Case Histories of Geological, Rock and Mining Engineering Including Underground Structures and Excavations. Paper No. GR-VI

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INTRODUCTION

The fields of geological, rock, and mining engineering are concerned with predicting and controlling the behavior of structures constructed in rock. These structures would include mines, tunnels, excavations, foundations, dams, and slopes, among others. While formal studies of the fields of geology and rock mechanics have contributed to improved understanding, natural variability of the ground necessitates application of a considerable amount of judgement in the engineering of structures constructed in rock. Thus, it is appropriate that the 4th International Conference of Case Histories in Geotechnical Engineering include a session on geological, rock, and mining engineering, so that we might all benefit from the project experience of others.

The purpose of this general report is to summarize the papers submitted for publication in this session and to encourage discussion among the professionals in attendance. A total of 12 papers were submitted to this session which discuss various aspects of the design and performance of excavations, tunnels, mines, slopes, and embankments. For discussion purposes, the papers in this session have been grouped into the following general categories:

1. Prediction/ Monitoring of Ground Movements;
2. Stability Computations for Underground Structures and Slopes; and
3. Rock Classification for Engineering Behavior.

PREDICTION AND MONITORING OF GROUND MOVEMENTS

Underground structures and excavations are frequently constructed in dense urban environments where control of ground movements during construction is important for protection of adjacent structures. Estimates of ground movements are usually made during design to assist the engineer in evaluating support requirements. Predictive tools available for this purpose include empirical relationships derived from past experience, closed-form elastic solutions based on simplified problem geometry and boundary conditions, and numerical analyses. Wide ranges in calculated magnitudes of ground movements can be obtained, which reflects uncertainties with respect to sources of movement, the significance of approach to construction and workmanship, and stress-strain characteristics of the ground. Thus, monitoring of ground movements at the time of construction is important to verify design, or facilitate changes in design as required to maintain stability and control the ground.

In his paper, *"Analysis and Performance of the NATM Excavation of an Underground Station for the Athens Metro,"* **Kavvadas** summarizes support requirements for a large underground opening (16.5 m by 110 m), and compares predicted ground response with measurements made during construction. The station excavation was made through weathered schist ranging in texture from a blocky mass with gouge-filled discontinuities to a soil-like material lacking relict structure of the parent material. Temporary support for the excavation consisted of a sprayed shotcrete liner (10 to 40 cm thick) and rock bolts (4.5 to 6 m long). Excavation was completed in 9 stages (Fig. 1). A 2D, plane strain FEM analysis was used to evaluate the excavation sequence, support requirements, and ground movements. Engineering properties were estimated using a variation of the RMR system. A wide range of strengths and stiffnesses (E = 120 to 800 Mpa) were selected to represent the ground response because of the variability of the weathering profile. Significant findings of the analysis can be summarized as follows:

1.) A wide range in maximum ground surface settlements were predicted, reflecting uncertainty with respect to the stress-strain and strength properties of the ground.

2.) Most of the ground settlement occurred during excavation of drifts 1 through 4 due to compression of the central pillar.

3.) The excavation was stable.

Maximum calculated ground surface settlements ranged from about 35 to 110 mm. Measured maximum settlements were about 15 to 18 mm. Kavvadas attributed the discrepancies to measurement locations and to use of stiffer support than assumed in the analysis.

Vaghar and Bobrow describe the performance of stiff and flexible excavation support systems in their paper *"Comparison of Two Excavation Support Systems in Clay; Central Artery/Tunnel, Boston, Massachusetts, USA."* The excavations were made through fills; soft to medium stiff organic silts with clay, sand, and peat lenses; and marine clays (Boston Blue Clay). Groundwater included a perched aquifer above the Boston Blue Clay and a confined aquifer in the tills and bedrock below the marine deposits. Excavation depths ranged from about 45 to 65 feet. Excavation support typically consisted of tied-back sheet piling. Where ground movements were a concern for performance of adjacent structures, a post-tensioned slurry wall ("T" section) supported by a combination of struts and tiebacks was used. Instrumentation included observation wells and vibrating wire piezometers, inclinometers, probe extensometers and heave gages, and deformation and crack monitoring points. Maximum lateral movements of the sheetpile wall were 15 inches (Fig. 2a), compared with maximum lateral movements for the slurry wall of 1 inch (Fig 2b). Maximum ground surface settlements in the range of 7 to 11.5 inches were measured. The comparatively large ground surface settlements were attributed to a combination of ground losses associated with tieback installation and consolidation of the fill, organic soils, and marine deposits resulting from reducing pressure heads in the aquifers. Modifications in tieback installation procedures, depressurization of the aquifers, and unsupported brace lengths were used to improve performance in other areas.

In their paper, *"Design, Construction and Monitoring for the Excavation of Shanghai World Plaza,"* **Huang et. al.** discuss the response of a 1 m thick slurry wall used to support a 18 m deep excavation in soft clays. The slurry wall was supported by three levels of struts, spaced vertically along the height of the wall about every 6 m. Deep pumped wells were used outside the excavation to reduce hydrostatic heads about 8 m. Deep pumped wells were also used inside the excavation to maintain a downward gradient for stability of the subgrade. Maximum vertical and lateral ground movements of about 200 and 120 mm, respectively, were observed. The maximum horizontal movement of the wall was between 0.2 and 0.3% of the wall height.

