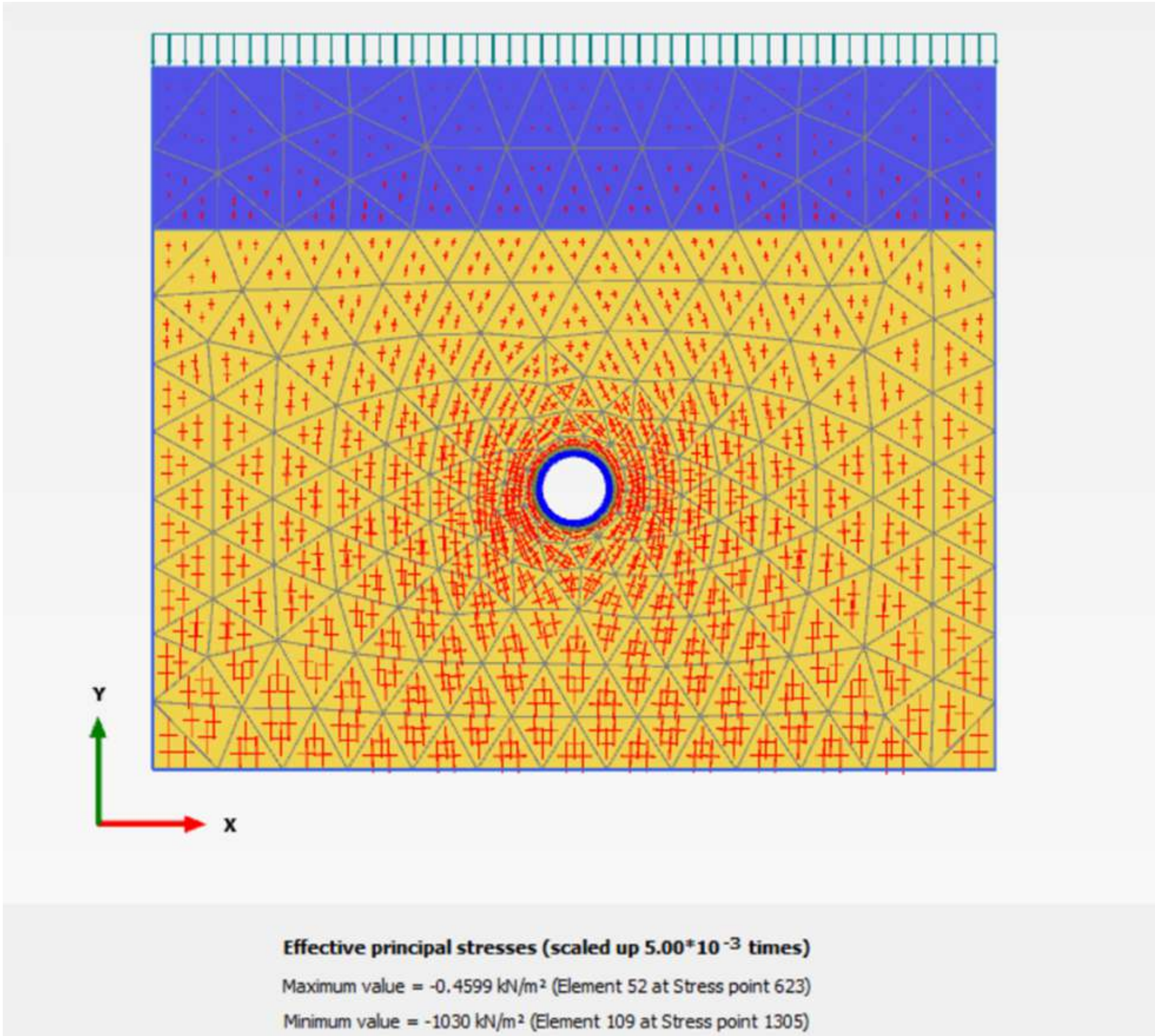



**Figure 144: Effective Principal Stress (#3B, 60m depth, GWL= +11m)**

# 5.2. Tables of Settlement during Excavation Phase

**Table 2: Excavation induced Settlement of #1A**

| Profile #1A, GWL= -60m | | Profile #1A, GWL= -20m | |
|---|---|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** | **Tunnel depth (m)** | **Settlement (mm)** |
| **25** | 9.34 | **25** | 7.78 |
| **35** | 5.18 | **35** | 4.204 |
| **45** | 3.84 | **45** | 3.024 |
| **55** | 3.238 | **55** | 2.611 |
| **65** | 2.905 | **65** | 2.623 |
| **75** | 2.476 | **75** | 2.56 |

**Table 3: Excavation induced Settlement of #1B**

| Profile #1B, GWL= -60m | | Profile #1B, GWL= -20m | |
|---|---|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** | **Tunnel depth (m)** | **Settlement (mm)** |
| **30** | 4.538 | **30** | 3.821 |
| **40** | 3.584 | **40** | 3.014 |
| **50** | 3.582 | **50** | 3.003 |

**Table 4: Excavation induced Settlement of #2A**

| Profile #2A, GWL= -60m | | Profile #2A, GWL= -20m | |
|---|---|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** | **Tunnel depth (m)** | **Settlement (mm)** |
| **25** | 11.18 | **25** | 10.05 |
| **50** | 3.899 | **50** | 3.397 |
| **75** | 3.188 | **75** | 3.035 |

**Table 5: Excavation induced Settlement of #2B**

| Profile #2B, GWL= -60m | | Profile #2B, GWL= -20m | |
|---|---|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** | **Tunnel depth (m)** | **Settlement (mm)** |
| **35** | 3.289 | **35** | 3.401 |
| **45** | 3.212 | **45** | 4.017 |
| **55** | 3.266 | **55** | 2.87 |

**Table 6: Excavation induced Settlement of #3A**

| Profile #3A, GWL= -4m | |
|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** |
| **45** | 4.777 |
| **60** | 2.56 |
| **75** | 2.252 |

**Table 7: Excavation induced Settlement of #3B**

| Profile #3B, GWL= +11m | |
|---|---|
| **Tunnel depth (m)** | **Settlement (mm)** |
| **35** | 6.536 |
| **45** | 3.919 |
| **60** | 2.711 |

## 5.3. Grouting Pressure for Achieving 10mm Surface Settlement and Volume Loss

**Table 8: Grouting Pressure and Volume Loss #1A**

| Profile #1A | | | | | | | |
|---|---|---|---|---|---|---|---|
| GWL= -20m | | | | GWL= -60m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) | Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 25 | 135 | 10.22 | 0.81 | 25 | 120 | 10.03 | 0.61 |
| 35 | 230 | 10.21 | 1.28 | 35 | 128 | 10.12 | 1.01 |
| 45 | 335 | 9.835 | 1.65 | 45 | 148 | 10.02 | 1.37 |
| 55 | 440 | 10.08 | 2.06 | 55 | 168 | 10.12 | 1.75 |
| 65 | 550 | 10.16 | 2.33 | 65 | 222 | 10.1 | 2.1 |
| 75 | 660 | 10.15 | 2.51 | 75 | 330 | 10.09 | 2.39 |

**Table 9: Grouting Pressure and Volume Loss #1B**

| Profile #1B | | | | | | | |
|---|---|---|---|---|---|---|---|
| GWL= -20m | | | | GWL= -60m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) | Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 30 | 205 | 10.1 | 1.4 | 30 | 149 | 10.13 | 1.12 |
| 40 | 291 | 10.1 | 1.61 | 40 | 163 | 10.1 | 1.4 |
| 50 | 379 | 10.02 | 1.88 | 50 | 147 | 10.1 | 1.61 |

**Table 10: Grouting Pressure and Volume Loss #2A**

| Profile #2A | | | | | | | |
|---|---|---|---|---|---|---|---|
| GWL= -20m | | | | GWL= -60m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) | Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 25 | 160 | 10.34 | 0.63 | 25 | 175 | 10.15 | 0.49 |
| 50 | 400 | 10.19 | 1.56 | 50 | 175 | 10.21 | 1.38 |
| 75 | 705 | 10.25 | 1.87 | 75 | 400 | 10.31 | 1.77 |

**Table 11: Grouting Pressure and Volume Loss #2B**

| Profile #2B | | | | | | | |
|---|---|---|---|---|---|---|---|
| GWL= -20m | | | | GWL= -60m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) | Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 35 | 270 | 10.09 | 1.5 | 35 | 178 | 10.29 | 1.28 |
| 45 | 352 | 10.14 | 1.72 | 45 | 187 | 10.15 | 1.54 |
| 55 | 435 | 10.13 | 1.96 | 55 | 165 | 10.09 | 1.71 |

**Table 12: Grouting Pressure and Volume Loss #3A**

| Profile #3A | | | |
|---|---|---|---|
| GWL= -4m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 45 | 502 | 10.01 | 0.91 |
| 60 | 640 | 10.09 | 2 |
| 75 | 800 | 10.04 | 2.57 |

**Table 13: Grouting Pressure and Volume Loss #3B**

| Profile #3B | | | |
|---|---|---|---|
| GWL= +11m | | | |
| Tunnel Depth (m) | Grouting Pressure (kPa) | Max Settlement (mm) | Volume Loss (%) |
| 35 | 532 | 10.28 | 0.93 |
| 45 | 632 | 10.2 | 1.38 |
| 60 | 815 | 10.21 | 1.99 |

# 5.4. Graphs

All of the data found in the research have similar results and followed a trend line. The graphs generated for the profile #1A is shown here.

