A SIMULATION STUDY OF TUNNEL EXCAVATION

A THESIS

submitted in fulfilment of
the requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY
in
WATER RESOURCES DEVELOPMENT

University of Roorkee, Roorkee
Certified that the attached Thesis/
Dissertation has been accepted for the
award of Degree of Doctor of
Philosophy / ~~Master of Engineering~~
....W. R. D. T. C.........vide notification
No. Ex/...100.../E-191/~~P-65 (Degree) dated~~...10.10.1983

Assistt. Registrar (Exam)

by

R. L. CHAUHAN

WATER RESOURCES DEVELOPMENT TRAINING CENTRE
UNIVERSITY OF ROORKEE
ROORKEE-247667 (INDIA)

November, 1982

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled 'A SIMULATION STUDY OF TUNNEL EXCAVATION' in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy, submitted in the Department of Water Resources Development Training Centre of the University is an authentic record of my own work carried out during the period from March, 1978 to Nov., 1982 under the supervision of Dr. Mahesh Varma, Dr. Bhawani Singh, and Sri I.C.Gupta.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

RLChauhan 23/11/82
(R. L. CHAUHAN)
Candidate's Signature

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Maheshvarma	23/11/82
(Dr. Mahesh Varma)	(Dr. Bhawani Singh)
Professor Construction Planning,	Professor of Geotechnical Engg.,
Water Resources Development	Department of Civil Engineering,
Training Centre ,	University of Roorkee,
University of Roorkee,	ROORKEE (U.P.)
ROORKEE (U.P.)	

(I. C . Gupta)
General Manager, Sedawgyi Project(Burma),
Water & Power Consultancy Services(India) Ltd.

D : 27.11.82

(Signatures of Supervisors)

ACKNOWLEDGEMENT

The author wishes to record his grateful thanks to several individuals and organisations who have helped him directly or indirectly in his research study presented here.

The inspiring and scholarly guidance offered by Dr. Mahesh Varma, Professor, Water Resources Development Training Centre and one-time teacher of the author; and by Dr. Bhawani Singh, Professor, Civil Engineering at University of Roorkee is gratefully acknowledged. Grateful thanks are also expressed for Sri I.C.Gupta, General Manager, WAPCOS for his help in data collection from on-going tunnelling projects.

To Professor S.C.Katoch, former Chairman, H.P.State Electricity Board, the author could perhaps never be sufficiently grateful. It was due to him that the author firstly found an opportunity to work on a tunnelling project, and then got the deputation to the Water Resources Development Training Centre at University of Roorkee as a Reader, which paved the way for undertaking this research study. But for Sri Katoch's favourable actions the doctoral studies of the author could perhaps never be possible.

Special thanks are due to the following persons who helped the author in collecting field data : Sri R.K.Malhotra, Sri Sudershan Kumar, Sri B.M.Salwan, Sri S.N.Bhardwaj, and Sri Ranjodh Singh for Beas-Sutlej Link Project : Sri G.N.Tandon, Sri Dev Verma, Sri R.N.Garg, and Sri S.N.Garg for Yamuna Project;

Major S.S.Chauhan and Sri V.K.Sharma for Baira Siul Project; Sri Santokh Singh for Salal Project; Sri K.Madhavan, Sri Vithal Ram, Sri D.P.Verma and Sri K.S.Sharma for Loktak Project; Sri U.S.Rajvanshi for Tehri Dam Project; Sri S.C.Jain for Lakhwar Dam Project; and Sri A.N.Borwankar for Pench Project.

The author also had useful discussions with Dr. Ashok Sahai of Department of Mathematics for statistical analysis; with Dr. G.C.Mishra of School of Hydrology and Sri S.Hazarika of W.R.D.T.C. for computer work; and with Dr. J.L.Jethwa and Dr. A.K.Dube of C.M.R.S.,Dhanbad for geological categorisation of rock formations. Sri Arun Kumar provided help in preliminary screening of data.

The author had useful exchange of ideas and access to literature provided by Dr. Peter J.Tarkoy, Dr. William A.Hustrulid, Prof. Fred Moavenzadeh, Dr. Bieniawski, Dr. Robert M.Stark, Dr. Ing.B.Maidl and Dr. H.Ishii.

And last but not the least, it is his great pleasure to acknowledge the perseverence of his wife Tara, silent neglect experienced by his children Neelam, Seema and Sunil and the encouragement provided by his elder brother Sri S.D.Chauhan which made this study possible.

The secretarial assistance and other facilities used at Water Resources Development Training Centre are also acknowledged.

ABSTRACT

The inherent uncertainties in tunnelling which may be due to geological formations, management effectiveness and equipment performance need to be studied through stochastic modelling. The conventional deterministic approach for evaluation of tunnel construction time is inadequate and results in incorrect time estimates which are generally on the lower side. The stochastic approach developed in this study would hopefully, provide more realistic estimates.

The present study has been an iterative process of development of a methodology involving collection of field construction data; its analysis; identification of the needs for more data; further data collection, and repeating analysis; and final validation of the statistical model. The causes for variations in tunnel advance rates have been identified as changes in job and management conditions. The classification systems have, therefore, been developed for both these conditions dividing them into three categories, viz., good, fair and poor.