STABILITY COMPUTATIONS FOR UNDERGROUND STRUCTURES AND SLOPES

In addition to evaluating ground movements during design, stability of the mass must be considered and supports sized appropriately to accommodate the change in stress. Support requirements for underground structures can be evaluated using a combination of empirical, theoretical, or numerical approaches.

Various rock mass classifications for estimating support have been proposed based on observed performance. Barton et. al. (1974), for example, provided guidelines for underground support based on a rock index, Q, that is a function of Deere's Rock Quality Designation (RQD), the number of joint sets, joint roughness and alteration, groundwater conditions, and a stress reduction factor. Similarity, Bieniawski (1974) discussed methods of excavation and support based on RQD, strength of the intact material, joint spacing, joint condition, and groundwater characteristics. Support of rock slopes, or wedges or blocks that are free to slide, can be evaluated using limit state analyses, Hendron et. al. (1980). Various closed-form elastic solutions are available for evaluating the stresses in a tunnel lining, Ghaboussi and Ranken (1974). Sophisticated numerical models can also be used to predict ground response and determine appropriate methods of support.

In their paper, *"Investigation of the Influence of the Clay Seams Around an Underground Excavation in Rock Salt,"* **Kwon and Wilson** combine field measurements, theoretical analyses, and numerical modeling to examine the influence of clay seams on roof stability in underground salt and potash mines. The study was preceded by a roof fall, measuring 10 m wide by 2 m high by 50 m long, at the Waste Isolation Pilot Plant (WIPP) on February 4, 1991. General site stratigraphy consisted of various evaporites interbedded with comparatively thin seams of clay. The failure at WIPP resulted from separation and slip of the roof beam along a clay seam located at a depth of about 2 m. Roof beam stability was quantified by considering the separation and relative slip calculated from beam theory and a numerical model. In addition, inclinometers installed in the roof of the opening were used to measure relative slip displacements at clay/evaporite contacts.

Goel, Jethwa, and Dube describe support requirements for two underground powerhouse caverns in their paper *"Experiences of the Support Designs in the Two Large Underground Openings in India"*. The powerhouse cavern at Sardar Sarovar was 23 m wide, 57 m high, and 210 m long, while the cavern at Koyna Stage IV was 20 m wide, 50 m high, and 145 m long. Subsurface conditions at the two sites consisted of a succession of basalt flows. At the Sardar Sarovar site, the basalts were intruded by steeply dipping dolerite dykes, whose contacts with the basalts were marked by shear zones. In addition, an agglomerate band was present near the roof of the cavern at some locations. Support requirements for the two caverns were worked out using a combination of empirical and numerical approaches. Preliminary support requirements for the caverns were determined based on the NGI Tunneling Quality Index proposed by Barton, Lien, and Lunde. In addition, stress and strain regimes around the openings were examined using a 3D FEM analysis. The modeling permitted identification of potential failure zones and generally suggested use of longer bolts than determined from the empirical method. Convergence monitoring following construction resulted in installation of some additional rock bolts in the vicinity of the agglomerate band (Fig. 3).

Fotieva and Bulychev discuss the problem of designing underground structures for seismic forces in their paper, *"Case Histories of Designing Tunnel Linings in Seismic Regions"*. The stresses in a tunnel lining associated with long longitudinal and shear waves were evaluated using elastic theory, in which the properties of the lining and tunnel medium were represented by a deformation modulus and Poisson's ratio. Compressive and shear stresses on the boundary of the elastic medium were given as a function of the earthquake intensity, the mass density of the medium, the propagation velocity of the medium, the period of oscillation of the medium, and a coefficient taking admissible damages into account. The method of seismic design was illustrated by two case histories: 1.) railway tunnel for the Baikal-Amur railway, and 2.) vertical shafts for the Rogun power station.

Petkovsek and Bevc describe an investigation to evaluate the causes of failure of a section of tunnel liner in their paper *"Remedial Works in the Ljubelj Tunnel"*. Some 18 square meters of the tunnel lining spalled off. The tunnel was originally constructed during WWII and was excavated through dolomite, limestone, and marl. Initial tunnel support consisted of a cast-in-place concrete liner along selected reaches. In the 1960's a cast-in-place concrete liner (16 cm) was added along the entire alignment. The investigation to evaluate causes of failure consisted of: review of available construction records, detailed mapping of the tunnel lining, drilling of coreholes to sample the liner, non-destructive testing, and testing of the concrete (mineralogical and chemical analyses, compressive strengths, and tensile strengths). The thickness and strength of the samples liner was extremely variable. The concrete structure was observed to be very porous and included variations in aggregate type and size. In general, the inner lining was observed to have good contact with the surrounding ground. The presence of a drainage layer prevented tight contact, however, between the inner and outer linings. Deterioration of the outer lining was exacerbated by freeze/thaw, humidity, corrosivity, and precipitation of calcium carbonates. Remedial efforts were completed in phases and consisted of 1.) installation of wire mesh held in-place by closely spaced bolts and 2.) installation of a water-tight membrane and construction of a new cast-in-place concrete liner.