## 5.4.1. Excavation induced Settlement of Profile #1A

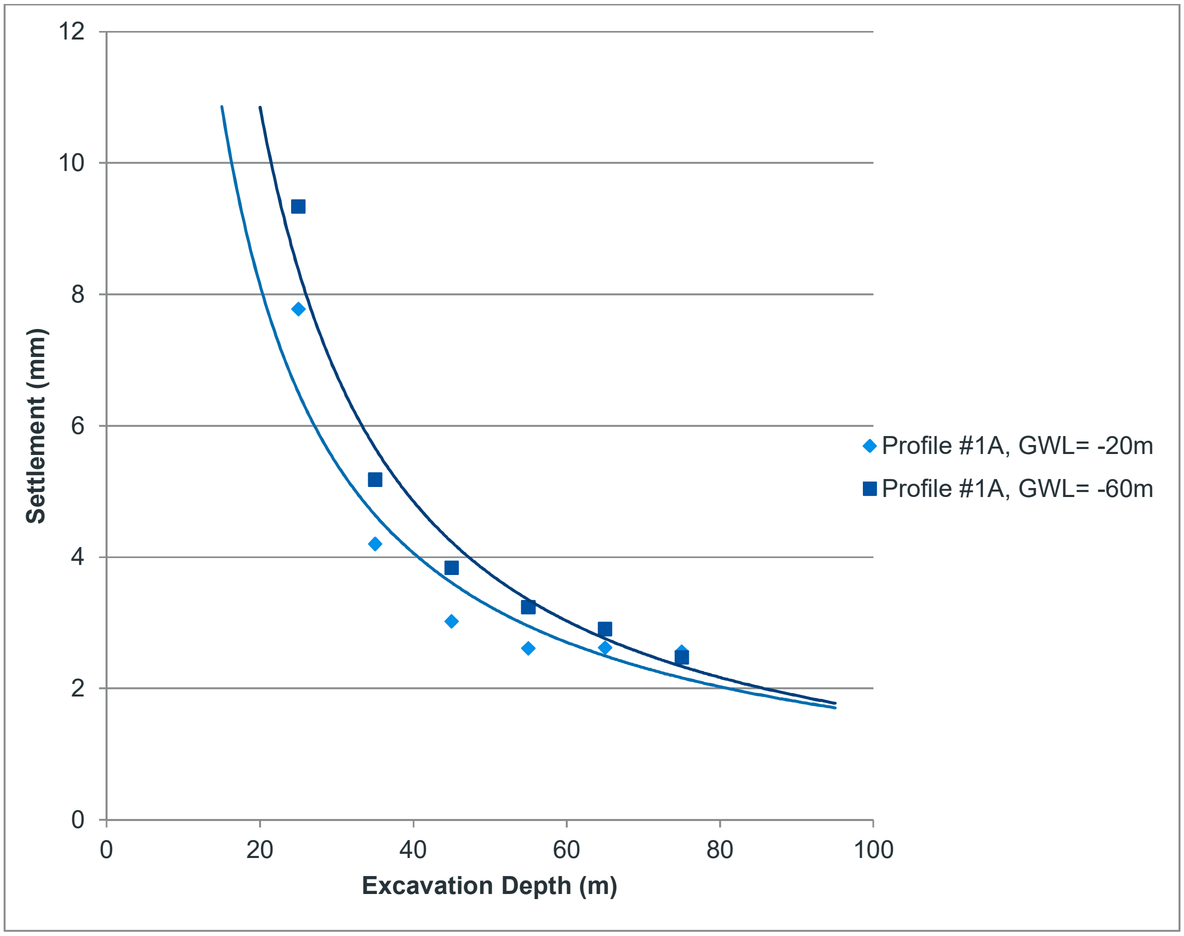



**Figure 145: Settlement vs Excavation Graph, #1A**

### 5.4.2. Required Grouting pressure for 10mm Surface Settlement, #1A

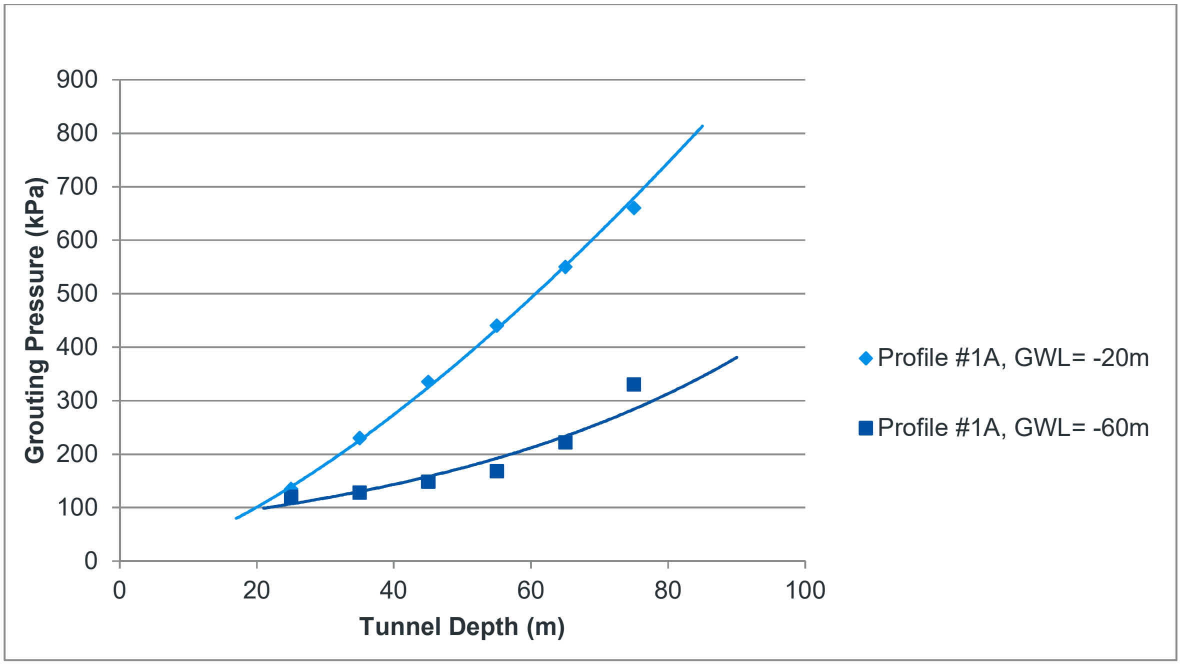



**Figure 146: Grouting Pressure vs Tunnel Depth, #1A**

### 5.4.3. Axial Force #1A, GWL= -20m & -60m

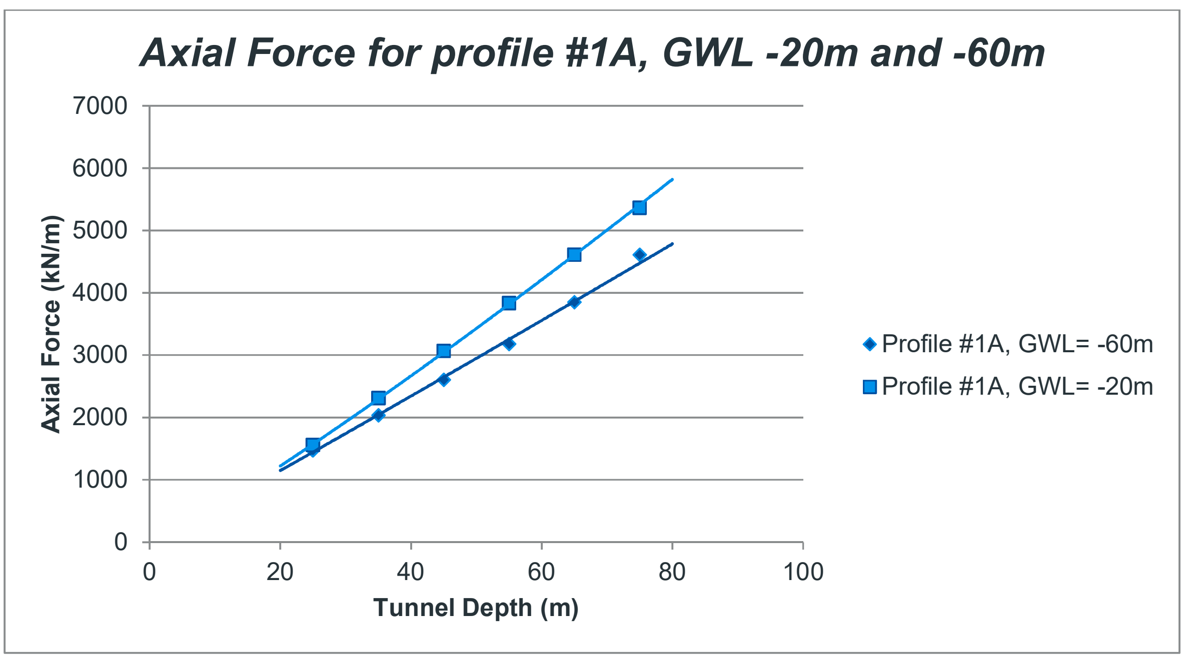



**Figure 147: Axial Force vs Tunnel Depth, #1A**

### 5.4.4. Bending Moment #1A, GWL= -20m

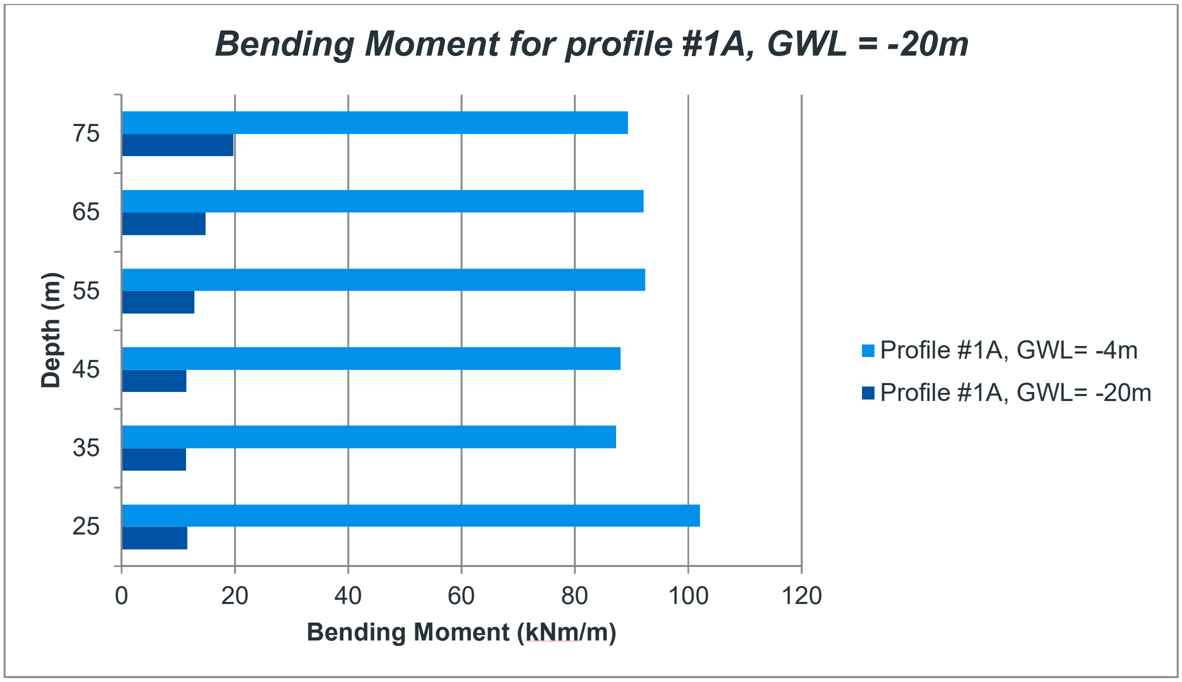



**Figure 148: Bending moment, #1A, GWL=-20m**

### 5.4.5. Bending Moment #1A, GWL= -60m

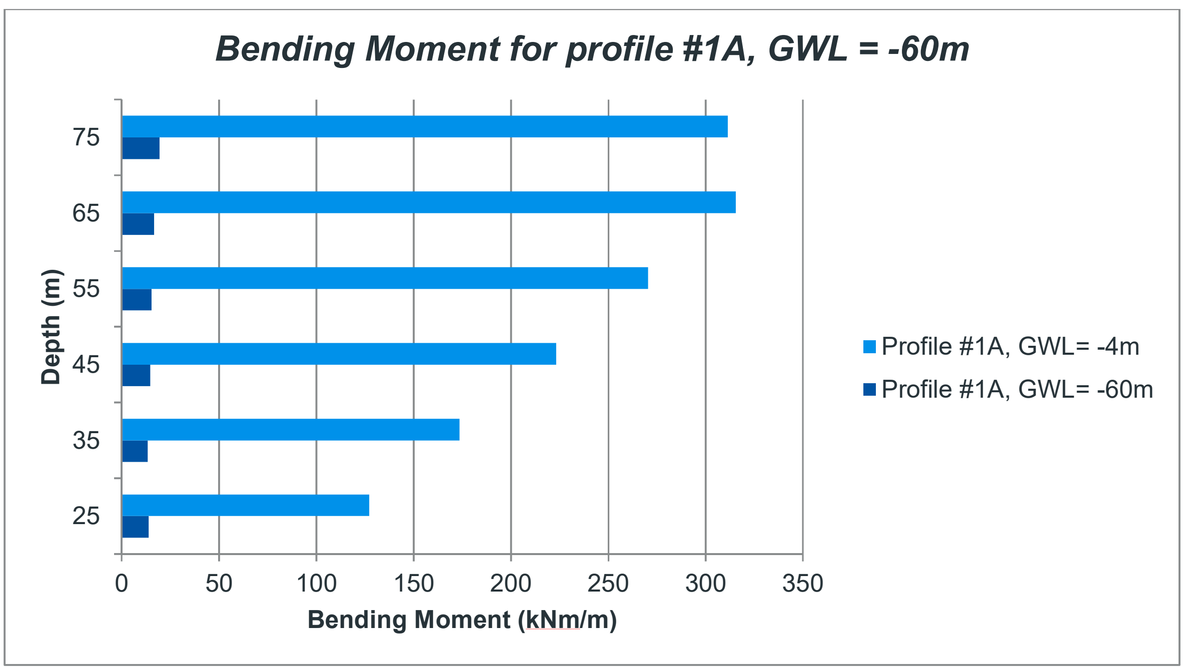



**Figure 149: Bending moment bar diagram, #1A, GWL=-60m**

### 5.4.6. Shear Force #1A, GWL= -20m

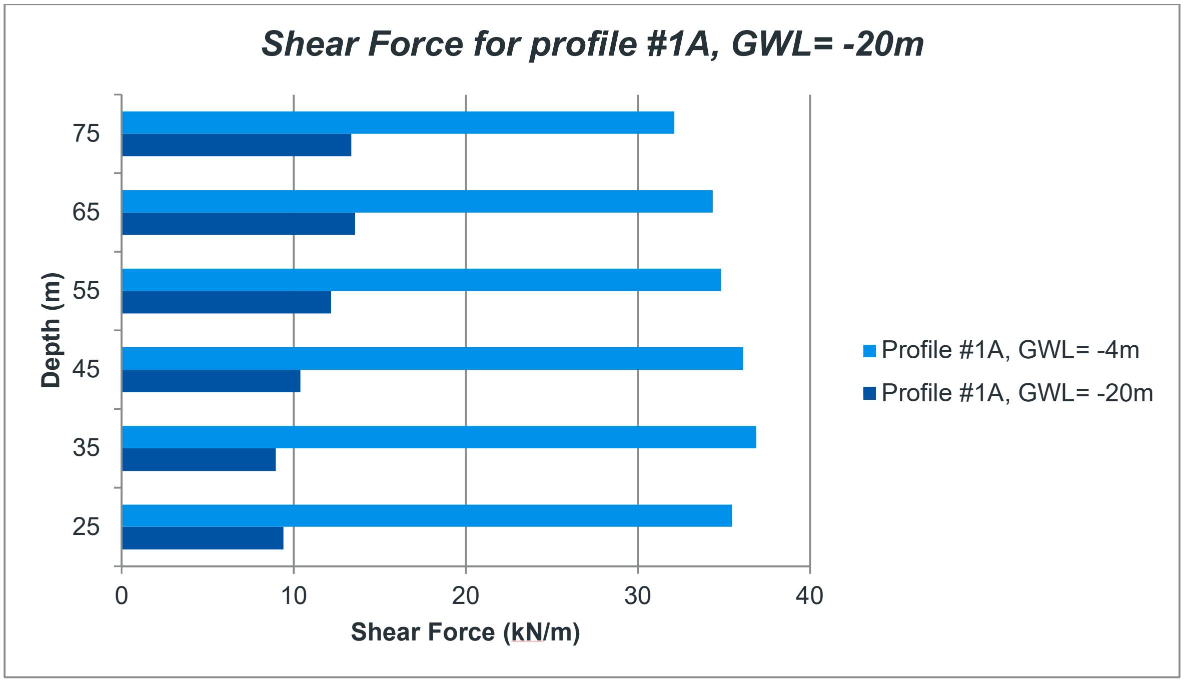



**Figure 150: Shear Force bar diagram, #1A, GWL=-20m**

### 5.4.7. Shear Force #1A, GWL= -60m

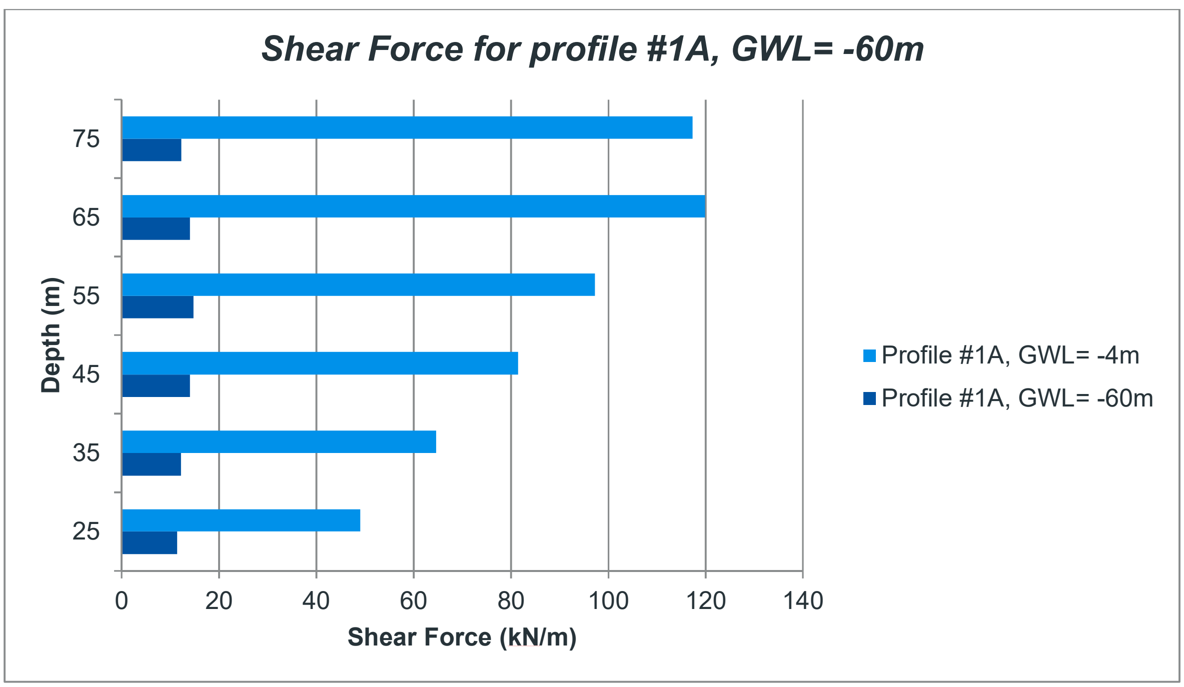



**Figure 151: Shear Force bar diagram, #1A, GWL=-60m**

### 5.4.8. Volume Loss, #1A, GWL= -20m

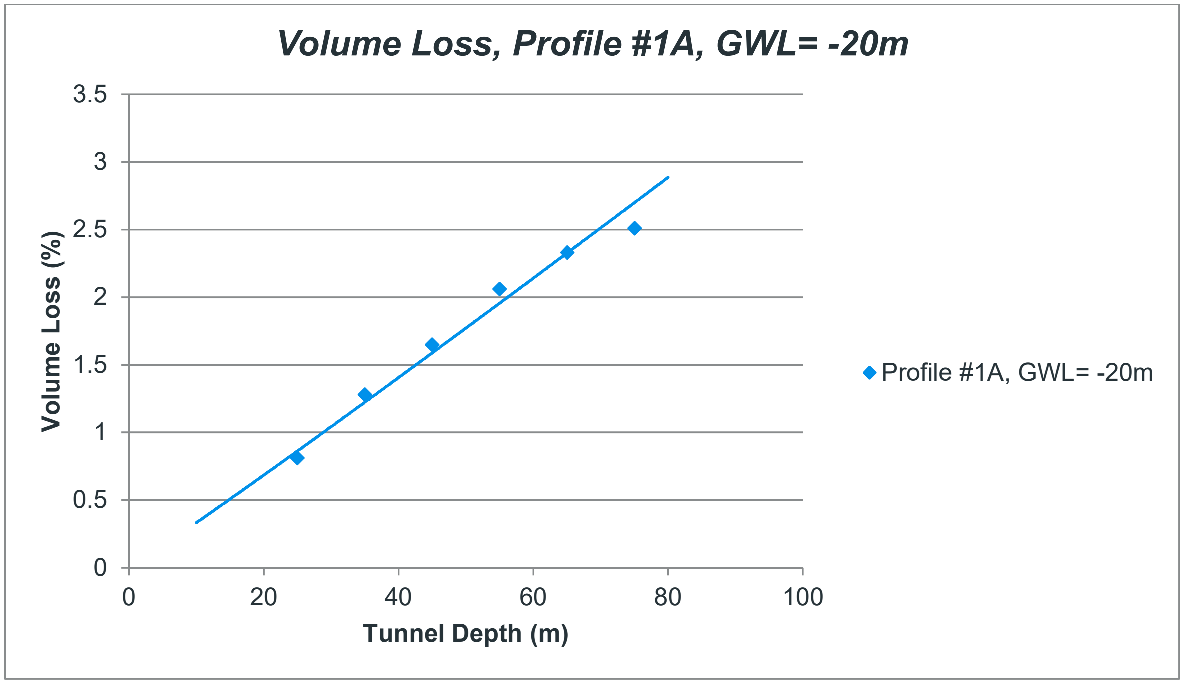



**Figure 152: Volume Loss vs Tunnel depth, #1A, GWL=-20m**

### 5.4.9. Volume Loss, #1A, GWL= -60m

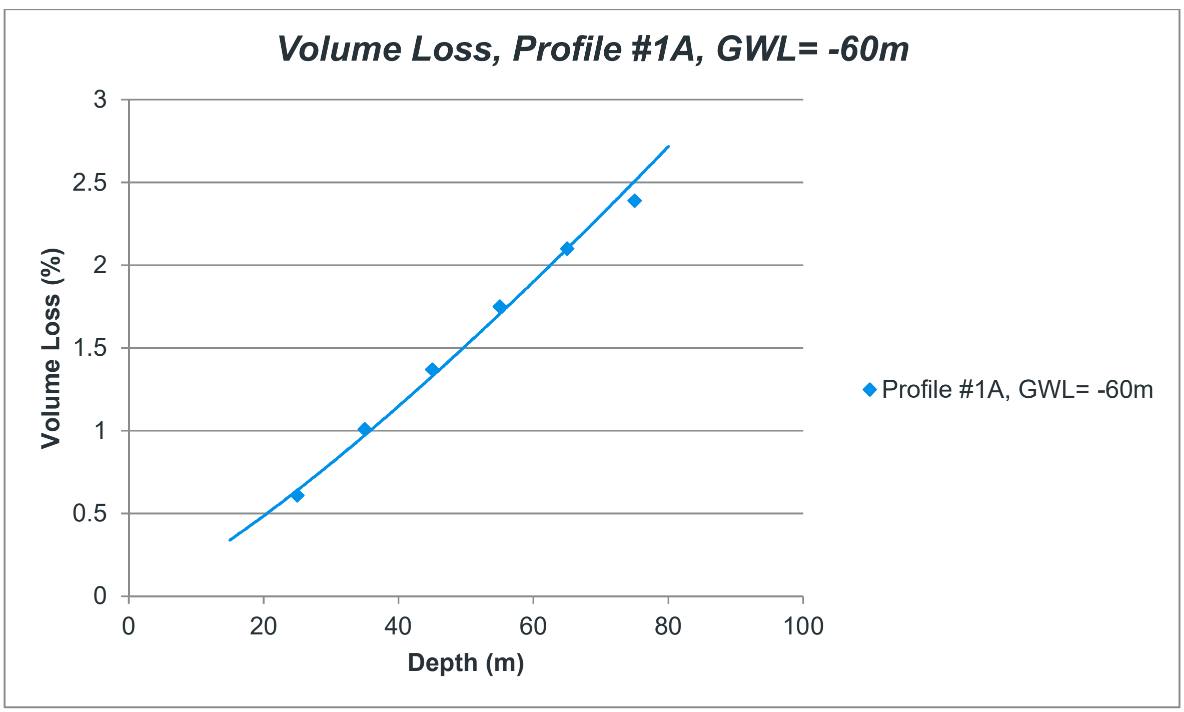



**Figure 153: Volume Loss vs Tunnel depth, #1A, GWL=-60m**

## 5.5. Discussion

From the results we can observe that as the depth of the tunnel excavation from the surface increases, the surface settlement induced by excavation decreases. And it is also observed that the settlement trough becomes wider as the depth of the tunnel excavation increases. These findings agree with the results obtained by Shahin et al., (2004) which states as the soil cover over the tunnel increases, the settlement trough becomes wider.

It can also be seen that, at Phase 4 to maintain a surface settlement of 10mm, the required grouting increases as the depth of the tunnel increases. It can also be observed that the required grouting is higher at shallower GWLs, where the tunnel is below the GWL. The reason for this is that as the tunnel depth increases or when the tunnel is below the GWL, the total stress on the tunnel increases. And to resist that stress higher grouting pressure is needed. And it is also observed that as the depth of the tunnel or depth of the cover soil increases, the volume loss of the tunnel also increases. For shallow tunnels, surface settlement is more dependent on crown drift rather than volume loss, but for deep tunnels, volume loss governs surface settlement (Shahin et al., 2011). So as the tunnel gets deeper the surface settlement becomes more dependent on volume loss. So, the volume loss increases with depth of tunnel excavation for maintaining a certain surface settlement.