The job conditions have been classified on the basis of six simple parameters. These are the geologic structure, rock strength, contact zones, RQD, joint spacing and joint orientation. All these parameters are normally evaluated during the investigation stage. The ranges of values for advance per round (APR) have also been identified for the three job conditions.

Rating values for different parameters affecting the management performance are proposed to classify the management conditions quantitatively. Further, it was noted that the points of inflexion on the curves of cumulative relative frequency(CRF)

versus equivalent monthly progress (EMP) indicate changes in the management conditions.

For each set of job and management conditions, there are two significant components of cycle time which are the actual working time (AWT) and the breakdown time (BDT). These have been found from statistical analysis of data to belong to log-normal and Weibull distributions respectively. The cycle time corresponds to a given advance per round (APR). The analysis for APR did not show a well defined statistical trend. Therefore, weighted average values were adopted.

Tunnel excavation for Pandoh-Baggi tunnel has been simulated on the basis of the classification for job and management conditions and the statistical analysis. The input to computer simulation model included nine statistical parameters for each of the nine sets of job and management conditions. All these 81 parameters have been evaluated from the field data of 3695 excavation cycles. The simulated values were found to be very close to the actual production records which indicated that proposed distributions for AWT and BDT and the classification of different job and management conditions for tunnelling project conform, by and large, to real job conditions.

Finally, a matrix of coefficients has been developed to evaluate the expected monthly progress under different sets of job and management conditions, where computer simulation may not be practicable. The coefficients of this matrix are applicable for full face tunnelling using drill and blast method, on a tunnel of any diameter. The effect of tunnel diameter is taken care of while estimating the ideal monthly progress.

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NOTATIONS

Symbol	Description
a	Location Parameter in Weibull Distribution
AWT	Actual Working Time
b	Scale Parameter in Weibull Distribution
BBDT	Scale Parameter for Breakdown Time
BDT	Breakdown Time
BSL	Beas-Sutlej Link
c	Shape Parameter in Weibull Distribution
CBDT	Shape Parameter for Breakdown Time
COV	Coefficient of Variation
CRF	Cumulative Relative Frequency
d	A Constant (Dependent on Sample Size and Function under Study)
EMP	Equivalent Monthly Progress
ESR	Equivalent Support Ratio
EX	Expected Value
EXA	Mean of Actual Working Time
EXB	Mean of Breakdown Time
exp	Exponent of
EY	Mean of Y
F	Frequency
f(x)	Function of x
F(x)	Cumulative Density Function of x
f(y)	Function of y
Gr	Granite
Ja	Joint Alteration Number
Jn	Joint Set Number
Jr	Joint Roughness Number

Jw	Joint Water Reduction Factor
K	Number of Uniformly Distributed Random Variates
i	Number of Observations
MPa	Mega Pascals
n	Total Number of Observations in the Sample
PP	Plotting Position
Q	Barton's Rock Mass Quality
r, R	Random Number
RF	Relative Frequency
r_i	Random Number Array
RMR	Rock Mass Rating of Bieniawski (1973)
RQD	Rock Quality Designation
RR	Rib Ratio
RSR	Rock Structure Rating of Wickham et al (1972)
SRF	Stress Reduction Factor
STDX	Standard Deviation of x
STDY	Standard Deviation of y
SZ	Shear Zone
TCT	Total Cycle Time
VX	Variance
x	Variate
$\bar{x}$	Mean
y	Log (x)
Z	Standard Normal Variate
σ	Standard deviation
σ_y	Standard Deviation of y
μ_y	Mean of y
π	Pi
Γ	Gamma Function

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CHAPTER 1

THE PROBLEM

1.1 Need for the Study

Excavation of tunnels has been fraught with many uncertainties particularly in the Himalayan region. The estimates of probable time for the completion of tunnels, made at the planning stage, have proved wrong as a matter of rule rather than an exception. The wide variations in the estimated and the actual rate of progress of tunnel excavation are primarily due to the lack of proper consideration for these uncertainties which may be grouped into the following three classes, viz.,

i) variations in ground conditions encountered;

ii) various types of breakdowns or hold ups; and

iii) quality of management.

The first of these entails changes in the method of excavation with changes in geological conditions and adoption of a drilling depth per round so that the pull out (length excavated in one cycle) is optimum while the rock could be supported within the bridge action period. The second pertains to the breakdowns or hold-ups in various operations in the tunnelling cycle. These hold-ups cause random delays. The actual working time for excavation varies from cycle to cycle even under the same ground conditions. This is primarily due to variability in the control being exercised by the management for performance of various operations in the tunnelling cycle which is the third of the above listed uncertainties. All the above three types of uncertainties have a random nature of occurrence with respect to the performance parameters associated with them. These parameters, which account for the three uncertainties, have been found to be the actual advance achieved from a particular depth of drilling, the breakdown time and the actual working time for each excavation cycle. All the three are amenable to statistical analysis.

The investigators in the past have developed models for simulating the muck handling system in the excavation cycle. The input to these models has been generally deterministic adopting the functional relationships and/or the data supplied by manufacturers of equipment. No attempt appears to have been made to simulate the tunnel excavation on the basis of field data; nor any attempt made to test the statistical models for the cycle time data. This aspect has been covered in the present study.