Mathews et. al. described the performance of a rock slope during discharges from the Tuttle Creek Resevoir in their paper, *"Erosion and Repair of Unlined Spillway Chute Excavated in Rock"*. The unlined portion of the spillway was excavated through interbedded limestones and shales. The spillway was 839 feet wide at the flip bucket and 200 feet wide at the downstream end. The chute had a vertical drop of 86 feet over a horizontal distance of about 3400 feet. In the Summer of 1993, a major flood event resulted in spillway releases that lasted for 21 days, with a peak discharge of 60,000 cfs. Nearly 400,000 cubic yards of material were eroded from the unlined chute resulting in escarpments ranging in height from 4 to 26 feet (Fig. 4). Daily observations of erosion and headcut were documented. A site-specific model, based on that developed by Temple and Moore (1994), was used to evaluate future headcut advance and risks to the concrete structure. In the model, the rate of headcut advance is expressed as a function of unit discharge, height of the headcut, and an aggregate headcut erodibility index. No significant risks to the concrete structure were inferred from the analysis provided future erosion could be prevented. Remedial repairs consisted of filling of major headcuts with grouted rock, placement of an average of 2 feet of soil over the exposed rock, and establishing a vegetative cover.

Santi evaluated stability of embankments in his paper, *"Stability and Permeability of Fluid Retention Berms Constructed From Highly Weathered Bedrock"*. The embankments were constructed from bedrock, weathered bedrock, and colluvium. In general, the fine-grained soils were used to construct the core of the embankments, while the coarser soils were restricted to the embankment shells. Foundation materials included colluvium underlain by interbedded limestones and shales. The objective of the study was to evaluate the stability of the embankments in the event of failure of one of the fluid filled tanks. In addition, the analyses were intended to determine whether or not the embankments would contain the fluid. Stability analyses were conducted with the assistance of a computer program (SSTABM EP56SF, Spencer-Wright Procedure). Because the scale of rock fragments in the embankment fills was many times greater than the diameter of typical samples, determination of representative fill strengths was the most significant challenge of the project. Strengths and permeabilities were estimated from conventional laboratory tests for embankment fills for which the largest particle size was less than 0.2 inches. Thus, results of laboratory testing tended to be biased towards the lower strength and permeability soils. Considerable judgement was applied in evaluating results of the analyses.

ROCK CLASSIFICATION FOR ENGINEERING BEHAVIOR

Rock classification provides a consistent framework for engineers to discuss rock behavior for underground projects, and to extrapolate from ground conditions and experience gained on other projects to a site under consideration.

Chern and Kao proposed a classification system to evaluate squeezing potential around tunnels in rock in their paper, *"Tunneling in Squeezing Ground"*. Numerical analyses were used to determine the relationship between tunnel closure and the extent of the plastic zone around a circular opening, and the ratio of rock mass strength to in-situ stress (Fig. 5). Three categories of tunnel response, slightly or non-squeezing, moderately squeezing, and highly squeezing, were identified on the basis of the trends established from the numerical analyses. Measured response of various case studies correlated well with the numerical trends.

In their paper *"Tunned: An Expert System for Tunneling Through Rock"*, **Paillasse and Franklin** discuss use of a computer program to assist engineers in designing tunnels. The computer program (Tunned) makes use of well-known rock classification systems, specifically the RMR and Q rock quality classifications. The relationship between stable span and stand-up time, for example, is evaluated using the non-linear relationship proposed by Franklin and Paillasse (1993), in which the quality of the rock mass is defined by the RMR System. Support requirements are evaluated based on correlations of the RMR and Q Systems. The choice between blasting and use of a T.M. is based on uniaxial compressive strength, tunnel diameter and length, and the variability of geologic conditions along the tunnel alignment.

Li and Li discuss the use of various rock mass classification systems for analysis of rock slopes in their paper, *"A Computer Aided Rock Mass Classification for Rock Slopes"*. The proposed geomechanical classification for rock slopes is based on the CSIR classification, Q classification, SRM classification, and the Chinese Engineering Rock Mass Classification (CERC). The classification system emphasizes the effects of favorably oriented combinations of joints, shear zones, and faults through the concept of "preferred planes".

SUMMARY AND DISCUSSION

A total of 12 papers were included in Session VI, Case Histories of Geological, Rock, and Mining Engineering Including Underground Structures and Excavations. The papers discussed various aspects of the analysis, design, and performance of tunnels, excavations, underground chambers, slopes and embankments. By sharing their experience with the reader, the authors have contributed to improved understanding of the behavior of structures constructed in soil and rock.

There are several significant themes with respect to practical approaches to problem solving that emerge from review of the papers discussed herein.

1.) Numerous predictive tools, with a wide range in their level of sophistication, are available to evaluate support requirements and ground movements for design of underground structures.

2.) Results from numerical modeling must be carefully considered. It is difficult to estimate strength, stress-strain, and volume change parameters for input into the material models. Furthermore, some sources of movement may not be adequately modeled.

3.) Although a wide range in support requirements and ground movements can be estimated from empirical relationships, they more accurately reflect the range of practical experience.

4.) Field monitoring of performance will continue to be an important part of design verification.

