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Study on the tunnel axial deformation mechanism and numerical simulation of three-dimensional finite element method

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Abstract

Recently, optical method has been adopted in tunnel convergence measurement at several long tunnel constructions both in Germany and Austria. The new convergence measurement is essentially a three dimensional and absolute measurement method, it has been observed, therefore, obvious axial deformation during the construction of tunnels.

In this paper, the mechanism of axial deformation of tunnels is analyzed in theory. And the tunnel axial deformation under various states are analyzed in detail by means of numerical simulation of three dimensional finite element method. It has been demonstrated both in theoretical analysis and three dimensional finite element calculations that the major factor leading to the tunnel axial deformation is that the initial geostress state of the tunnel area is 'inclined'.

1 Introduction

A new tunnel convergence measurement based on optical means came into being in Austria. In the last four years this method of optical convergence measurement has been applied in the constructions of four long tunnels, including Channel Tunnel across Pas de Calais, Innstal Tunnel of Austria (12.7km) and Nantenbach Tunnel of Germany (3.9km). Since this new method is a three dimensional measurement method and the result obtained is the absolute displacement, it has been observed, therefore, obvious axial deformation during the tunnel constructions, and such axial deformation is of universal significance.

Figure 1 gives out the time variation curve of ratio α between axial and vertical deformations at three measurement points (L,C,R) arranged on the roof of the tunnel 2753 meters away from the north portal of Innstal Tunnel in Austria.

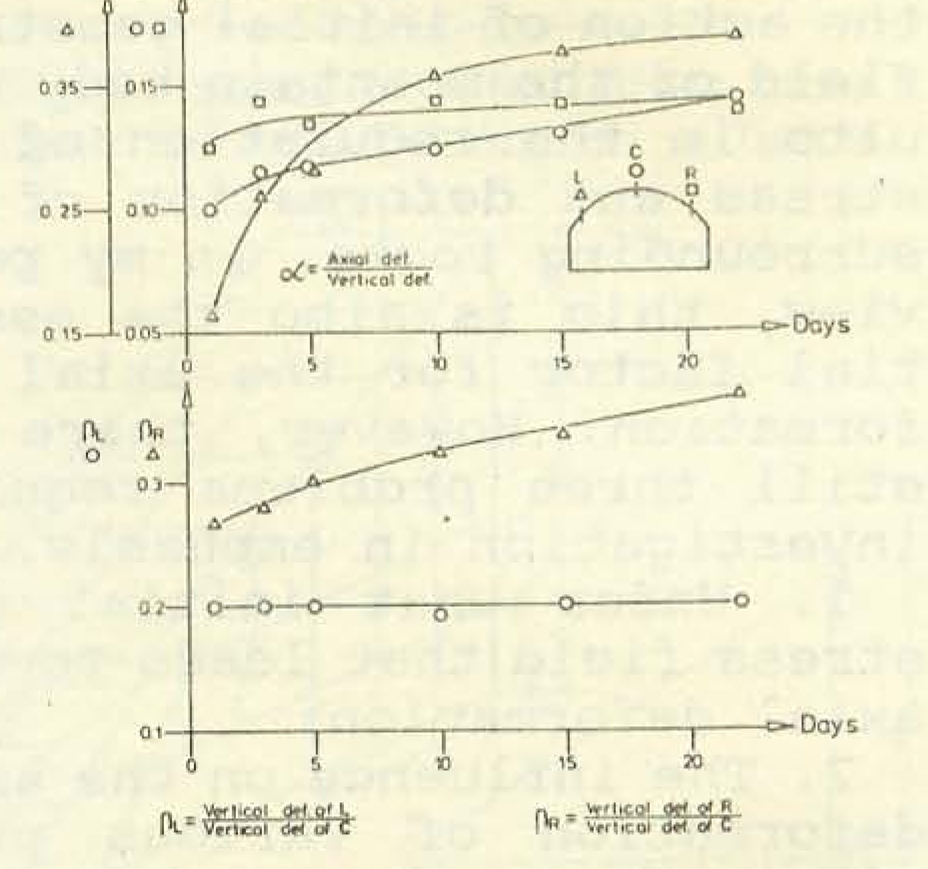


Fig.1 Measurement Curves of a railway long tunnel in Austria

The long tunnel axial deformation observed at present has the following features:

1. If the tunnel is divided into left and right parts, their axial deformations of the roof are usually pointing to their own portals

2. The axial deformation at the point on the roof is ob-

vious. The ratio between axial and vertical displacements could reach as high as 15% (see Figure 1).

3. With the increase of time, i.e. with the increase of the distance between the excavation face and the measurement section, this ratio between axial and vertical displacements increases gradually and becomes to be stable.

Axial deformation during the construction of tunnels is a new problem, and there has not been any study on its reason. This paper is the first attempt on the problem.

2 Mechanism Analysis on Axial Deformation of Tunnels

The most essential factor leading to the deformation around the tunnel during the excavation should be said to that the excavation unloading under the action of initial geostress field of the mountain body results in the regulation of the stress and deformation of the surrounding rocks. In my point view, this is also the essential factor for the axial deformation. However, there are still three problems required investigation in emphasis.

1. Under what initial geostress field that leads to what axial deformation;
2. The influence on the axial deformation of various principal stresses among the initial geostress field; and
3. The influence on the axial deformation of the local three dimensional effects near the excavation face.

In this paper, the relationship is analyzed between the two most essential models of initial geostress fields and the tunnel axial deformation. Since these two models are typical, they can be used to deduce the situations under other models.

2.1 *Model I of Initial Geostress Field*

This model is diagrammatically represented in Table 1.