1.2 Proposed Methodology

A methodology has been developed for realistic assessment of the tunnel excavation time for all types of conditions obtainable on tunnelling projects. For this purpose a large volume of field construction data has been collected from several tunnelling projects in the Himalayan region through personal visits and through questionnaires. Gaps in recorded data were observed and the deficiency was made good through personal discussions with the engineers and technicians who worked on the construction of these projects.

The various hydro-electric projects visited for collection of tunnel construction data included Beas - Sutlej Link, Yamuna, Baira-Siul, Giri, Loktak, Salal, Tehri Dam, Lakhwar Dam and Pench. The data collected pertained to the following aspects of tunnel construction for each tunnel heading :

i) Geological formations along the tunnel alighment;

ii) Monthly progress of excavation;

iii) Working cycle time for different periods and under different job and management conditions which include the time taken for individual operations in a tunnelling cycle ;

iv) Breakdown time;

v) Equipment data; and

vi) Other data reflecting conditions of management.

On the basis of the information furnished from the above, the job conditions and the management conditions which existed on the project and are also likely to exist on tunnelling projects in general, have been classified into three categories each, viz., good, fair, and poor.

The job conditions have been classified mainly on the basis of geological formation along the profile taking into account the rock lithology, extent of jointing, compressive strength and general dip and strike of the formation. The presence of water and inflammable gases has also been given consideration. Another important consideration in this classification has been the adoption of a drilling depth necessary to obtain an advance rate for which all operations in the excavation cycle (viz., drilling, loading and blasting, defuming, shifting jumbo, scaling, mucking and rock supporting) could be completed within the bridge action period.

The management conditions have also been grouped into three classes designated as good, fair and poor. The various factors affecting the tunnelling rate which are attributable to management's responsibility have been considered for this classification. These factors in the descending order of their influence on the tunnelling rate are :

i) Overall job planning, including selection of equipment;

ii) Training of personnel;

iii) Equipment availability and preventive maintenance;

iv) Operation supervision;

v) Incentives to workmen;

vi) Co-ordination;

vii) Punctuality of staff;

viii) Environmental conditions; and

ix) Rapport.

The above factors have been further sub-divided and numerical values assigned to each to evaluate an overall rating for the management.

The cycle time data has been grouped according to the above classification of job and management conditions into nine classes and analysed for further studies. Statistical analyses have been carried out for the working time, the breakdown time and the advance per round and the results of these analyses have been used for simulation of tunnel excavation.

1.3 Scope of Study

Simulation studies can be useful and reliable only when the model is a true representation of reality and inputs are reliable. Therefore, it is essential that substantial field data be collected for validation of the simulation model. This data has been collected for the present study from a large number of projects. However, for purpose of analysis the data of only the Pandoh-Baggi tunnel of Beas-Sutlej Link project has been used due to its availability in sufficient volume and detail.

Classification systems for job conditions and management conditions have been developed which combined together result in a unified classification system for tunnelling. The field data has been divided into nine categories according to the proposed classification system. Each category or class has three performance parameters and the corresponding three types of data have been subjected to statistical analysis. These are actual working time (AWT), **Breakdown** time (BDT) and the advance per round (APR). While two of these, viz, AWT and BDT have been found to fit into known probability distributions, the APR values have not been found to conform to any such pattern, and therefore, the weighted average values have been used for this parameter while simulating tunnel excavation.

Based on the results of statistical analyses and the classification system, excavation of Pandoh-Baggi tunnel has been simulated with the help of a computer simulation model developed for this purpose. The results of this simulation were found to agree closely with the actual progress achieved under different job and management conditions.

A matrix of job and management factors has been developed from the data for evaluating tunnel advance rates without computer simulation. The frequency distribution curves of monthly progress in each job condition have been used to find the values of actual monthly progress of tunnel excavation under good, fair and poor management conditions which is indicated by points of inflexion on the cumulative frequency distribution curves. The ideal progress has been computed on the assumption of good management and optimal equipment availability. The job and management factors in the matrix are defined as ratios of actual monthly progress to achievable monthly progress under corresponding set of job and management conditions. Knowing the achievable production for a tunnelling project, these factors could, hopefully, yield values of expected production under different management conditions on the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical Development of Tunnelling Techniques

The methods of construction of tunnels have improved on the principle of Darwins theory from the use of animal bones and horns for rock breakage in 3800 BC to use of fire setting methods, wedging and chipping used until 1679 AD (87). Manual drilling and gun powder came into use during late seventeenth century and continued till later part of nineteenth century, when modern innovations including mechanical appliances for drilling, high explosives for blasting, and locomotives for muck haulage were introduced sometime after 1860. This mechanization was further supplemented with the introduction of equipment for loading of muck during the period 1907-1929 AD. It was during this period that heavier jack hammers of 52- to 97- kg class were also introduced.

Full face tunnelling with light drilling jumbos, using detachable drill bits and car handling system was adopted during the second quarter of twentieth century. During this period two distinct methods for drilling were in vogue. In the American method heavy drifters on hydrobooms were used whereas in the Swedish method lighter rock drills were mounted on ladders.