ACKNOWLEDGMENT

The authors wish to acknowledge that the figures contained herein have been taken directly from the referenced papers.

REFERENCES

Barton, N., Line, R., and Lunde, J. (1974) "Engineering Classification of Rock Masses for the Design of Tunnel Support", Rock Mechanics, Vol. 6, No. 4, pp. 189-236.

Bieniawski, Z.T. (1974) "Geomechanics Classification of Rock Masses and its Application in Tunneling", Proceedings of the 3rd International Conference on Rock Mechanics, ISRM, Denver, Vol. 11A, pp. 27-32.

Deere, D.U. (1964) "Technical Descriptions of Rock Cores for Engineering Purposes", Rock Mechanics and Engineering Geology, Vol. 1, No. 1, pp. 17-22.

Franklin, J.A. and Paillasse, M. (1993) "Maximum Span and Stand-Time of Underground Excavations", Proceedings of International Congress on Mine Design, Kingston, Ontario, pp. 443-453.

Ghaboussi, J. And Ranken, R.E. (1974) Tunnel Design Considerations: Analysis of Medium-Support Interaction, Report No. FRA-ORDD 75-24, Federal Railroad Administration, U.S. Department of Transportation

Hendron, A.J., Cording, E.J., and Aiyer, A.K. (1980) Analytical and Graphical Methods for Analysis of Slopes in Rock Masses, Technical Report GL-80-2, Prepared for U.S. Army Engineer Nuclear Cratering Group, Livermore, California, 148 pp.

Temple, D.M. and Moore, J.S. (1994) "Headcut Advance Prediction for Earth Spillways", Am. Soc. Agr. Engrs. Paper No. 942540, presented at the 1994 ASAE International Winter Meeting, Atlanta, Georgia.

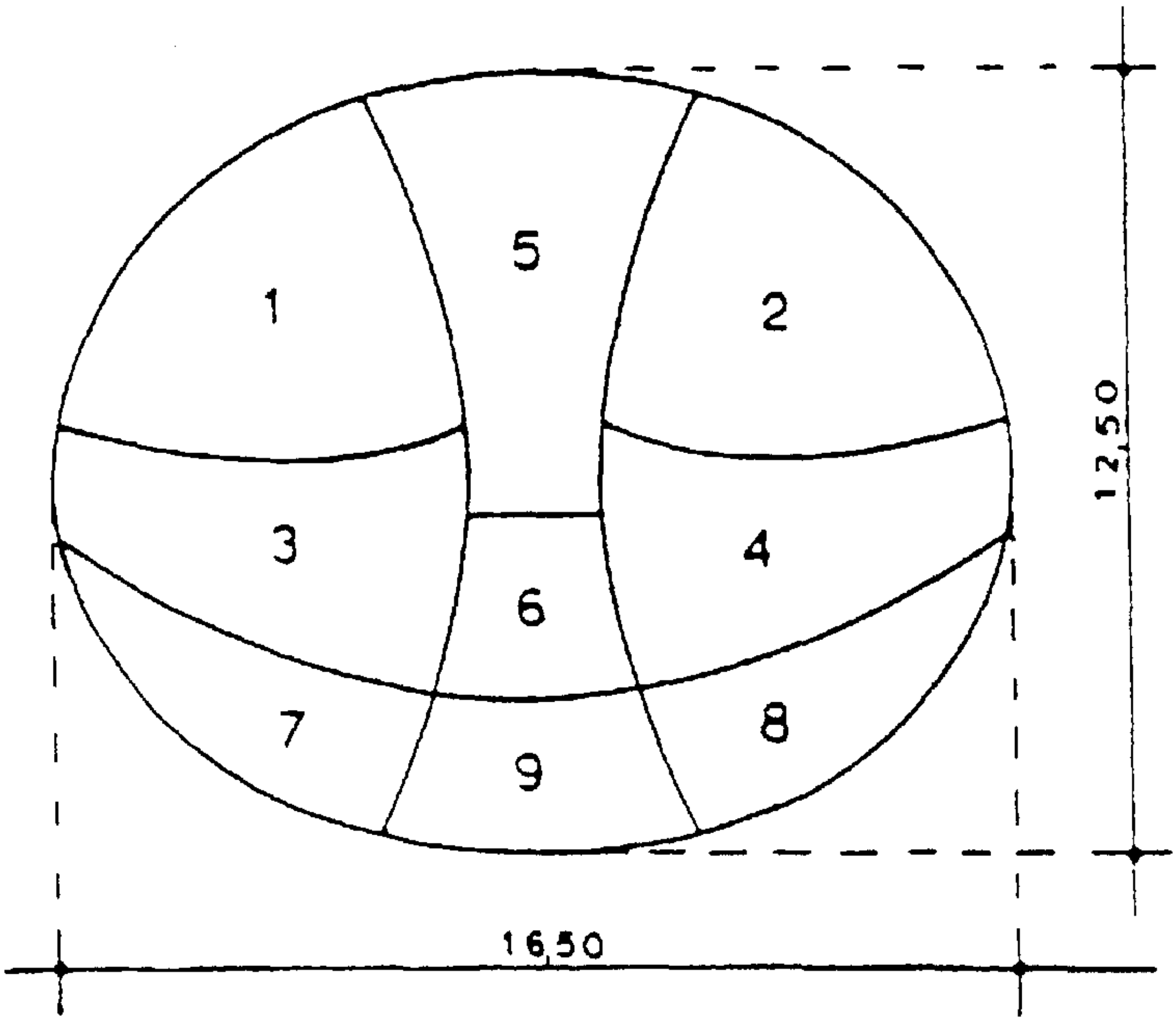

Fig. 1 Station Geometry and Excavation Stages (Kavvadas)