From the study it can also be observed that Axial forces experienced by the lining increases as the depth of the tunnel increases. Also, the axial force experienced is much greater in shallow GWL conditions where the tunnel is under the GWL. And if the tunnel was above the GWL during the original GWL condition, then when the GWL rises the Axial force experienced by the tunnel lining also increases. Otherwise, if the tunnel was below the GWL in original GWL condition, the rise in GWL doesn't affect axial forces in the lining. This increase in axial force occurs due the build up of pore water pressure around the tunnel lining when the tunnel is below the GWL. Also, the Bending moment and Shear forces experienced by the tunnel lining increases as the GWL rises in the future regardless of tunnel position in the original GWL condition. This occurs due the change in total stress on tunnel lining due to the rise in GWL.

# CHAPTER 6. CONCLUSION & RECOMMENDATIONS

## 6.1. Conclusion

From our analysis the conclusion we have reached are as follows:

1) As the depth of the tunnel increases, excavation-induced surface settlement decreases.
2) Axial Force of tunnel increases as the depth of the tunnel increases.
3) Volume loss increases as the depth of the tunnel increases.
4) If the tunnel was above Groundwater level. The rise in Groundwater level over the tunnel causes the Axial Forces, Bending Moment, and Shear Forces to increase in the tunnel lining. Otherwise only Bending Moment and Shear Forces increase as the Groundwater level increases.
5) For tunnel design, shallow tunnels must be given special consideration to control surface settlement caused by excavation.
6) For lining design, special consideration must be given to tunnels in deeper depths and shallower Groundwater level, as the lining stresses are higher in those conditions.
7) As depth increases, more grouting pressure is needed for achieving a safe level of settlement
8) Higher Grouting Pressure is required for shallow Groundwater levels. Also tunnels of higher depth requires higher Grout Pressure to achieve safe amount of settlement
9) If the water level rises to -4m, the surface is predicted to heave

## 6.2. Further Study

1) The Study could be conducted considering building loads from shallow and piled foundations.
2) Drained drainage conditions can be used for clay type soils and compared.