The ultimate in mechanization in tunnel excavation was achieved with introduction of tunnel boring machine (TBM), or mole during the construction of diversion tunnels for Oahe

Dam in USA during 1953-54 (16). The concept of mole had been introduced as far back as in 1852 to drive Hoosac Tunnel in Western Massachusetts through granite formation. The introduction of TBM necessitated use of high speed back up system for muck removal and also for support erection. Thus, conveyor belts for muck removal and jigs mounted on TBM for support erection were evolved to match the TBM productivity. The applicability and performance characteristics of TBM under different conditions of geology are discussed by various authors (16, 124, 125, 126, 131).

2.2 Conventional Tunnelling Methods

The methods for excavation of tunnels vary according to type of ground conditions, tunnel length, the size and shape of tunnel section and the management decision regarding the choice of equipment. Several authors have suggested various methods for different tunnelling situations (30,37,68,79,84,85,86,104, 105,111,114,118,119,130,145,147). The full face single stage excavation in good to fair ground conditions is suggested for tunnels of diameter upto 8 m by Katoch (68). Katoch suggested two stage excavation by heading and benching method for tunnels of diameter more than 8 m to economize on tunnelling cost and also to speed up tunnelling rate. The multidrift, pilot drift, forepoling and pregrouting methods were suggested for poor ground conditions. The adoption of any particular method depends upon the specific tunnelling situation. Rabcewicz (114); Muller (99); Nussbaum (105); and Ward (147) have suggested the adoption of what is popularly known as 'New Austrian Tunnelling Method' for poor rocks particularly those squeezing in nature.

2.3 Optimization of Excavation Process

For making the conventional drill and blast method efficient and cost effective several types of drilling patterns for tunnels of different diameter within various rock conditions have been suggested by Fraenkel (30); Katoch (68) and others. The quality, quantity and distribution of explosive charges to obtain effective blasting results have also been discussed by Fraenkel (30); Katoch (68); Langefors et al (79); Pequignot(111); and Szechy (130). The overall effect of blasting is improved by the application of delay firing in the form of better fragmentation and lesser damage to the surrounding rock.

The diameter, depth and number of holes in a drilling pattern have a significant effect on the cost and advance rate of tunnelling. Hamrin et al (40) have developed a computerized approach for calculating drilling patterns, charge weights and costs of tunnel driving. Wild (152) suggested that an increase of 1 mm in diameter of explosive cartridges results in decreasing the number of holes in a blasting pattern by 3 percent. However, the diameter of drill holes used normally has been dictated by the commercially available sizes of explosives (111).

The drilling depth and hence the advance per round (APR) is a significant parameter in rapid excavation of tunnels (79). The maximum advance is limited by the size of a tunnel, the drilling pattern and the availability of suitable drilling equipment. To achieve maximum advance from a particular depth of drill holes requires experimentation which at times extends from 3 to 6 months (17,79). In many cases shorter rounds give a better working cycle and more rapid advance per day. It is particularly desirable to adopt such an advance per round which can be completed within one working shift. This principle was applied in excavation of head race tunnel in Giri Project (117), where 1 m advance per shift of 8 hours was adopted for a 5 m diameter tunnel driven in highly squeezing ground conditions. Dutta and Barman (28) have conducted an experimental study in a pilot tunnel to arrive at the maximum pull for a particular drilling pattern, drilling depth and amount of charge.

Maidl (84) has also suggested a method for computing depth of round, number of drill holes and drilling time for tunnel construction.

The optimization of the excavation process involves control of the three main interdependent activities, viz.,drilling, blasting and mucking. The overbreak has also to be controlled at the same time, and thus, modern methods of smooth blasting and presplitting have been developed (68). The suitable drilling pattern, depth of round and the amount of explosive charges can be computed theoretically or determined experimentally for the various situations obtainable on tunnelling projects. The optimization of the whole process including mucking and erection of supports has been studied through computer analysis and the results applied to actual tunnelling situations (18,74,103).

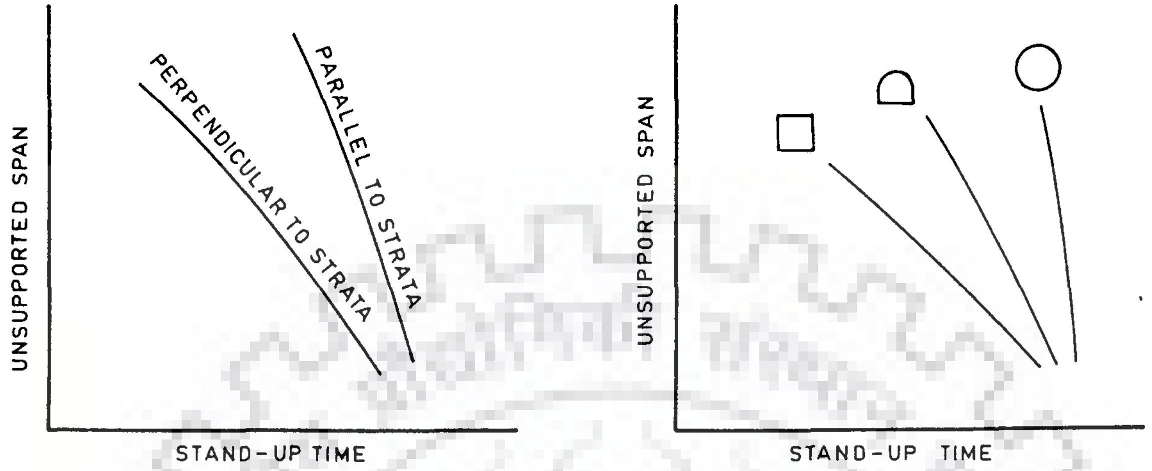
2.4 Classification of Tunnelling Conditions

Classification systems have been developed so far primarily to evaluate the tunnel support requirements. No system exists to classify the tunnelling conditions for the purpose of deciding the method of excavation, the drillability or the fragmentation characteristics of the rock masses. The classification systems which are in existence for rock supporting purposes are of two types (i) the qualitative, and (ii) the quantitative. These are discussed in sub-paras below.