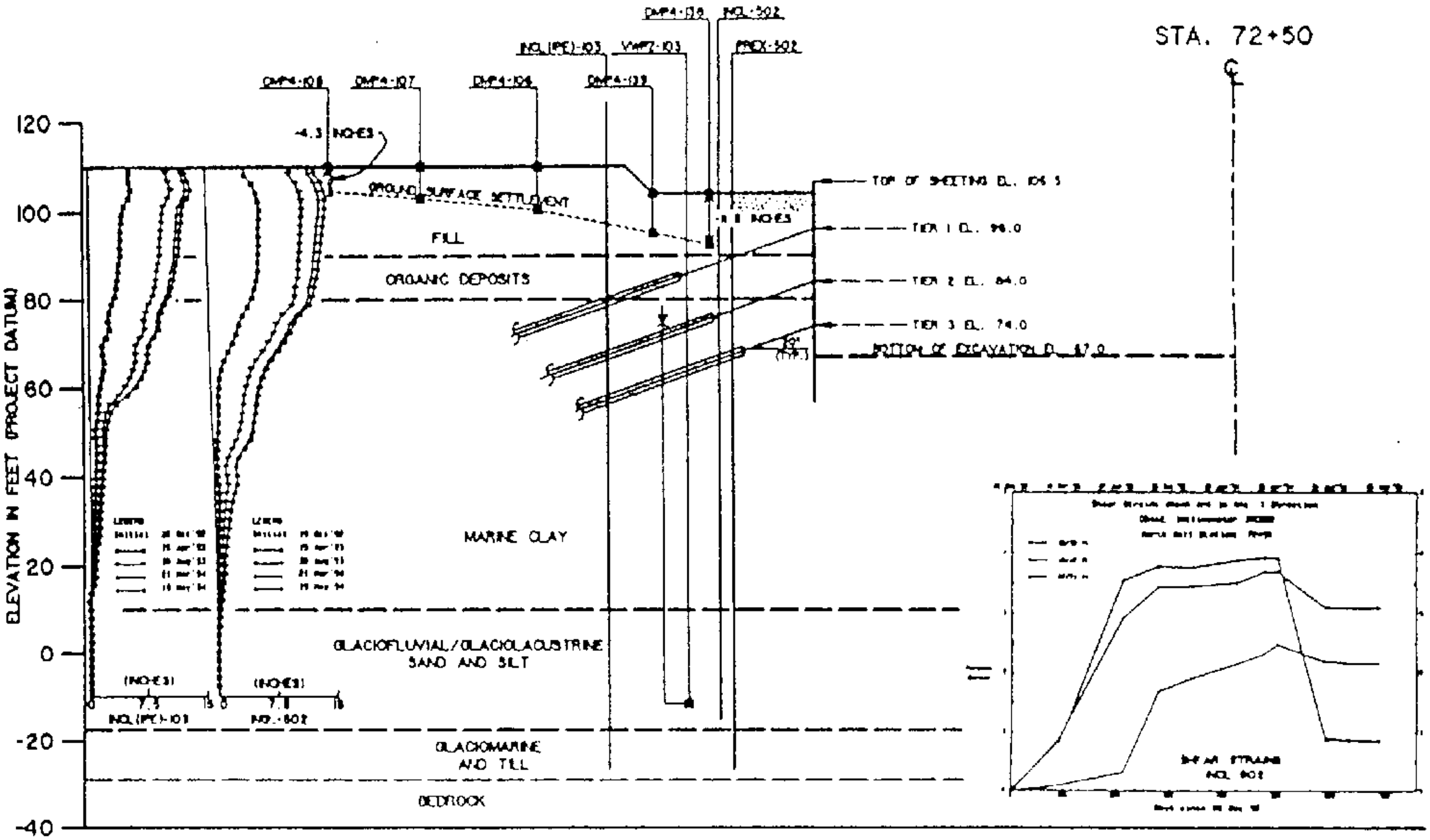

Fig. 2a Deformations at Station 72+50, Sheet Pile Wall (Vaghar and Bobrow)