3) 3D finite element analysis can be carried out to determine more accurate lining forces and 3D behavior of soil.
4) Ground response for different types of excavation methods such as NATM or Cut and Cover method can also be considered.

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- *Volume loss due to tunnelling: Calculating volume loss directly from tunnel deformation in Plaxis – Dingbat Data*. (n.d.). Retrieved May 25, 2022, from https://www.dingbatdata.com/2017/11/19/volumelossinplaxis/

# APPENDIX

## Appendix A: Tabulated Data of max Axial Force, Shear Force and Bending Moment

| | Profile #1A, GWL= -60m | | | Profile #1A, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **25** | 1470 | 11.4 | 13.84 | 1481 | 49.01 | 127.1 |
| **35** | 2033 | 12.15 | 13.45 | 2035 | 64.59 | 173.6 |
| **45** | 2605 | 13.99 | 14.63 | 2605 | 81.44 | 223.1 |
| **55** | 3180 | 14.78 | 15.27 | 3180 | 97.24 | 270.4 |
| **65** | 3850 | 14.02 | 16.62 | 3850 | 119.9 | 315.4 |
| **75** | 4609 | 12.2 | 19.45 | 4609 | 117.3 | 311.3 |

| | Profile #1A, GWL= -20m | | | Profile #1A, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **25** | 1557 | 9.405 | 11.54 | 1556 | 34.2 | 100.1 |
| **35** | 2310 | 8.952 | 11.34 | 2724 | 36.45 | 85.33 |
| **45** | 3068 | 10.38 | 11.42 | 3622 | 36.16 | 90.41 |
| **55** | 3834 | 12.16 | 12.83 | 4525 | 33.49 | 87.52 |
| **65** | 4610 | 13.57 | 14.8 | 5439 | 36.35 | 90.7 |
| **75** | 5361 | 13.33 | 19.73 | 6344 | 33.4 | 92.78 |

| | Profile #1B, GWL= -60m | | | Profile #1B, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **30** | 1848 | 4.34 | 11.58 | 1989 | 44.77 | 119.1 |
| **40** | 2373 | 37.67 | 23.2 | 2385 | 74.26 | 195.5 |
| **50** | 2894 | 13.66 | 14.51 | 2894 | 86.51 | 247.3 |

| Profile #1B, GWL= -20m | | | | Profile #1B, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **30** | 1996 | 6.011 | 11.73 | 1996 | 23.08 | 51.47 |
| **40** | 2680 | 32.81 | 21.24 | 2680 | 32.81 | 38.17 |
| **50** | 3388 | 10.08 | 12.91 | 3388 | 36.99 | 93.51 |

| Profile #2A, GWL= -60m | | | | Profile #2A, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **25** | 1504 | 14.16 | 16.88 | 1569 | 51.94 | 139.6 |
| **50** | 2899 | 14.67 | 15.06 | 2914 | 101.6 | 268.6 |
| **75** | 4628 | 15.39 | 18.76 | 4628 | 131.1 | 338.6 |

| Profile #2A, GWL= -20m | | | | Profile #2A, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **25** | 1583 | 12.56 | 15.04 | 1583 | 40.16 | 107.7 |
| **50** | 3452 | 10.79 | 11.94 | 3452 | 39.09 | 94.49 |
| **75** | 5374 | 13.48 | 14.44 | 5374 | 34.46 | 85.08 |