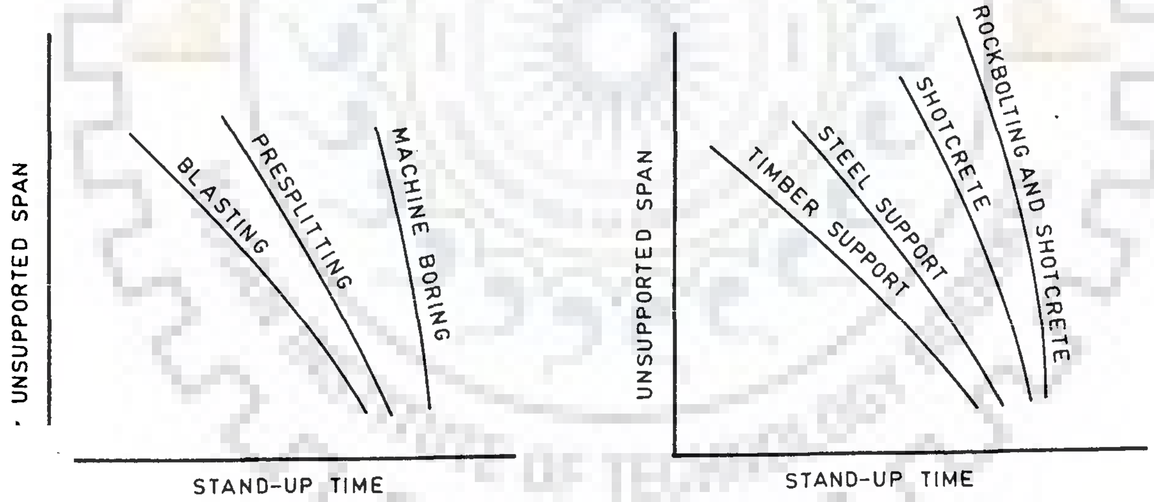
2.4.1 Qualitative systems for rock mass classification

The first qualitative rock mass classification system was propounded by Terzaghi (133) who described the rock mass qualitatively with respect to rock pressure phenomenon. Rock load factors were also given by him for each rock type. His nine classes of rock masses are : (i) hard and intact, (ii) hard, stratified or schistose, (iii) massive to moderately jointed, (iv) moderately blocky and seamy, (v) very blocky and seamy, (vi) completely crushed but chemically intact, (vii) squeezing at moderate depth, (viii) squeezing at great depth, and (ix) swelling.

Lauffer (76) introduced the effective span of the unsupported rock mass as his criterion for classification. His classification system which can be correlated to that of Terzaghi's as also to modern support methods is depicted pictorially in Figs. 2.1 and 2.2. He has categorized his rock classes from A to G, where A signifies stable rock and G heavy squeezing rock.