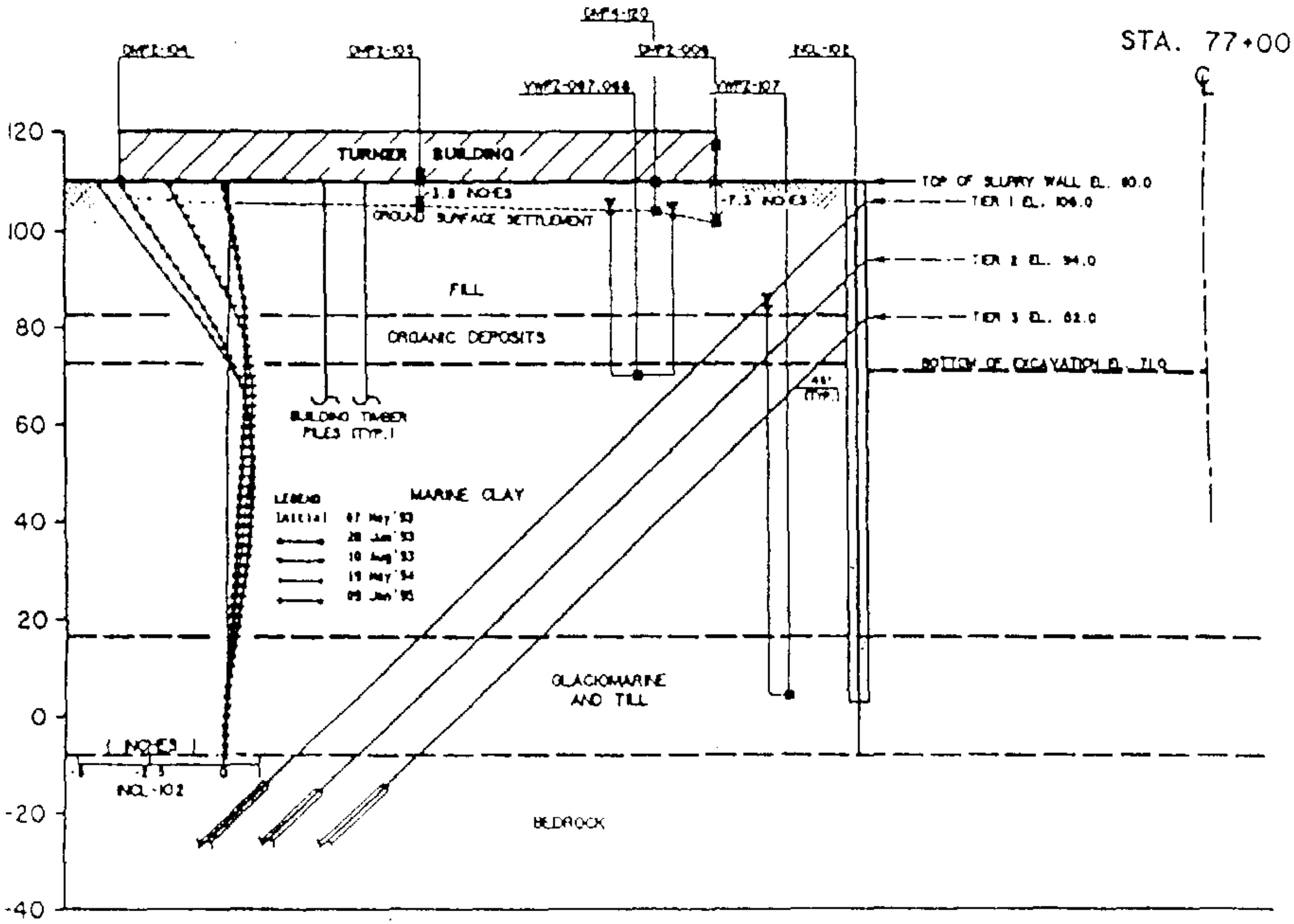

Fig. 2b Deformations at Station 77+00, Slurry Wall (Vaghar and Bobrow)