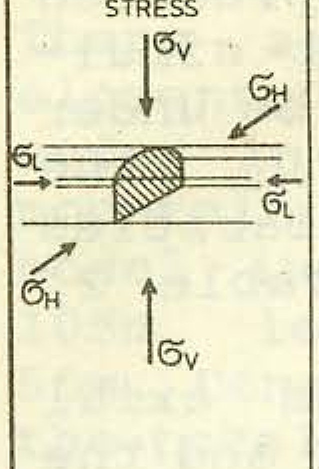
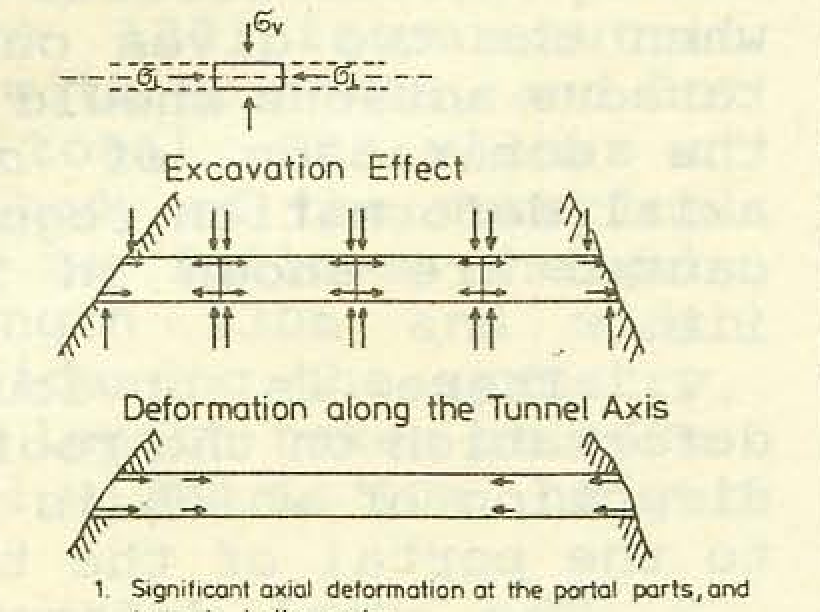
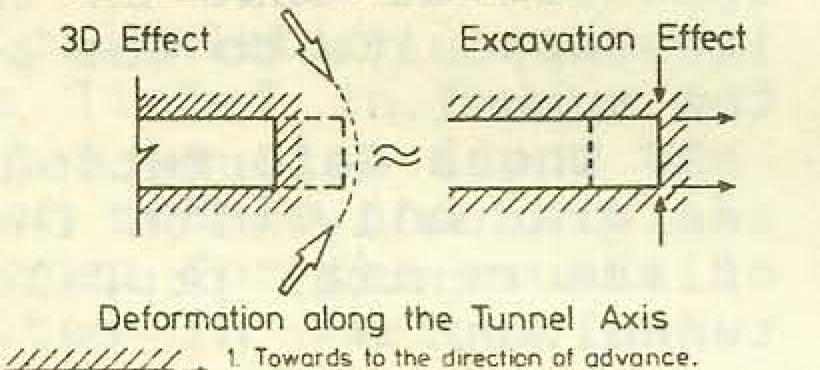
The action planes of two principal stresses σ_v and σ_H are the cross sections of the tunnel, however, σ_v and σ_H are not necessarily vertical or horizontal. In order to be concise in the following analysis they are treated both in vertical and horizontal directions.

2.1.1 *Influence on the axial deformation of σ_v and σ_H*

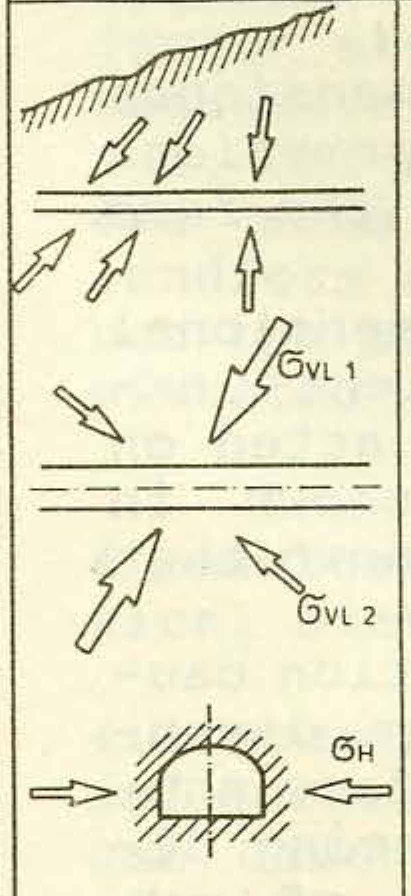
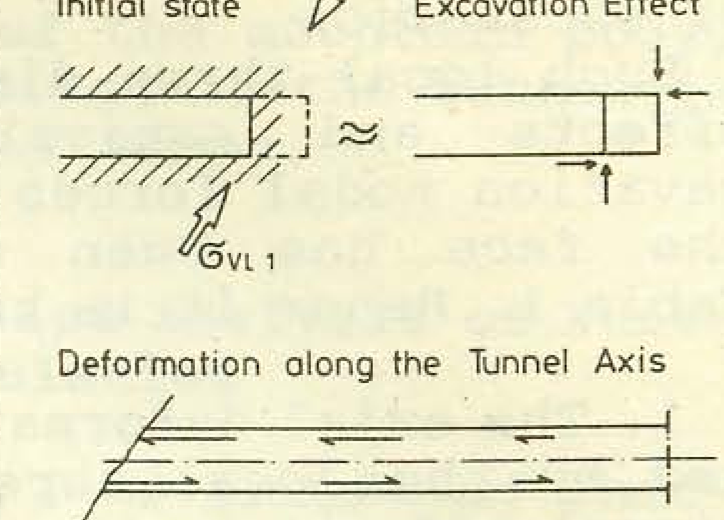
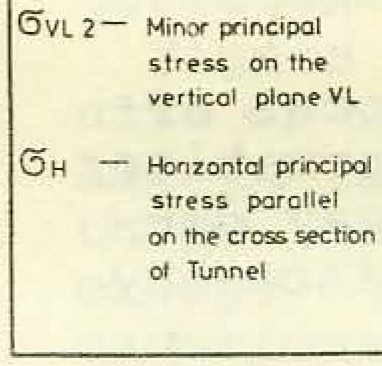
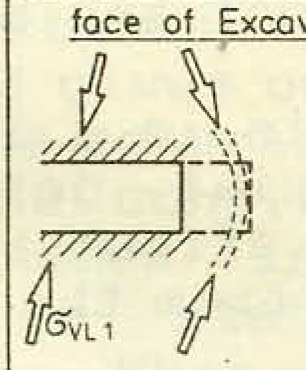
It is known that σ_v and σ_H are the most essential factors leading to the deformation of tunnel cross sections. Since the action planes of σ_v and σ_H are orthogonal to the tunnel axis, it can be deduced, in respect to the plane deformation concept, it is impossible for them to result in obvious axial deformation.