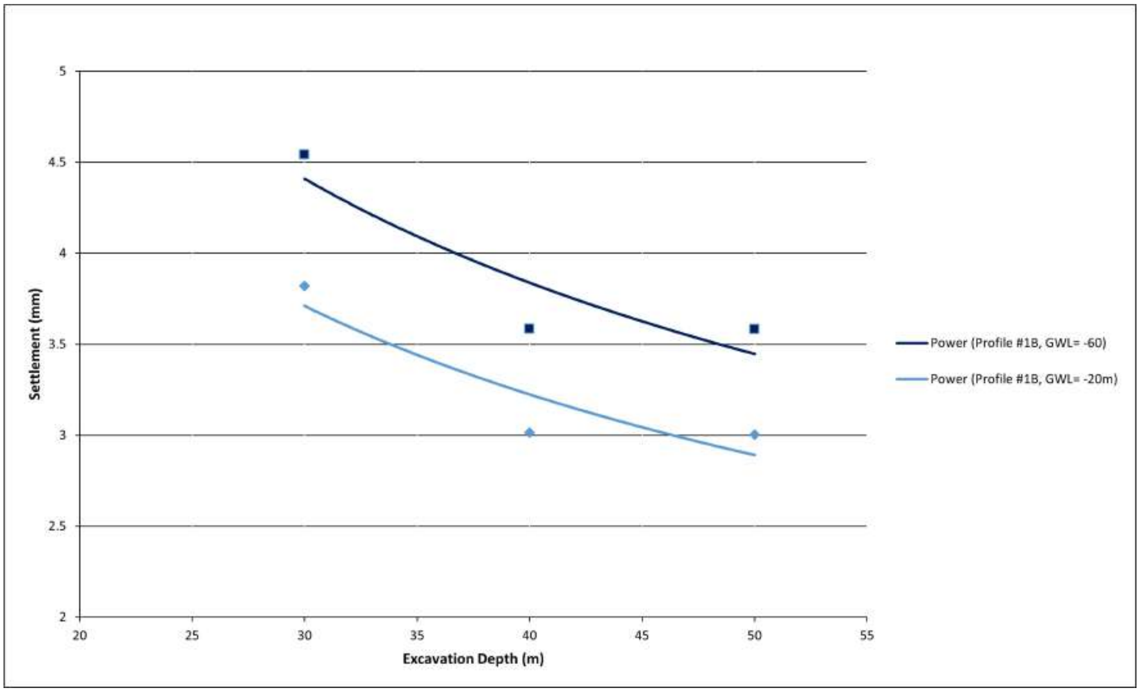
| Profile #2B, GWL= -60m | | | | Profile #2B, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **35** | 2143 | 4.223 | 12 | 2347 | 60.13 | 154.7 |
| **45** | 2667 | 40.48 | 23.62 | 2701 | 86.54 | 223.8 |
| **55** | 3180 | 15.24 | 14.98 | 3180 | 100.6 | 275.7 |

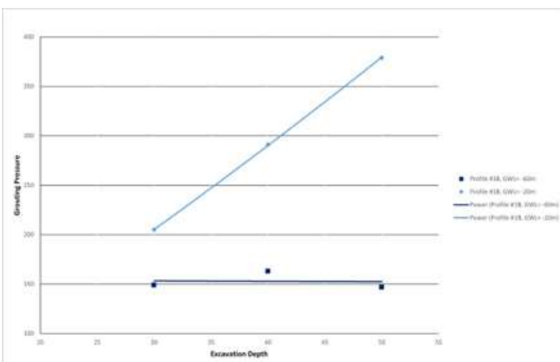
| Profile #2B, GWL= -20m | | | | Profile #2B, GWL= -4m | | |
|---|---|---|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **35** | 2365 | 6.856 | 13.41 | 2365 | 35.44 | 88.48 |
| **45** | 3051 | 34.41 | 22.66 | 3051 | 34.41 | 56.13 |
| **55** | 3756 | 11.23 | 12.93 | 3756 | 38.09 | 95.65 |

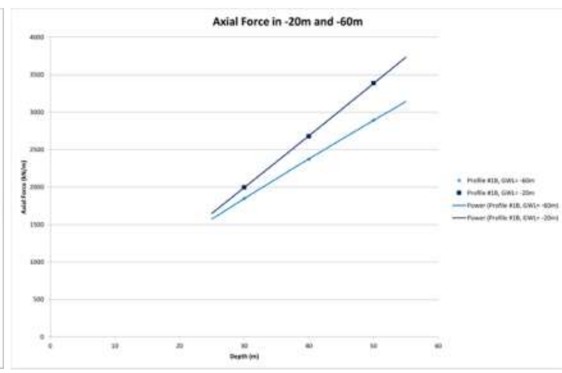
| Profile #3A, GWL= -4m | | | |
|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **45** | 3362 | 10.83 | 14.39 |
| **60** | 4498 | 11.41 | 13.01 |
| **75** | 5652 | 13.02 | 22.76 |

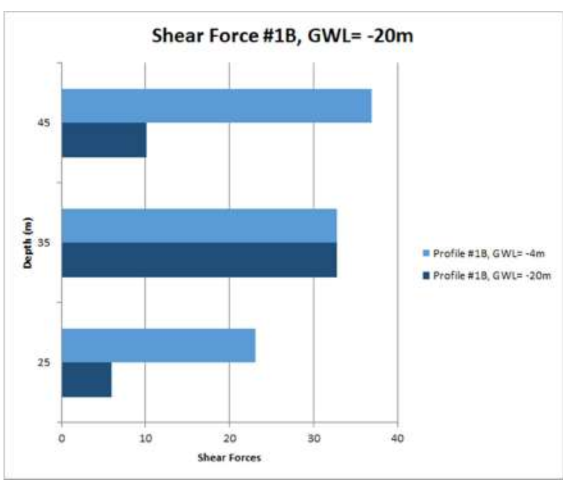
| Profile #3B, GWL= 11m | | | |
|---|---|---|---|
| **Tunnel depth(m)** | **Max Axial Force(kN/m)** | **Max Shear Forces(kN/m)** | **Max Bending moment(kNm/m)** |
| **35** | 3180 | 8.93 | 15.1 |
| **45** | 4644 | 10.17 | 13.8 |
| **60** | 5168 | 12.26 | 22.19 |

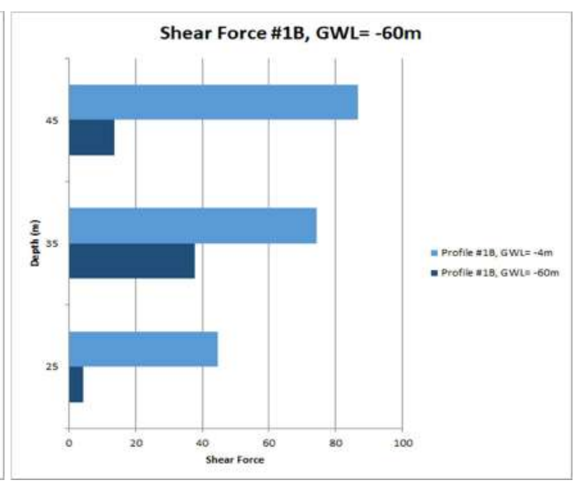
# Appendix B: Graphs for Profiles #1B, #2A, #2B, #3A, #3B