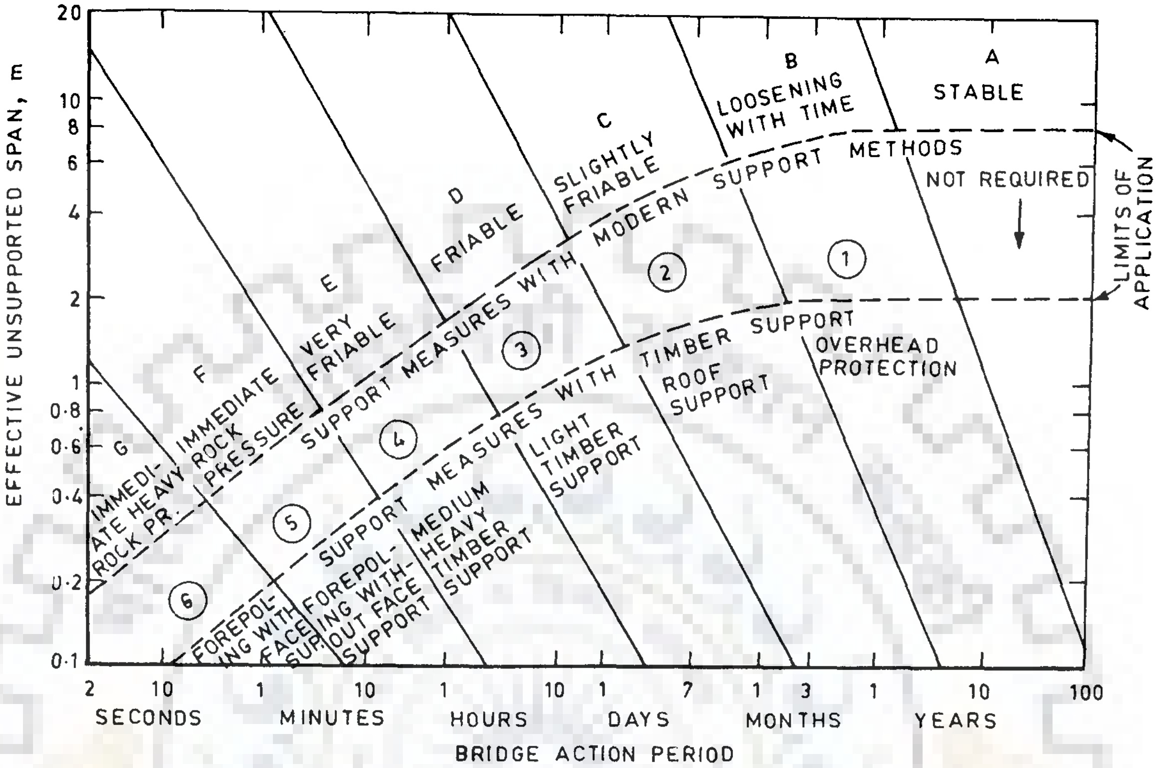


a-ORIENTATION OF TUNNEL AXIS b- SHAPE OF CROSS SECTION



CAVATION METHOD d- SUPPORT METHOD

CTORS INFLUENCING ROCK MASS STABILITY DURING TUNNELLING
(SCHEMATICALLY AFTER LAUFFER, 1958)



(1) SHOTCRETE 2-3 Cm THICK, IN THE ARCH ONLY; OR ROCK BOLTS SPACED 1·5 - 2·0 m AND WIRE MESH

(2) SHOTCRETE 2-3 Cm THICK, IN THE ARCH ONLY; OR ROCK BOLTS SPACED 1·0 - 1·5 m AND WIRE MESH

(3) SHOTCRETE 5-7 Cm THICK AND WIRE MESH; OR ROCK BOLTS SPACED 0·7 - 1·0 m AND WIRE MESH PLUS SUBSEQUENT SHOTCRETING 3 Cm THICK

(4) SHOTCRETE 7-15 Cm THICK AND WIRE MESH; OR ROCK BOLTS (IF POSSIBILE) SPACED 0·5 - 1·2m AND IMMEDIATE SHOTCRETING 3 - 5 Cm THICK; OR STEEL OR CONCRETE LAGGING ON STEEL ARCHES

(5) SHOTCRETE 15-20 Cm THICK, WIRE MESH AND STEEL ARCHES, FACE SUPPORT BY SHOTCRETING; OR STEEL LAGGING ON STRUTTED STEEL ARCHES AND SUBSEQUENT SHOTCRETING

(6) STEEL LAGGING ON STRUTTED STEEL ARCHES AND IMMEDIATE SHOTCRETING

FIG. 2·2 CLASSIFICATON OF ROCK MASS WITH RESPECT TO TUNNELLING AND SUPPORT METHODS
(AFTER LAUFFER, 1958)

c - E

FIG. 2·1

Terzaghi's and Lauffer's rock mass classification systems which reflect practical experiences are most suitable for selecting the tunnel route and cross-section where empirical approach is used for the design. This serves as the basis for tendering and preliminary estimation of tunnel costs and construction time (64).

Lauffer's additional parameters like bridge action period and span of unsupported rock mass, which are determined during construction, serve as the basis for deciding advance per round (Fig.2.2).

2.4.2 Quantitative systems for rock mass classification

Deere (23) proposed a classification system based on fracture spacing and called this Rock Quality Designation (RQD). RQD is defined as the ratio, between sum of lengths of core pieces which are 10 cm or longer in length and the total length of rock core drilled, expressed as a percentage. He, thus, divided the rock types into 5 categories on the basis of RQD :

RQD (percent)	Rock Quality
0 - 25	Very poor
25 - 50	Poor
50 - 75	Fair
75 - 90	Good
90 -100	Excellent

Wickham, Tiedemann and Skinner (150,151) introduced the concept of Rock Structure Rating (RSR) and proposed a quantitative classification system called Ground Support Prediction

Model. The RSR concept considered two broad categories of factors influencing the rock mass behaviour around tunnel openings. These are : geological factors, viz., rock type; joint pattern (spacing); joint orientation (dip and strike); discontinuities (condition of joint); faults, shears and folds; rock material properties; ground water and degree of weathering or alteration; and construction factors, viz., size of tunnel opening, direction of drive and method of excavation.

The above factors have been grouped into three parameters named A, B and C. Parameter A represents general geology of the rock mass; B, the joint pattern; and C, the ground water and joint conditions.

Each factor has been evaluated on the basis of past experience and corresponding weighted numerical values have been assigned which reflect the relative effect of the factor on the overall support requirement.

The RSR of a given mass for a tunnelling project is defined as the sum of the values of parameters A, B and C corresponding to the local characteristics of this rock mass. The RSR has been found to vary from a lowest possible value of 19 of the worst possible rock condition to a maximum of 100 for ideal condition.

In this method the rock pressure is considered to increase directly with tunnel size (as believed by past investigators). This system is more suited to conventional tunnelling method with drill and blast method for excavation and supporting with steel arches because 90 percent of case histories which form the basis for evolution of this system employed this method.

The correlation between RSR and rib ratio (RR) is shown in Fig. 2.3. RR is defined as the ratio between theoretical rib spacing and actual rib spacing.