2.1.2 *Influence of the axial initial geostress σ_L*

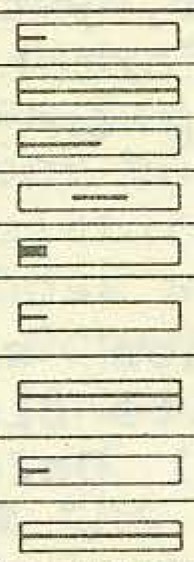
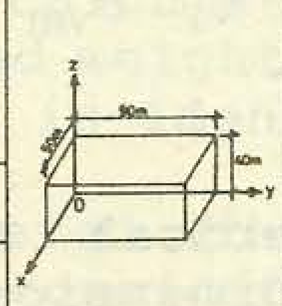
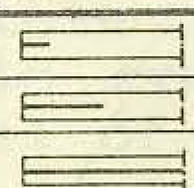
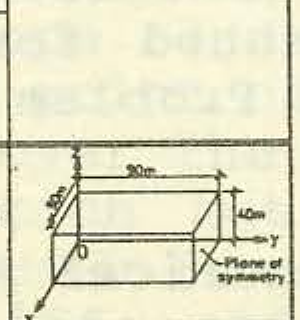
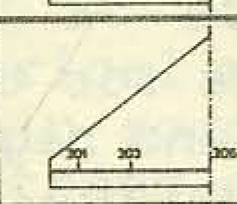
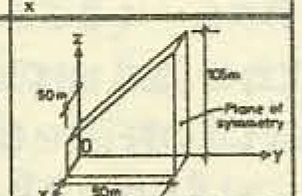
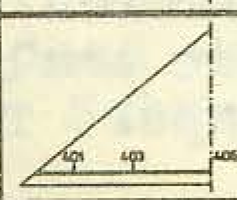
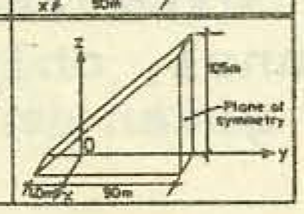
The initial stress state prior to the tunnel excavation and the corresponding excavation effects can be simplified into what is given in Table 1. Except the portal areas, the effect of the axial stress σ_L of other areas resulted from the excavation unloading are equivalently opposite to the same cross section. Generally, it is impossible to have axial deformation along the tunnel axis, only near the portal it is possible, where the directions of axial

Initial stress state I	Effect upon the Deformation of the Tunnel along the Longitudinal Axis
	a. General Effect of σ_V and σ_H No significant influence because the normality with the longitudinal axis. b. General Effect of σ_L Initial state (Longitudinal section)  1. Significant axial deformation at the portal parts, and towards to the center. 2. No significant effect after some distance from portals.
σ_V – Vertical principal stress σ_H – Horizontal principal stress parallel to the cross section of Tunnel σ_L – Horizontal principal stress parallel to the longitudinal axis of Tunnel	c. Local 3D Effect of σ_V and σ_H in the Region near the face of Excavation  1. Towards to the direction of advance. 2. Axial Deformation on the Top and Bottom are the same Directions. 3. At the cross section out of the local effect region the axial deformation will be return back to "zero".

Tab.1: The Influence of Initial stress state I upon the Axial Deformation of Tunnel

Initial stress state II	Effect upon the Deformation of the Tunnel along the Longitudinal Axis
	a. General Effect of σ_{VL1} Due to the σ_{VL1} being the major principal stress and playing the dominant role, only the effect of σ_{VL1} is discussed.  1. Significant axial deformation on the roof of tunnel in the direction towards to portal. 2. Significant axial deformation on the bottom against portal. 3. Gradually decreasing to zero at the "Central symmetrical Plane" of tunnel.
σ_{VL1} — Major principal stress on the vertical plane VL including the longitudinal axis of Tunnel σ_{VL2} — Minor principal stress on the vertical plane VL σ_H Horizontal principal stress parallel on the cross section of Tunnel 	b. Local 3D Effect in the Region near the face of Excavation  1. Decrease the axial deformation on the roof by σ_{VL1} in certain degree. 2. Increase the axial deformation on the bottom by σ_{VL1} in certain degree.

Tab.2: The Influence of Initial stress state II upon the Axial Deformation of Tunnel.

Number of case	Status of Excavation	Initial stress state	Calculation Model
101		$\sigma_z = -\gamma h$ $\sigma_x = \sigma_y = \frac{1}{2}\sigma_z$ $\gamma = 25\ KN/m^3$ $E = 10^6\ KN/m^2$ $\mu = 0.25$	
106			
109			
110			
111			
102		$\sigma_z = -\gamma h$ $\sigma_y = 0$ $\sigma_x = \frac{1}{2}\sigma_z$	
108		$\sigma_z = -\gamma h$ $\sigma_x = 2\sigma_z$ $\sigma_y = \frac{1}{2}\sigma_z$	
105		$\sigma_x = \sigma_z = 0$ $\sigma_y = -\frac{1}{2}\gamma h$	
107			
201		Calculated by dead weight of hill	
203			
206			
301		Calculated by dead weight of hill	
303			
306			
401		Calculated by dead weight of hill	
403			
406			