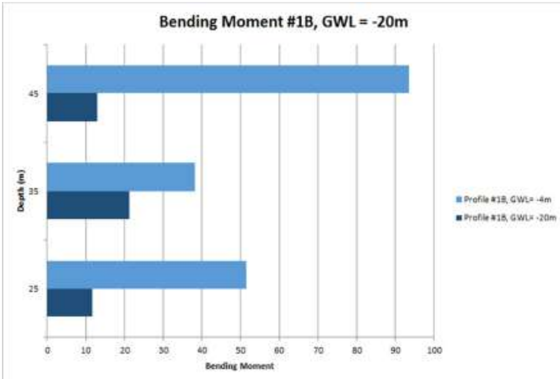


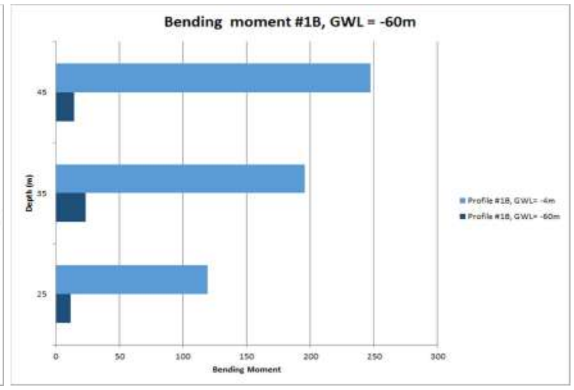



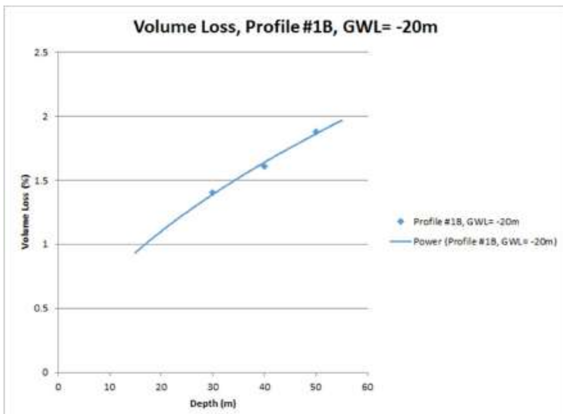


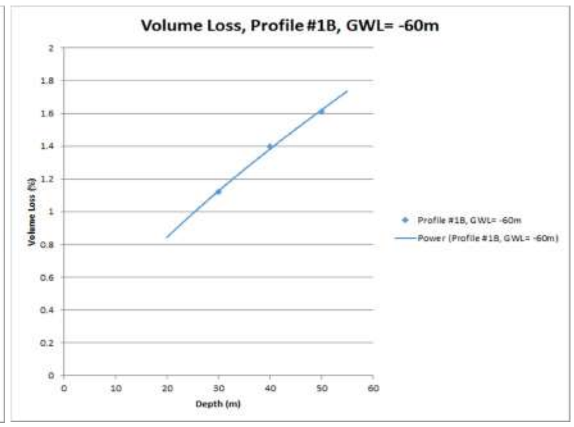



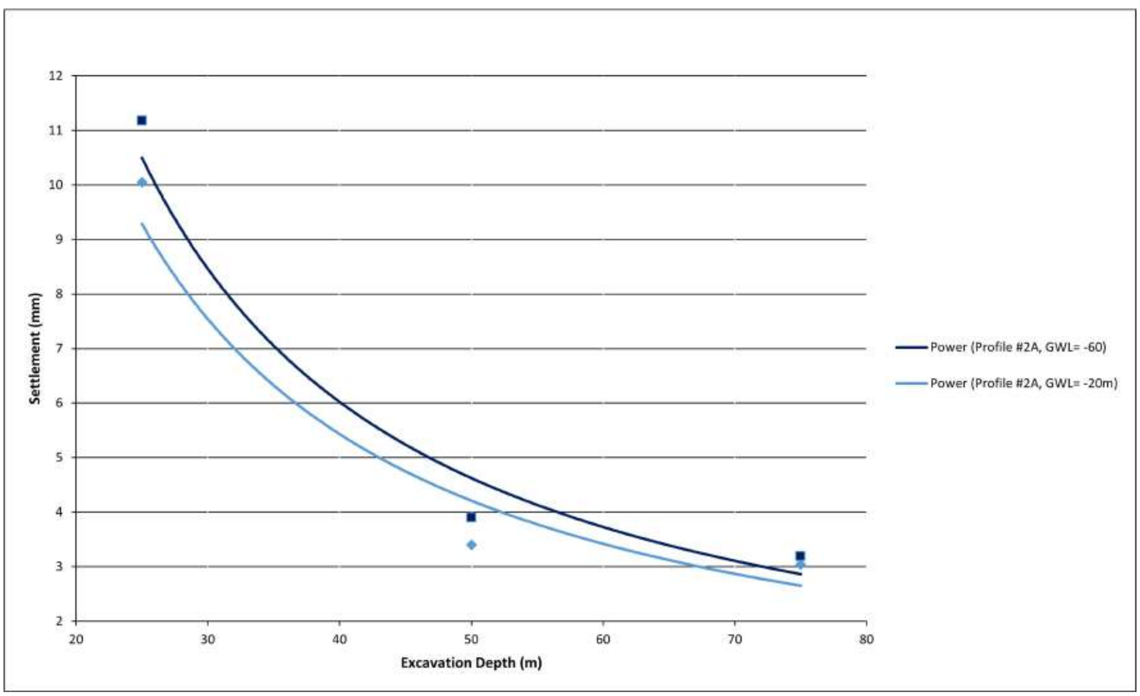



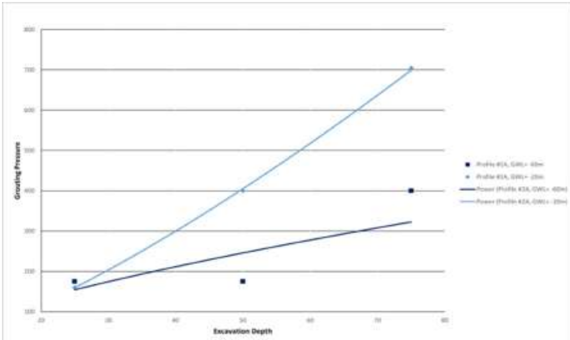

Bending Moment #1B, GWL = -20m
Depth (m)
45
35
25
0
10
20
30
40
50
60
70
80
90
100
Bending Moment
Profile #1B, GWL= -4m
Profile #1B, GWL= -20m

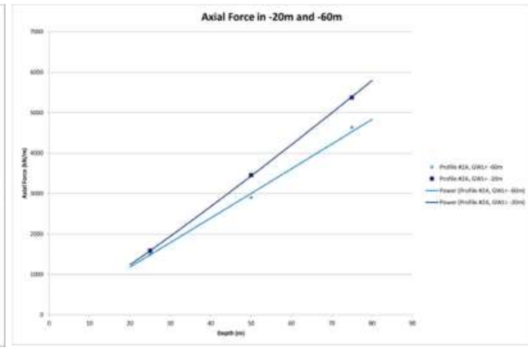

Bending moment #1B, GWL = -60m
Depth (m)
45
35
25
0
50
100
150
200
250
300
Bending Moment
Profile #1B, GWL= -4m
Profile #1B, GWL= -60m

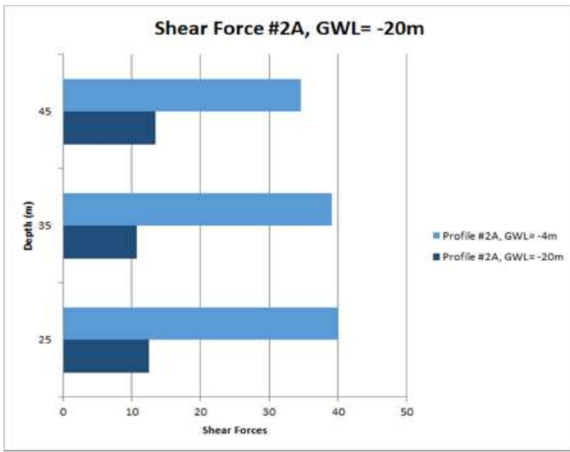

Volume Loss, Profile #1B, GWL= -20m
Volume Loss (%)
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
Depth (m)
Profile #1B, GWL= -20m
Power (Profile #1B, GWL= -20m)

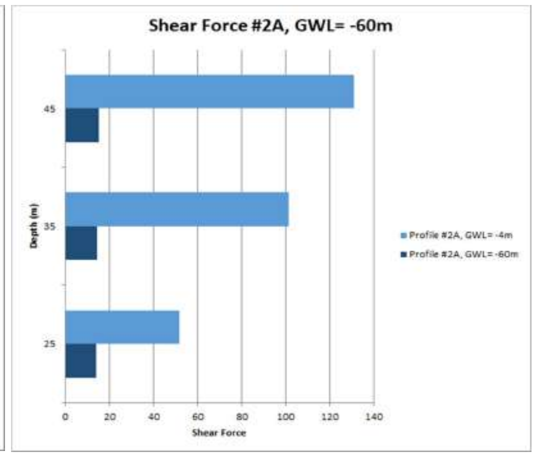

Volume Loss, Profile #1B, GWL= -60m
Volume Loss (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
Depth (m)
Profile #1B, GWL= -60m
Power (Profile #1B, GWL= -60m)

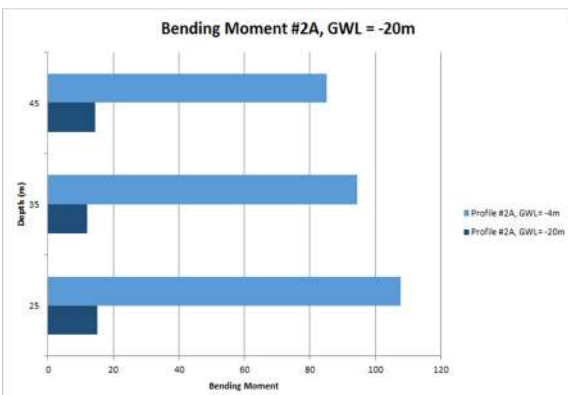

12
11
10
9
8
7
6
5
4
3
2
Settlement (mm)
20
30
40
50
60
70
80
Excavation Depth (m)
Power (Profile #2A, GWL= -60)
Power (Profile #2A, GWL= -20m)

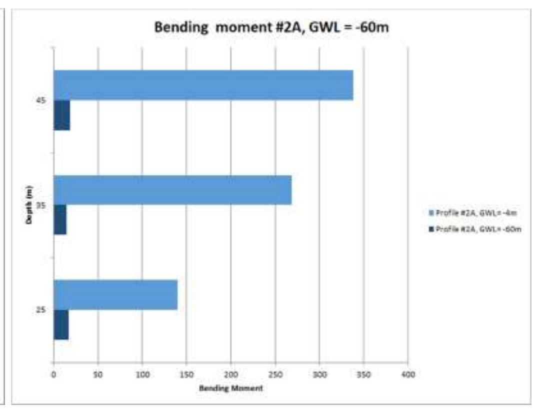

Grouting Pressure
Excavation Depth

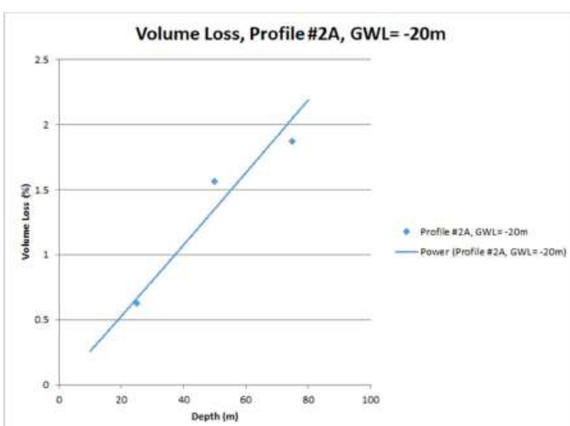

Axial Force in -20m and -60m
7000
6000
5000
4000
3000
2000
1000
0
Axial Force (kN/m)
0
10
20
30
40
50
60
70
80
90
Depth (m)

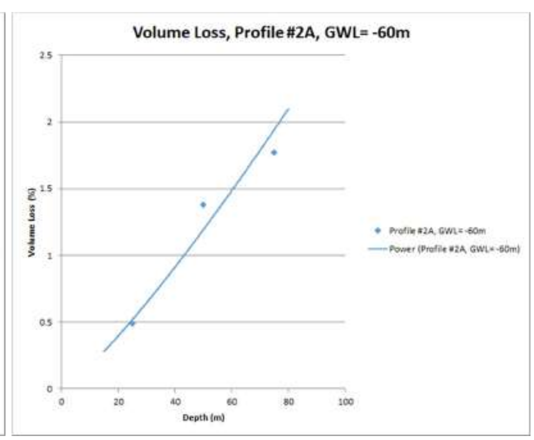

Shear Force #2A, GWL= -20m
45
35
25
Depth (m)
0
10
20
30
40
50
Shear Forces
Profile #2A, GWL= -4m
Profile #2A, GWL= -20m