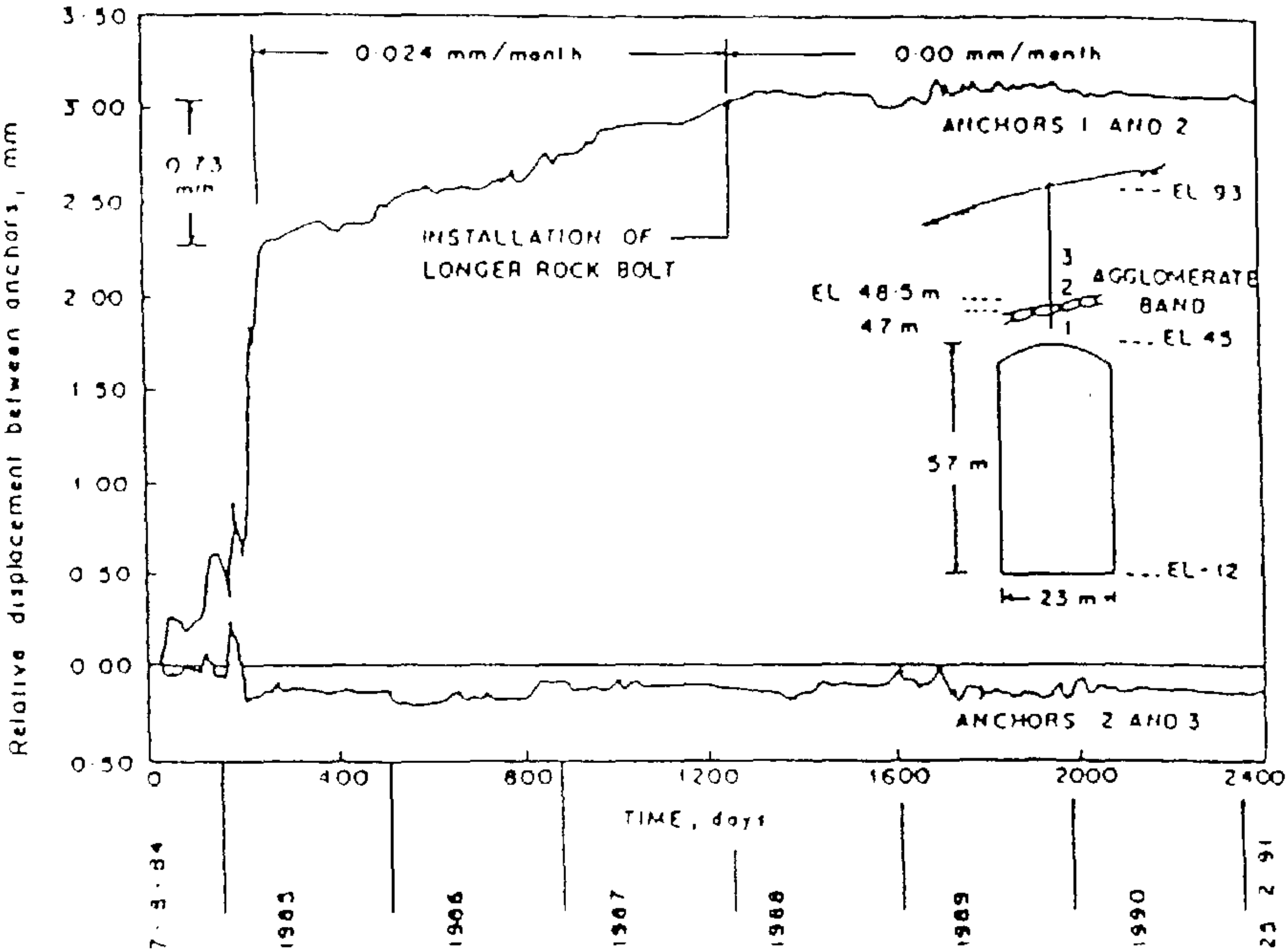

Fig. 3 Monitoring of Agglomerate Band by MPBX in Powerhouse Cavern of Sardar Sarovar Project Gujrat, India (Goel et. al.)