Tab.3: Cases of Numerical Calculations

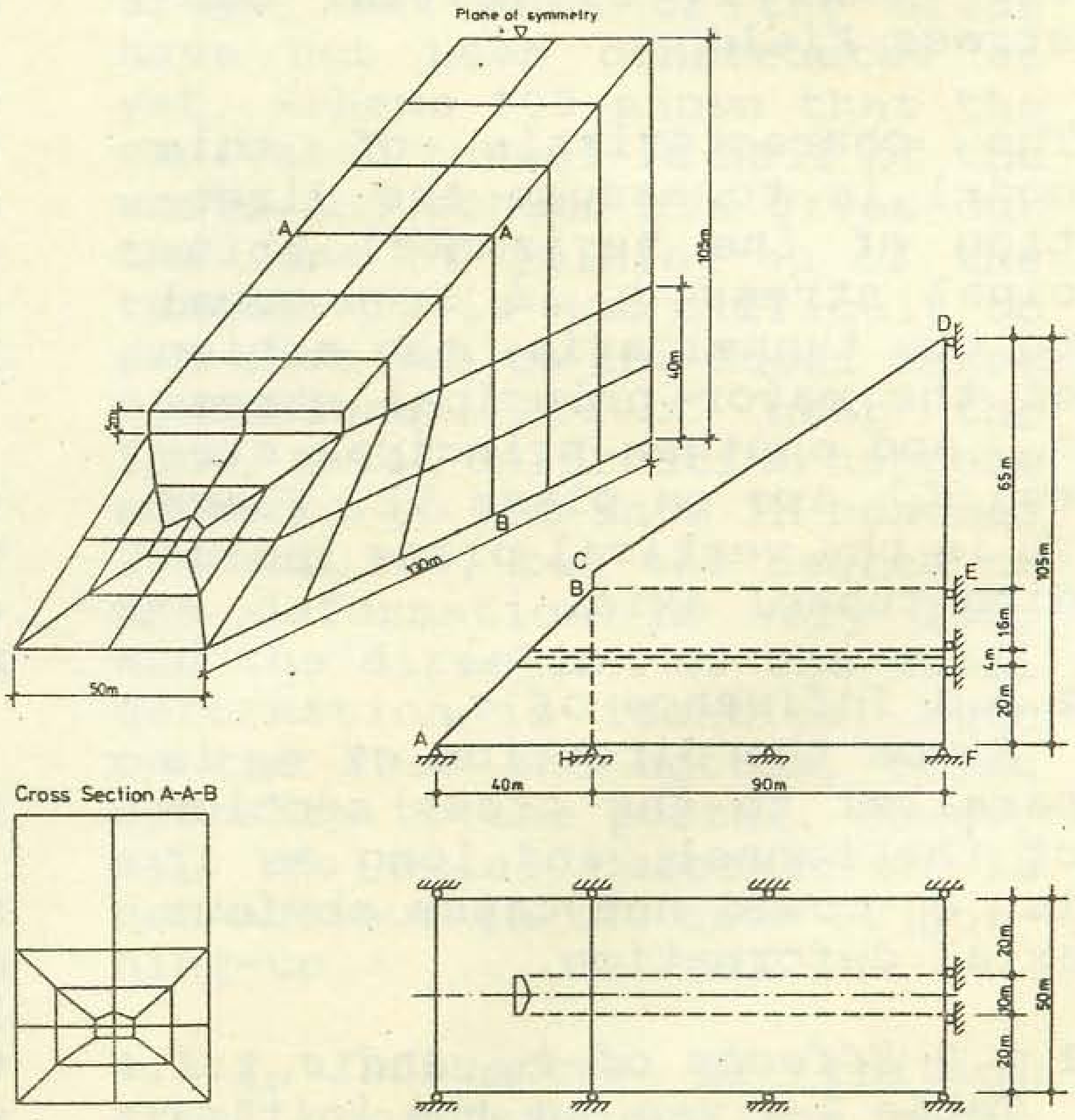


Fig. 2 Calculation Model for Cases 401, 403 and 406
(For Cases 301, 303 and 306 the H B C D E F H part is used; For Cases 201, 203 and 206, only the part of H B E F H is used.)

deformations are opposite to the corresponding portals.

2.1.3 *Local three dimensional effects and axial deformations caused by σ_v and σ_H near the face of excavation*

Such local three dimensional effects and equivalent excavation nodal forces acted on the face has been shown in Table 1. Hence it is known that

1. The axial deformation caused by the local three dimensional effects on the face should point to the advancing direction of the face of excavation .
2. The direction of axial deformations are identical between tunnel roof and bottom.

3. Since this is a local effect, the axial deformation caused by the effect away certain distance from the face may be ignored.

2.2 *Model II of Initial Geostress Field*

The characteristic of this model is to assume the direction of the horizontal principal stress σ_H is orthogonal to the tunnel axis, the action of the major principal stress σ_{VL1} and another principal stress σ_{VL2} are on plane VL. Plane VL is the vertical plane including tunnel axis.

2.2.1 *Influence of σ_H*

Since the direction of σ_H is parallel to the cross section of the tunnel, and long as it is, σ_H could not cause obvious axial deformation.

2.2.2 *Effects of σ_{VL1} and σ_{VL2}*

Table 2 gives out the initial state and the corresponding excavation effect of σ_{VL1}. The excavation effect of σ_{VL2} is opposite to that of σ_{VL1}, however, the former is the major principal stress, therefore, the synthetic effects produced when the two gives out simultaneous actions should be under the domination of σ_{VL1}, the axial deformation regularities caused are shown in Table 2, i.e.

1. There is obvious axial deformation on the roof and the direction of which is pointing to the portal of the tunnel.
2. The axial deformation on the bottom plate is also obvious, but the direction is opposite to that on the roof, i.e. opposite to the portal of the tunnel.
3. These deformations decrease gradually with the coming of the central profile of the tunnel.

2.2.3 *Three dimensional effect at the areas near the face of excavation*

Although this local three dimensional effect decreases the axial deformation caused by σ_{VL1} and σ_{VL2} on the roof, yet it increases the axial deformation caused by σ_{VH1} and σ_{VH2} on the bottom.