Bieniawski (7) has proposed another quantitative classification system which includes Deere's RQD and several other factors listed below (31) :

(i) Rock Quality Designation (RQD), (ii) state of weathering, (iii) uniaxial compressive strength of intact rock, (iv) spacing of joints and bedding, (v) strike and dip orientation, (vi) separation of joints, (viii) continuity of joints, and (viii) ground water inflow.

Bieniawski (7,8) recognized that each parameter does not necessarily contribute equally to the behaviour of rock mass. He assigned ratings to each parameter in five categories. The sum of ratings is called Rock Mass Rating (RMR) which varies from 0 to 100. The five classes of rock masses as categorized by Bieniawski are shown in Fig.2.4.

Barton, Lien and Lunde (5) of the Norwegian Geotechnical Institute (NGI) have also prepared an index for the determination of tunnelling quality of a rock mass. This starts with Deere's RQD and allows for the influence of joint set (Jn), joint roughness (Jr), joint alteration (Ja), joint water (Jw), and a stress reduction factor (SRF). The resulting rock mass quality (Q) is given by

$$Q=(RQD/Jn)X(Jr/Ja)X(Jw/SRF)$$

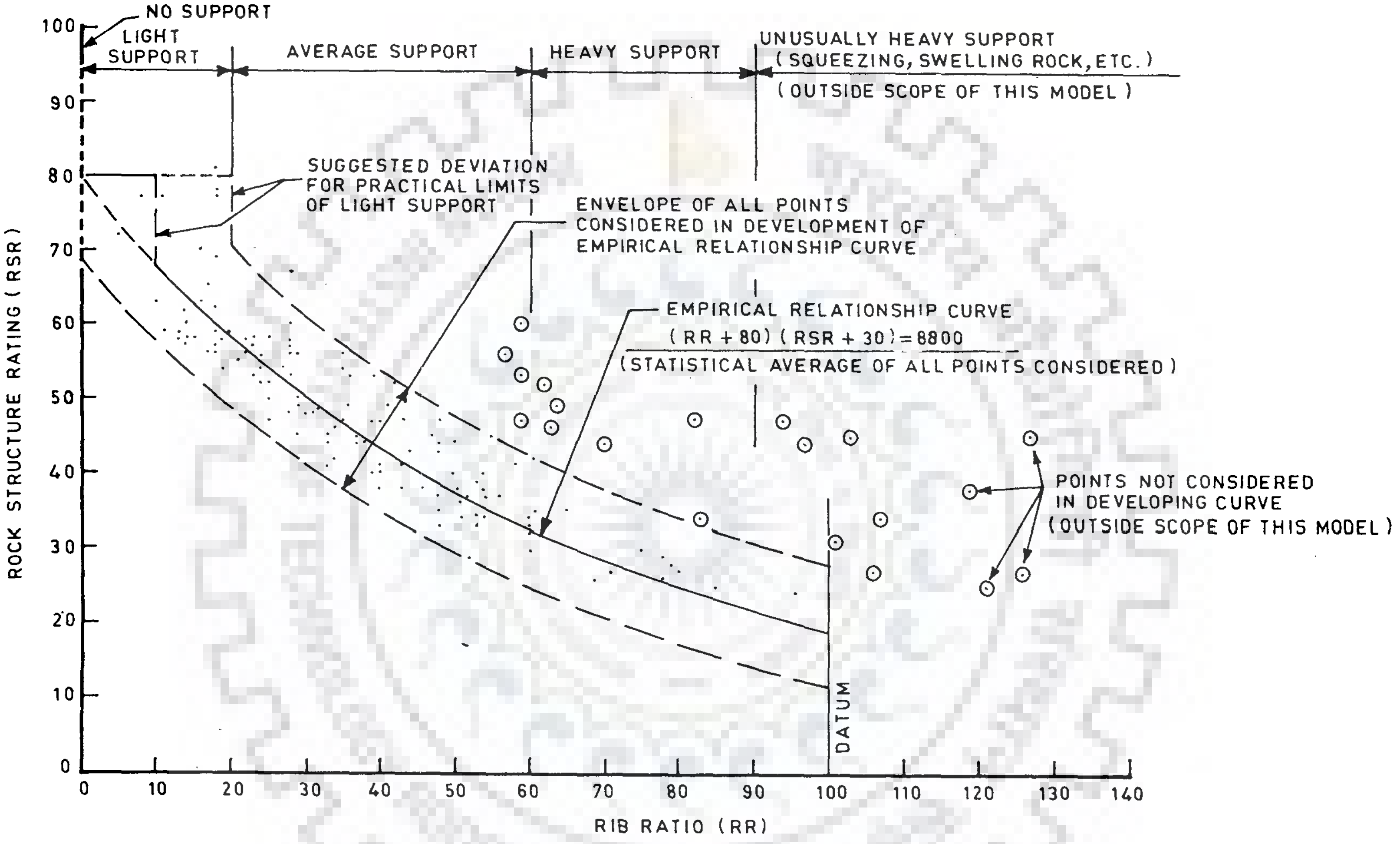


FIG. 2·3 FINAL CORRELATION OF RSR AND RR
(FROM JACOBS ASSOCIATES, 1974)