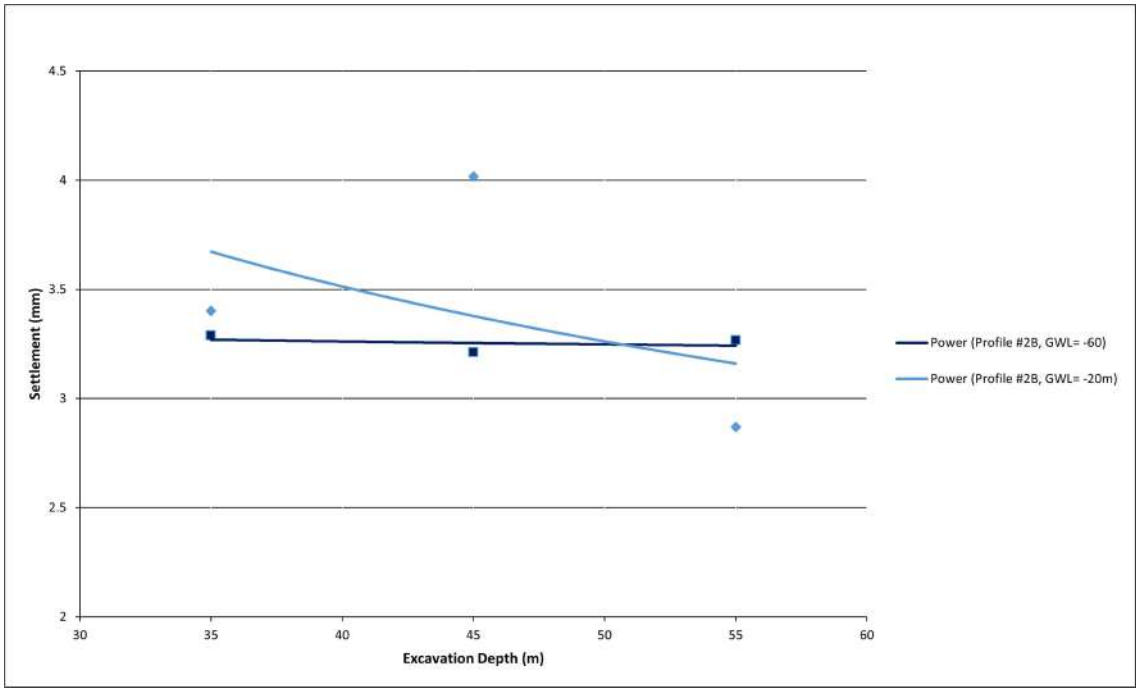

Shear Force #2A, GWL= -60m
45
35
25
Depth (m)
0
20
40
60
80
100
120
140
Shear Force
Profile #2A, GWL= -4m
Profile #2A, GWL= -60m

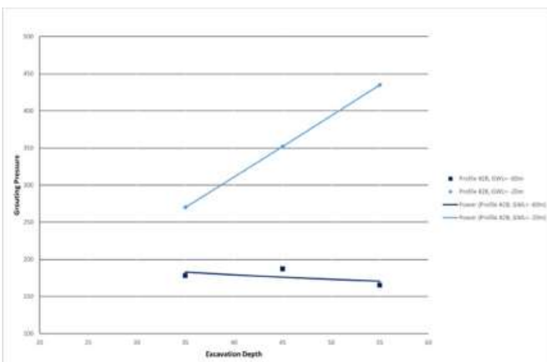

Bending Moment #2A, GWL = -20m
45
35
25
Depth (m)
0
20
40
60
80
100
120
Bending Moment
Profile #2A, GWL= -4m
Profile #2A, GWL= -20m

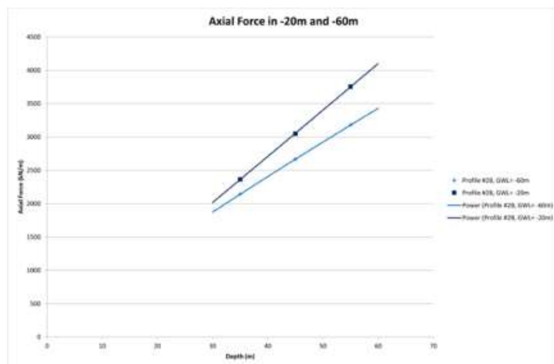

Bending moment #2A, GWL = -60m
45
35
25
Depth (m)
0
50
100
150
200
250
300
350
400
Bending Moment
Profile #2A, GWL= -4m
Profile #2A, GWL= -60m

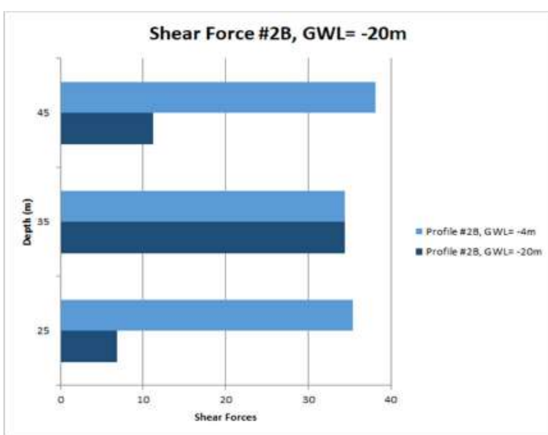

Volume Loss, Profile #2A, GWL= -20m
2.5
2
1.5
1
0.5
0
Volume Loss (%)
0
20
40
60
80
100
Depth (m)
Profile #2A, GWL= -20m
Power (Profile #2A, GWL= -20m)

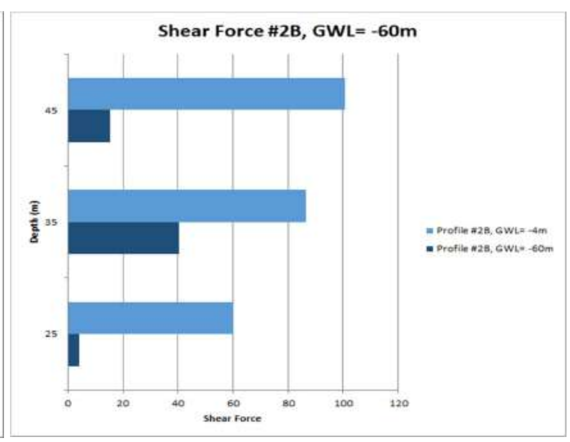

Volume Loss, Profile #2A, GWL= -60m
2.5
2
1.5
1
0.5
0
Volume Loss (%)
0
20
40
60
80
100
Depth (m)
Profile #2A, GWL= -60m
Power (Profile #2A, GWL= -60m)

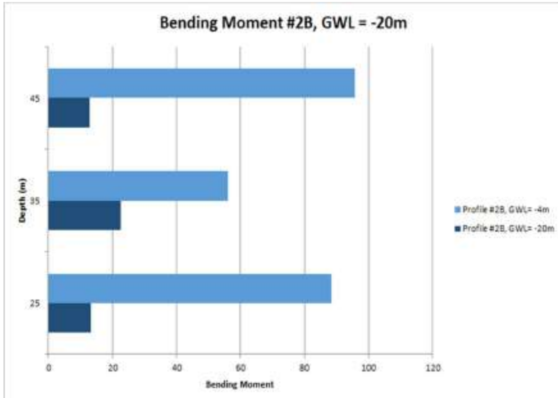

4.5
4
3.5
3
2.5
2
Settlement (mm)
30
35
40
45
50
55
60
Excavation Depth (m)
Power (Profile #2B, GWL= -60)
Power (Profile #2B, GWL= -20m)

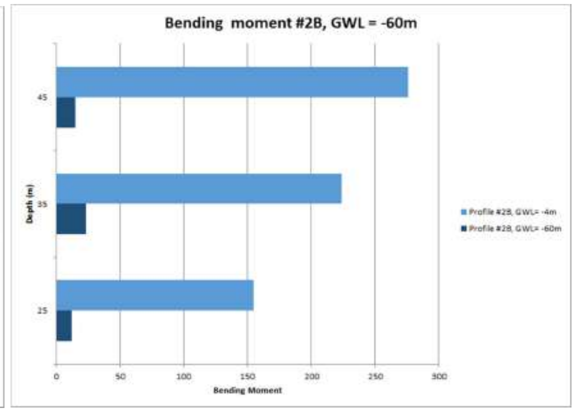

Grouting Pressure
Excavation Depth

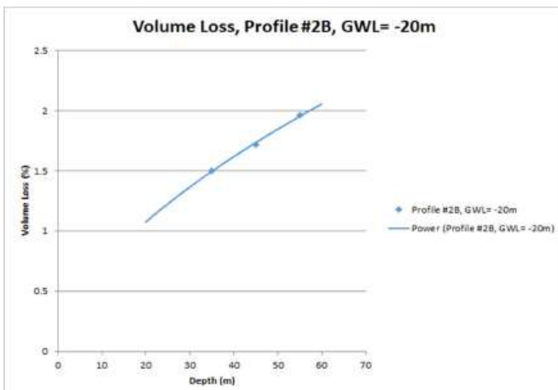

Axial Force in -20m and -60m
Depth (m)

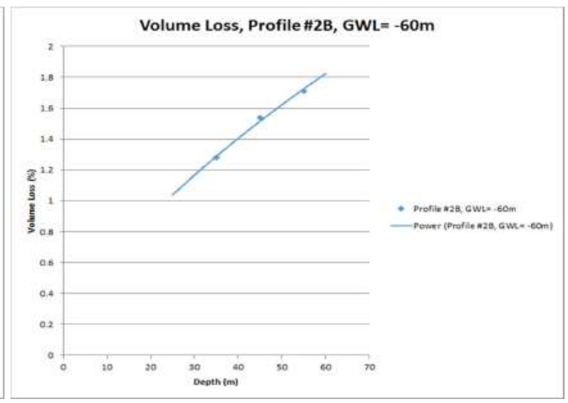

Shear Force #2B, GWL= -20m
45
35
25
Depth (m)
0
10
20
30
40
Shear Forces
Profile #2B, GWL= -4m
Profile #2B, GWL= -20m

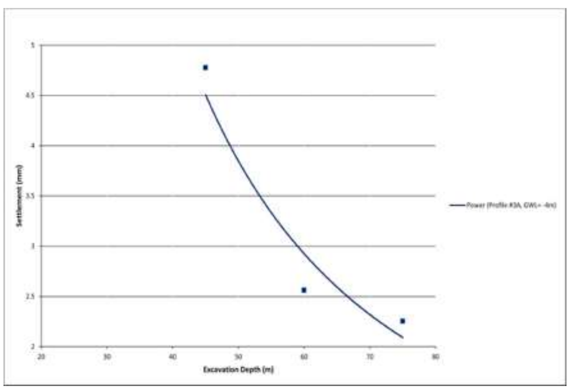

Shear Force #2B, GWL= -60m
45
35
25
Depth (m)
0
20
40
60
80
100
120
Shear Force
Profile #2B, GWL= -4m
Profile #2B, GWL= -60m