3 Numerical Simulation with Three Dimensional Finite Element Method for Tunnel Deformation Problem

3.1 *Numerical Model*

Since the simulation is for the deformation mechanism and regularity with the excavation of the tunnel, only elastic analysis is given in this paper. The program adopted is FINAL provided by Professor Swoboda. To meet with different initial stress states, combinatorial patterns are adopted for discretization. Figure 2 gives out the combinatorial pattern and the three dimensional mesh. There are 132 isoparametric elements with 20 nodes, and 707 nodes in total. The values of mountain body of the numerical model is as follows: height, 105m, length 130m and width 50m. Considering the symmetry, the total length taken as 260m. The tunnel width is 10m, height 7m.

3.2 *Calculation Schemes*

Various calculation schemes have been listed in Table 3, where it can be also found the calculation models and initial stress states for the mountain body adopted in various calculation schemes.

1. The initial stress fields of those numbered with 1xx are artificially input in calculations and are of homogeneous fields with considering different excavation steps.

3. The schemes numbered with 2xx are those whose initial stress fields are calculated in respect to the dead weight, the calculation model is identical to those with 1xx.

4. Schemes numbered with 3xx are those that consider the case of the slope landform where the highest point of the mountain body is over the symmetric cross section but the portal of the tunnel is situated at steep cliff; and the numerical simulation is carried out in accord with the initial geostress state calculated from the dead weight.

5. Scheme 306 is the case when the whole tunnel is joined up. And scheme 301 is the consideration that only the adjacent areas of the portal are excavated.

6. The schemes numbered with 4xx also consider the slope landform of the mountain body, but the portal of the tunnel is situated at slope.

4 Results and Analysis of Numerical Simulation

4.1 *Model I of Simulated Initial Geostress Field and Numerical Calculations and Analyses of Different Excavation States*

4.1.1 *Influence on the axial deformation of different excavation states*

Figure 3 gives out three results of the schemes calculated. All of the conditions in the three schemes are identical except the states of excavations. What scheme 201 shows is that the excavation of tunnel are done near the portal areas, but most of the areas have not been constructed as yet. Scheme 203 shows that the excavated tunnel is half of the whole.And scheme 206 gives out the case of joining-up of the tunnel. It is not difficult to see that due to the local three dimensional effect near the face, axial deformation happens adjacent to the face in schemes 201 and 203, but the degree of the deformation is very low, and the direction of the axial deformation is identical both on the roof and bottom, being opposite to the portal. However, the axial deformation is not obvious in the case of joining-up.

4.1.2 *Influences of initial axial geostress and the ratio*

of horizontal and vertical main stress

The results of calculations for schemes 106, 107 and 108 are shown in Figure 4, all of them are the cases of joining-up of the tunnel. The stress states of the schemes are given in Table 3.

In scheme 107, there is only initial axial geostress, therefore, the roof and bottom deformations definitely shows the influence of the axial geostress. From Figure 4 it can be seen that the existence of the initial axial geostress results in obvious axial deformation only near the portal of the tunnel, and the direction of the axial deformations both at roof and bottom are identical and point to the central cross section.

In schemes 106 and 108, there are identical vertical initial geostress, but the values between horizontal and vertical principal stress are 0.5 and 2.0. And the value of axial initial geostress is identical to that of scheme 107. From Figure 4 we could see the vertical and horizontal initial geostress and their ratio variations do not show obvious influence on the scale and regularities of axial deformation.

4.1.3 *Influence of local three dimensional effect on axial deformation*

The local three dimensional effects shown in Figure 3 are based on the excavation advancing from the portal to the center.

Calculation scheme 110 shown in Figure 5 is the excavation from the central part of the tunnel to the left and right portals. Now the axial deformation is still local, and the deformations are identical both at the roof and bottom pointing to the portals, however, the deformation still follows the principle that the direction of the axial deformation is identical to the advance direction.

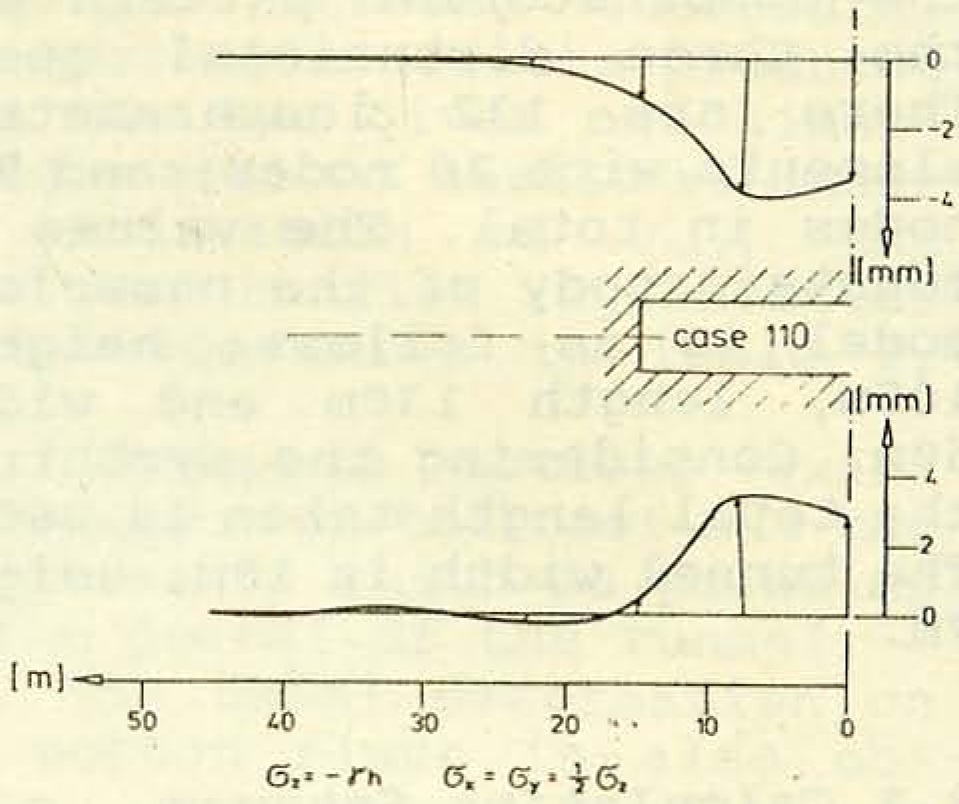


Fig. 5 Diagram of Deflection of Tunnel for case 110

4.2 *Model II of Simulated Initial Geostress and Analysis of Numerical Calculations of Slope Landform*