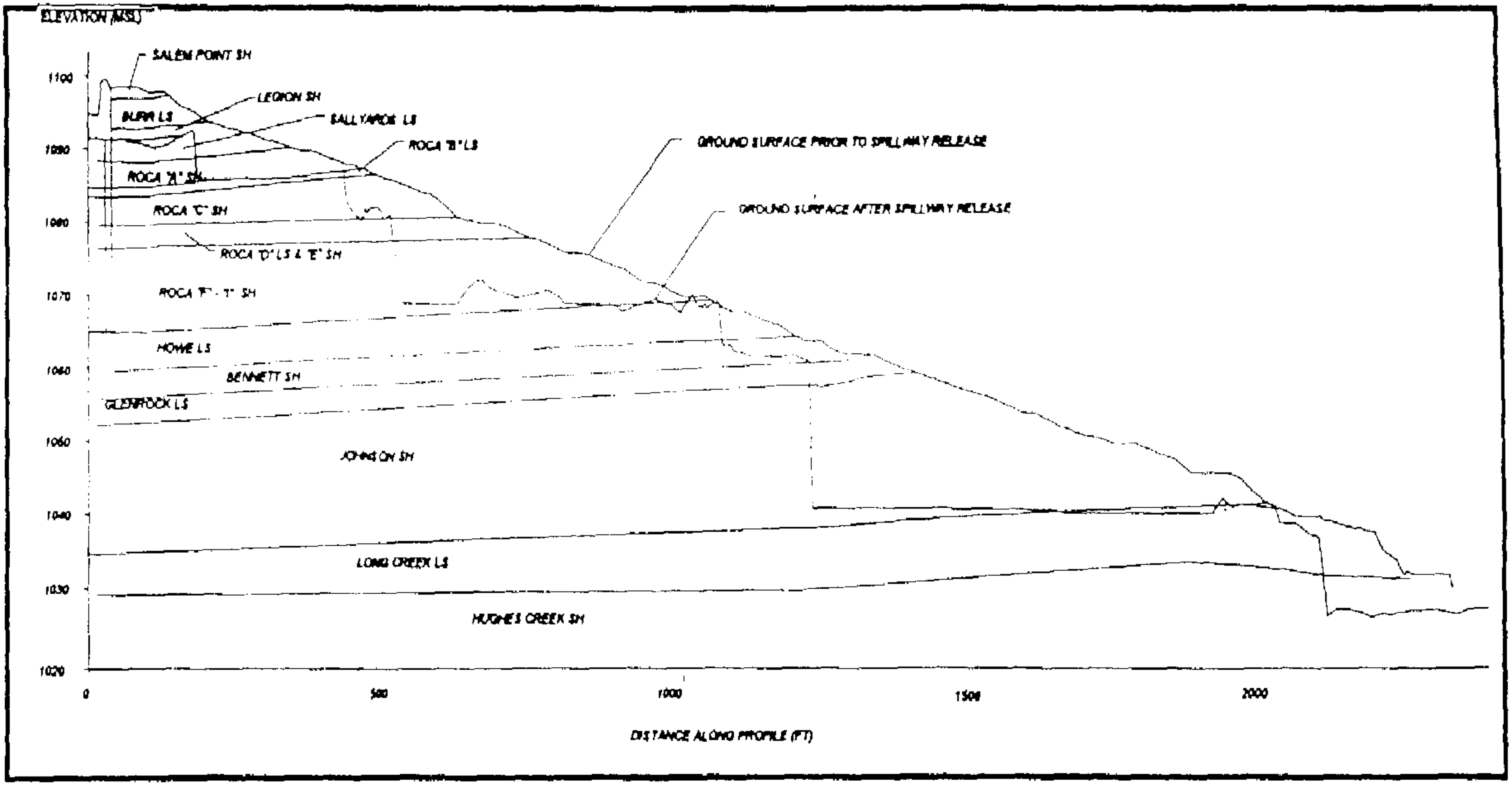

Fig. 4 Profile Along Right Side of the Spillway (Mathews et. al.)

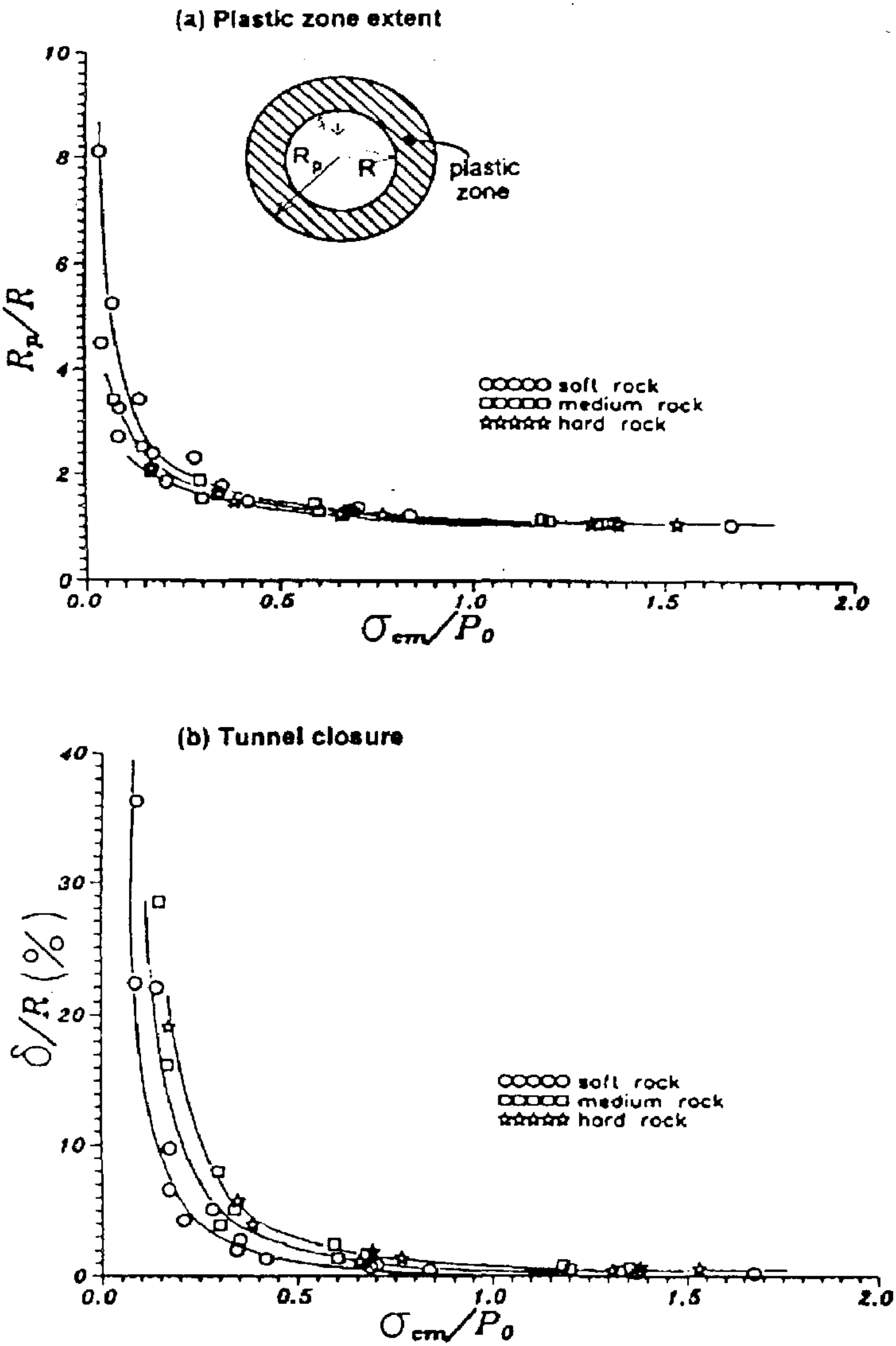

Fig. 5 Results of Plastic Zone Extent and Tunnel Closure of Unsupported Tunnel by Numerical Analysis (Chern and Kao)