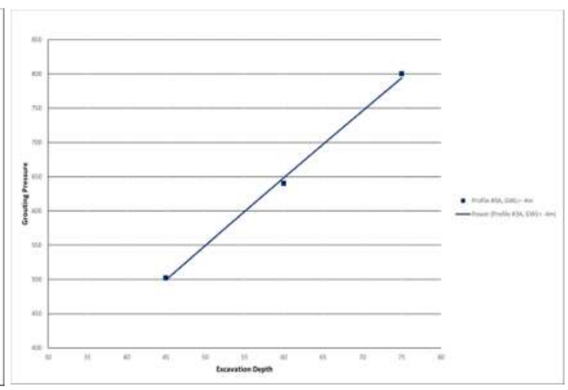

Bending Moment #2B, GWL = -20m
Depth (m)
Bending Moment
Profile #2B, GWL= -4m
Profile #2B, GWL= -20m

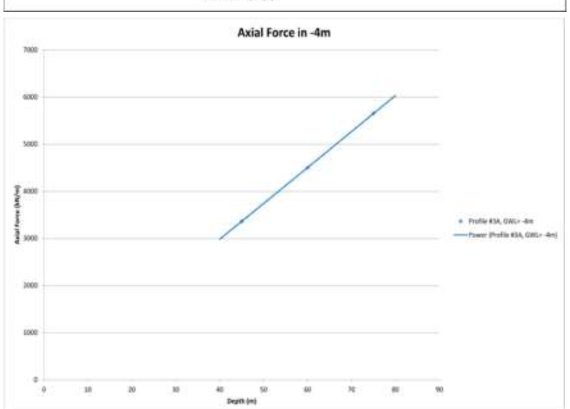

Bending moment #2B, GWL = -60m
Depth (m)
Bending Moment
Profile #2B, GWL= -4m
Profile #2B, GWL= -60m

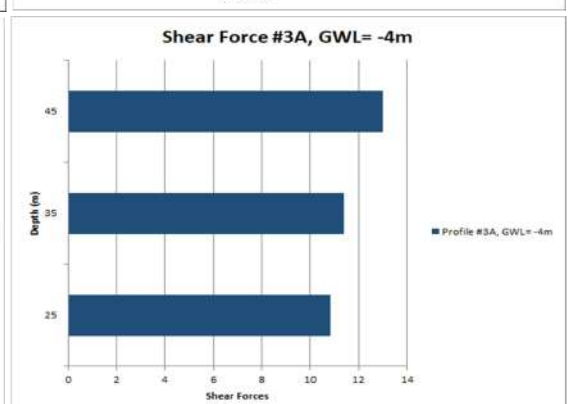

Volume Loss, Profile #2B, GWL= -20m
Volume Loss (%)
Depth (m)
Profile #2B, GWL= -20m
Power (Profile #2B, GWL= -20m)

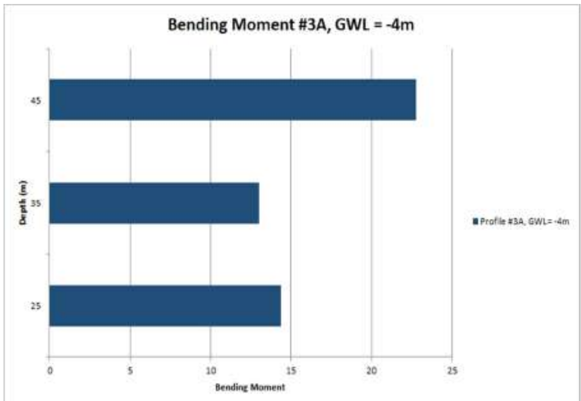

Volume Loss, Profile #2B, GWL= -60m
Volume Loss (%)
Depth (m)
Profile #2B, GWL= -60m
Power (Profile #2B, GWL= -60m)

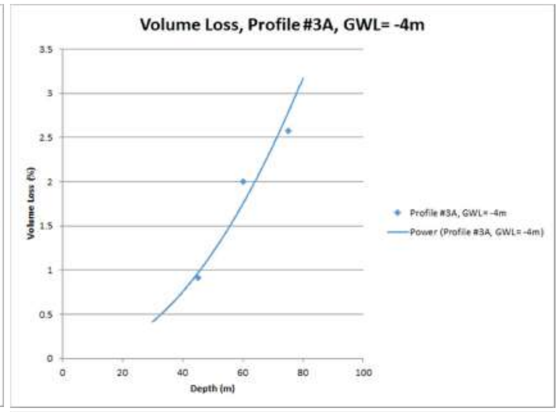

Excavation Depth (m)

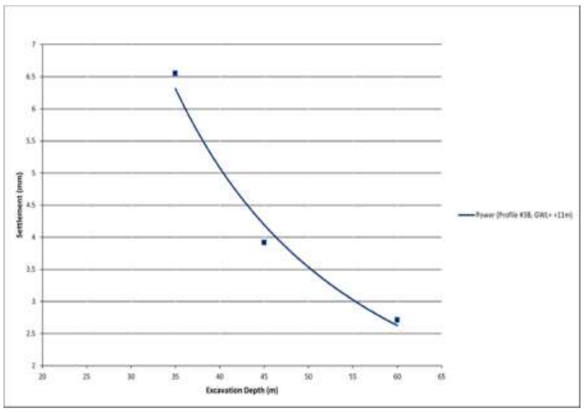

Grouting Pressure
Excavation Depth

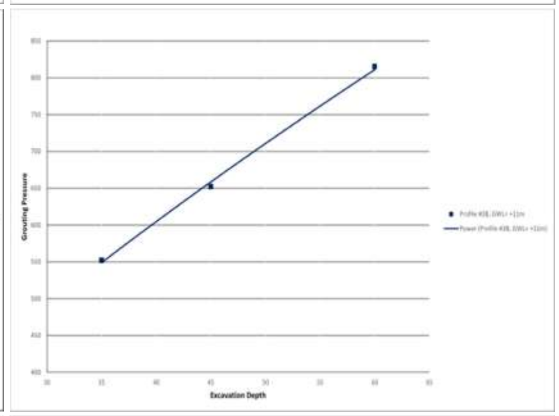

Axial Force in -4m

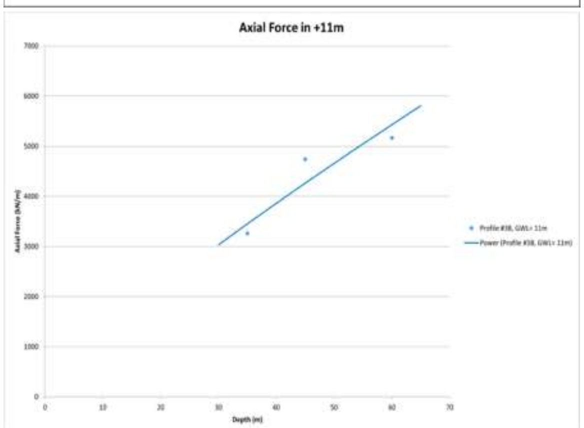

Shear Force #3A, GWL= -4m
Depth (m)
Shear Forces
Profile #3A, GWL= -4m

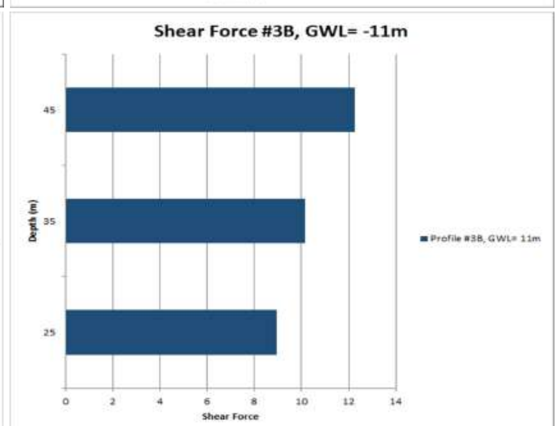

Bending Moment #3A, GWL = -4m
Depth (m)
Bending Moment
Profile #3A, GWL= -4m

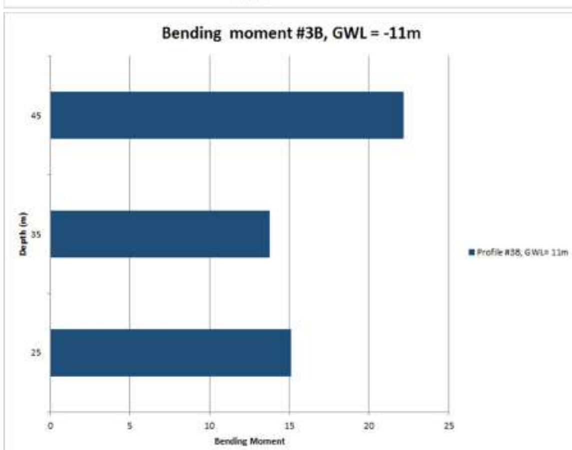

Volume Loss, Profile #3A, GWL= -4m
Volume Loss (%)
Depth (m)
Profile #3A, GWL= -4m
Power (Profile #3A, GWL= -4m)

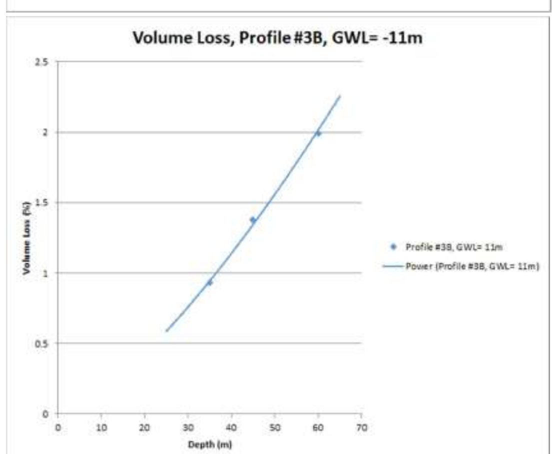

Settlement (mm)
Excavation Depth (m)


Grouting Pressure
Excavation Depth


Axial Force in +11m
Depth (m)


Shear Force #3B, GWL= -11m
Depth (m)
Shear Force
Profile #3B, GWL= 11m


Bending moment #3B, GWL = -11m
Depth (m)
Bending Moment
Profile #3B, GWL= 11m


Volume Loss, Profile #3B, GWL= -11m
Volume Loss (%)
Depth (m)
Profile #3B, GWL= 11m
Power (Profile #3B, GWL= 11m)