4.2.1 *The case of steep cliff near the portal*

Generally, due to the influence of the slope landform, the initial geostress of the rock body in the area of the tunnel is of the state of Model II, i.e. the major principal stress is inclined and points to the portal of the tunnel. However, in the case of steep cliff, the major principal stress near the portal is nearly vertical. Figure 6 gives out the calculations of three schemes of 301, 303 and 306. To sum up, the axial deformation on the roof still falls into the regularity of the analysis in theory, i.e. pointing to the portal; while at bottom, it is opposite to that of the roof. Since the influence of the steep cliff, the direction of the axial deformation near the portal area is reversed.

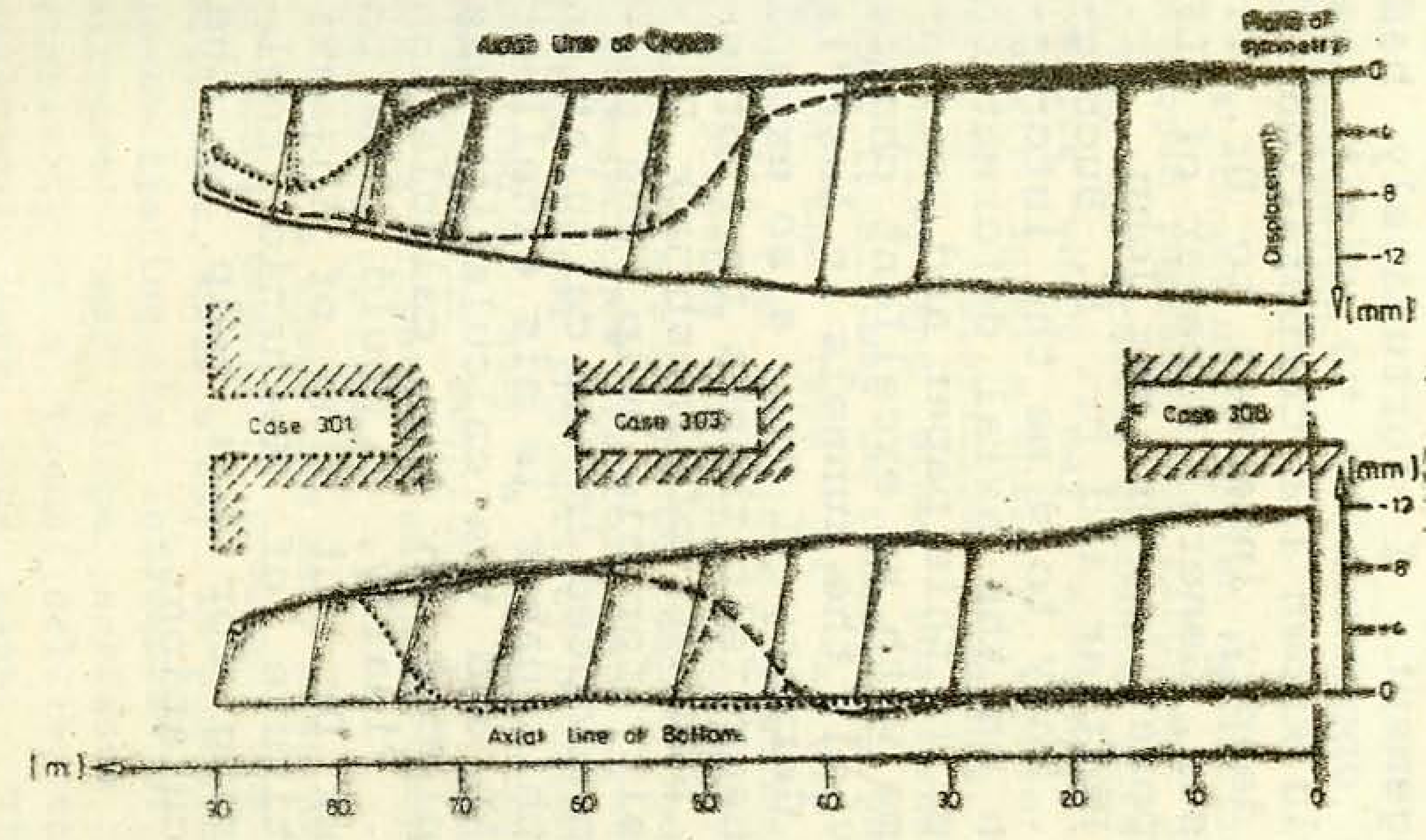


Fig. 6 Diagrams of Deflections of Tunnel for Cases 301, 303 and 306 (Longitudinal Section)

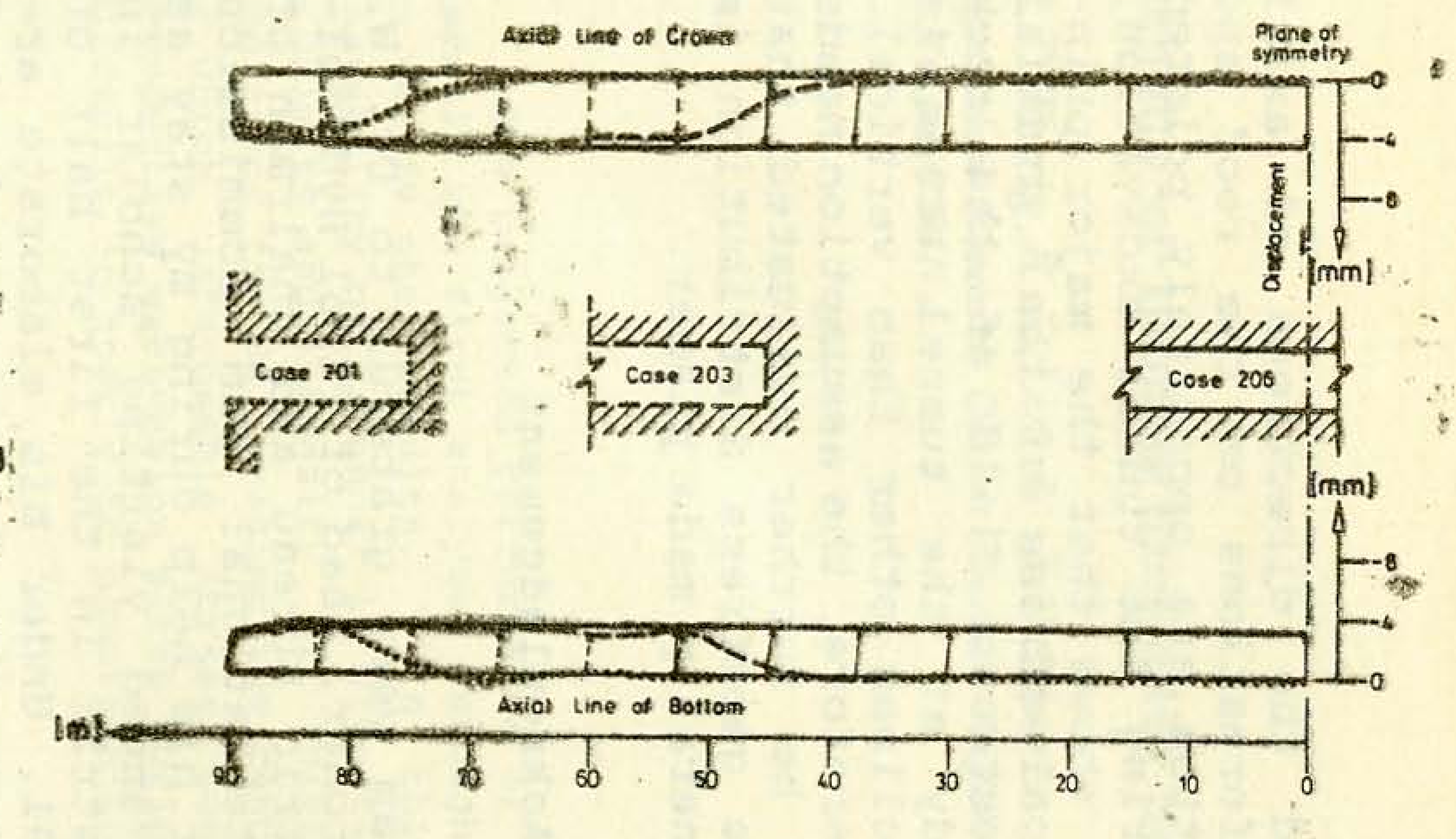


Fig. 5 Diagrams of Deflection of Tunnel for Cases 201, 203 and 206 (Longitudinal Section)

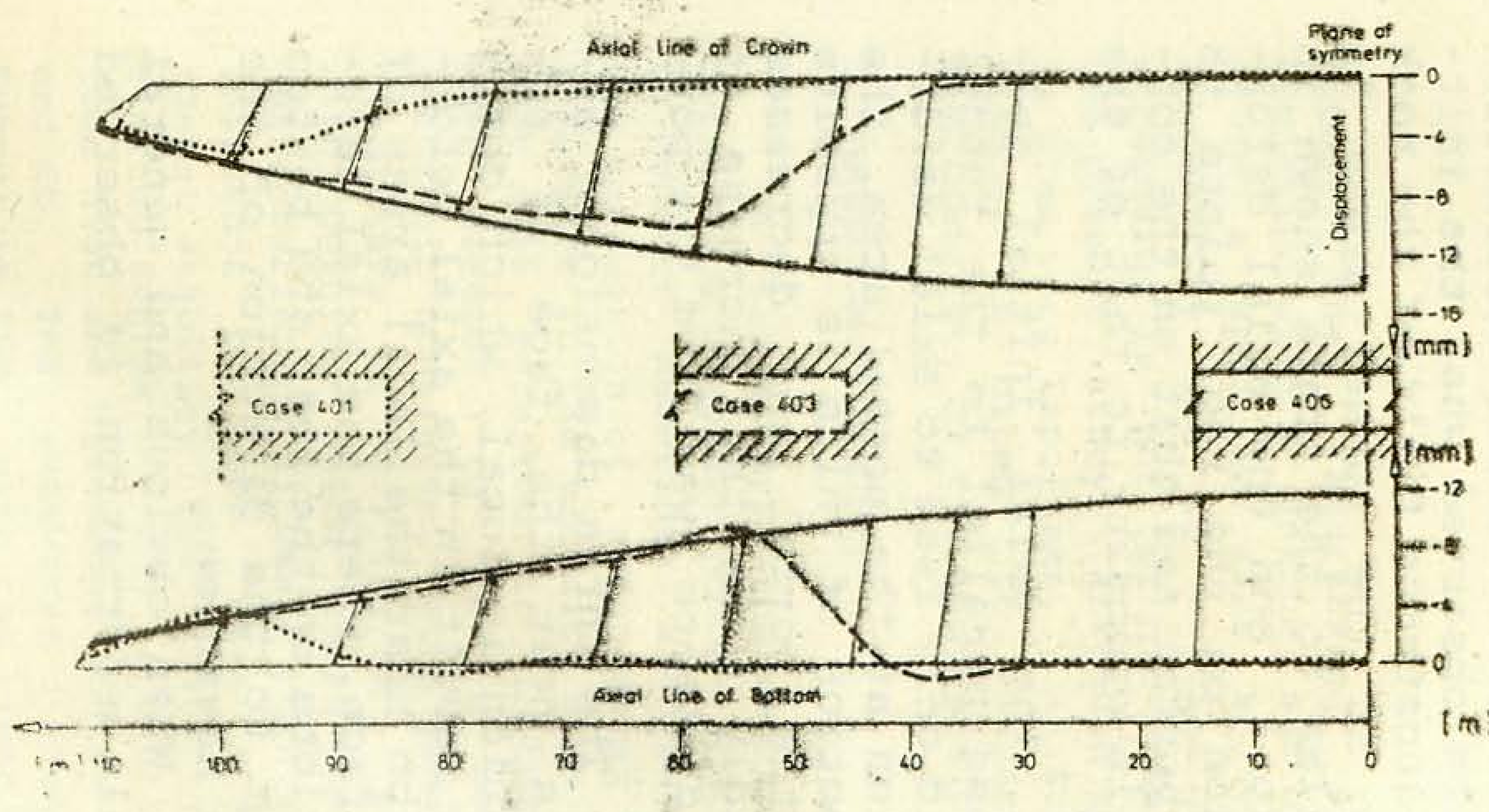


Fig. 7 Diagrams of Deflections of Tunnel for Cases 401, 403 and 406 (Longitudinal Section)

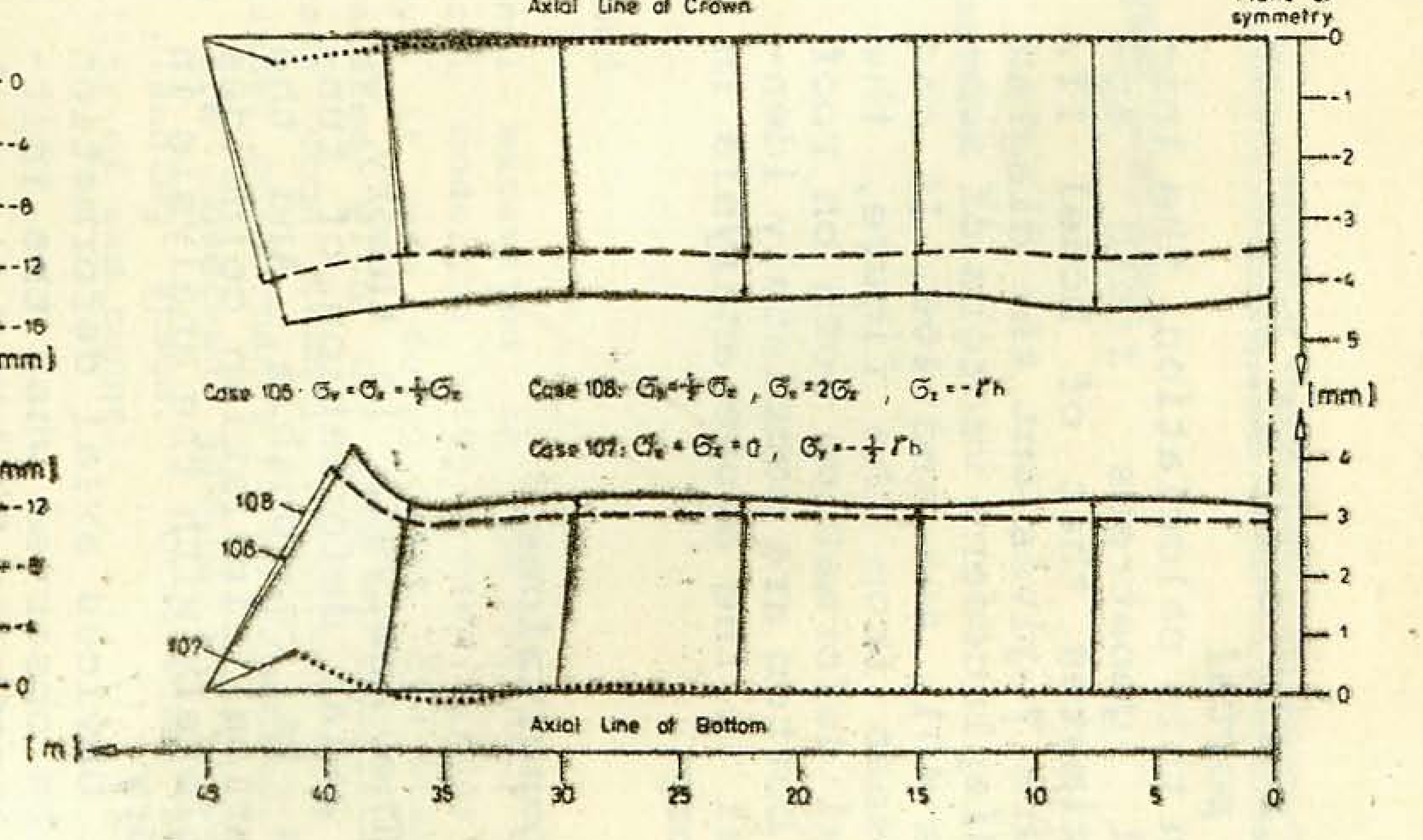


Fig. 4. Diagrams of Deflections of Tunnel for Cases of 106, 107, 108.

4.2.2 *The case of slope near the portal*

In this calculation, the initial geostress field approximates that of Model II. Figure 7 gives out the diagram of displacement vectors of schemes 401, 403 and 406. It can be seen from the figure, the axial deformation both on roof and bottom are completely identical to the above analysis in theory.

5. Conclusions

1. The analysis in theory on the axial deformation of tunnels is reasonable. And the numerical simulation coincides completely with the analysis in theory.

2. Obvious axial deformation can be observed when the initial geostress field of the rock body at the tunnel areas is similar to the state shown in Table 2, and the axial deformation on the roof points to the portal and that on the bottom is opposite to that of the roof.

3. The axial initial geostress parallel to the tunnel could only lead to axial deformation at the portal area, the direction of which is opposite to the portal and decreases rapidly with the increase of the distance away from the portal.

4. The three dimensional effects near the face of excavation is local, which could only result in the axial deformation near the local areas of the face, where the axial deformations on the roof and bottom point to the direction of the face advances.

5. When obvious and general axial deformation is observed and the directions of axial deformations on the roof and bottom are oppositely pointed during the tunnel excavation, it shows that the major principal stress of the initial geostress field of the rock body at the tunnel areas is inclined other than vertical. Therefore, the assumption needs to be further evaluated that the geostress distribution is generally made planar.

6 Acknowledgement

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