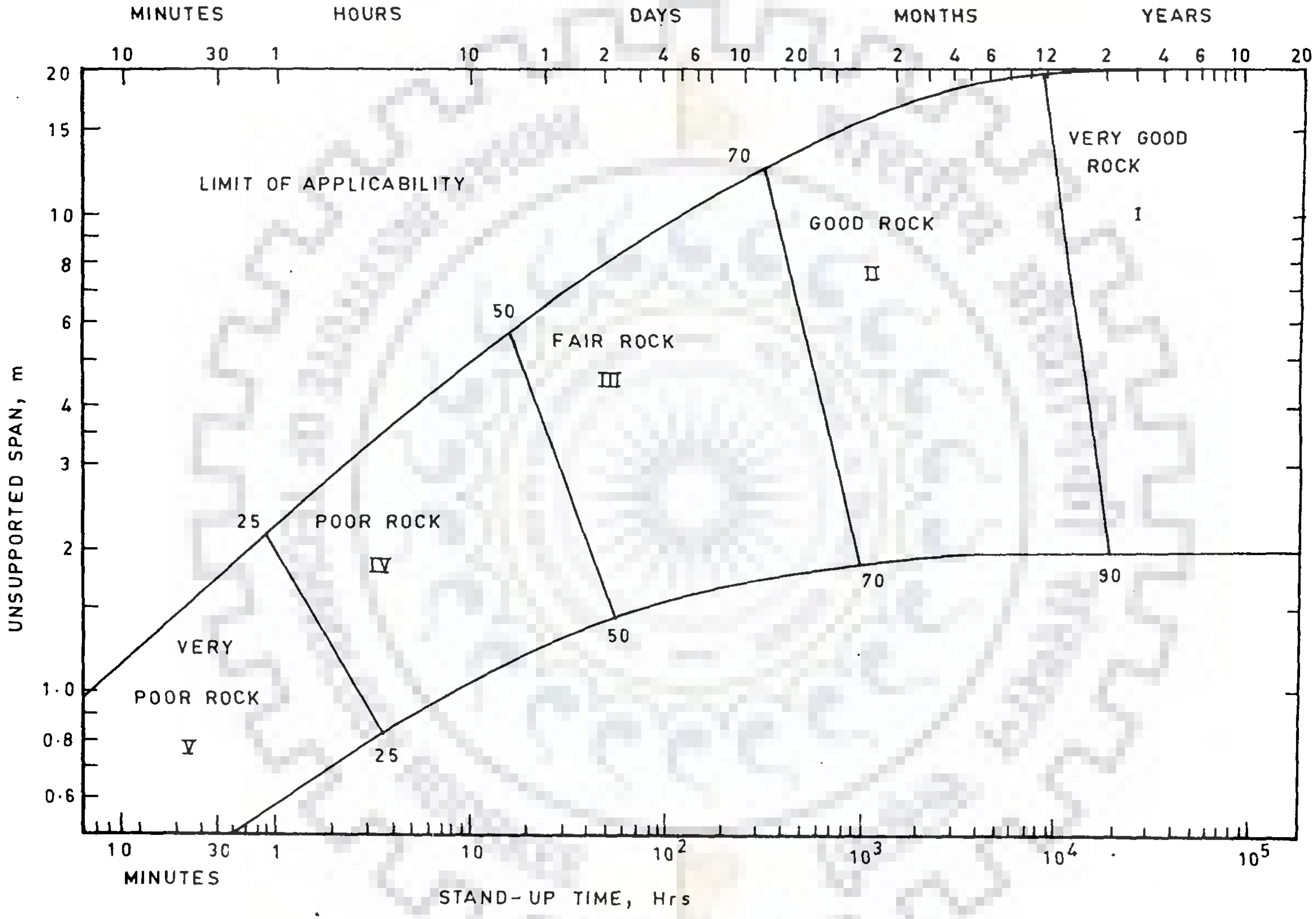


FIG. 2·4 GEOMECHANICS CLASSIFICATION OF ROCK MASSES FOR TUNNELLING
(AFTER BIENIAWSKI, 1973)

The first factor (RQD/Jn) represents the structure of a rock mass, viz., the block size; the second factor (Jr/Ja) represents the roughness and frictional characteristics of the joint walls or filling materials, viz., the inter block shear strength; and the third factor (Jw/SRF) is a complicated empirical factor describing the active stresses.

The ratings for various parameters have been given and final rock mass quality is used to divide the rock mass into 38 categories as shown in Fig.2.5 for purpose of support requirements. The value of Q may vary from a minimum of 0.001 to a maximum of 1000. Hence it appears that Barton's system is the most sensitive quantitative classification system to date.

2.5 Statistical Approach

2.5.1 Sampling

In statistical analysis the population or universe and the sample play a significant role. To derive information about the population parameters, random sampling has to be done(6,146). If we had equally well established and stable laws of personal bias, subjective sampling could be used (109). Markovic(88) also suggested that the samples should be drawn after fixing certain operating criteria.

2.5.2 Statistical parameters

The information about population parameters can be projected from the knowledge of the first four moments of sample statistic. Schmeiser and Deutsch(123) have used the four moments, viz., mean, variance, skewness and kurtosis with suitable transformations to develop a versatile four parameter family of probability distributions suitable for simulation.

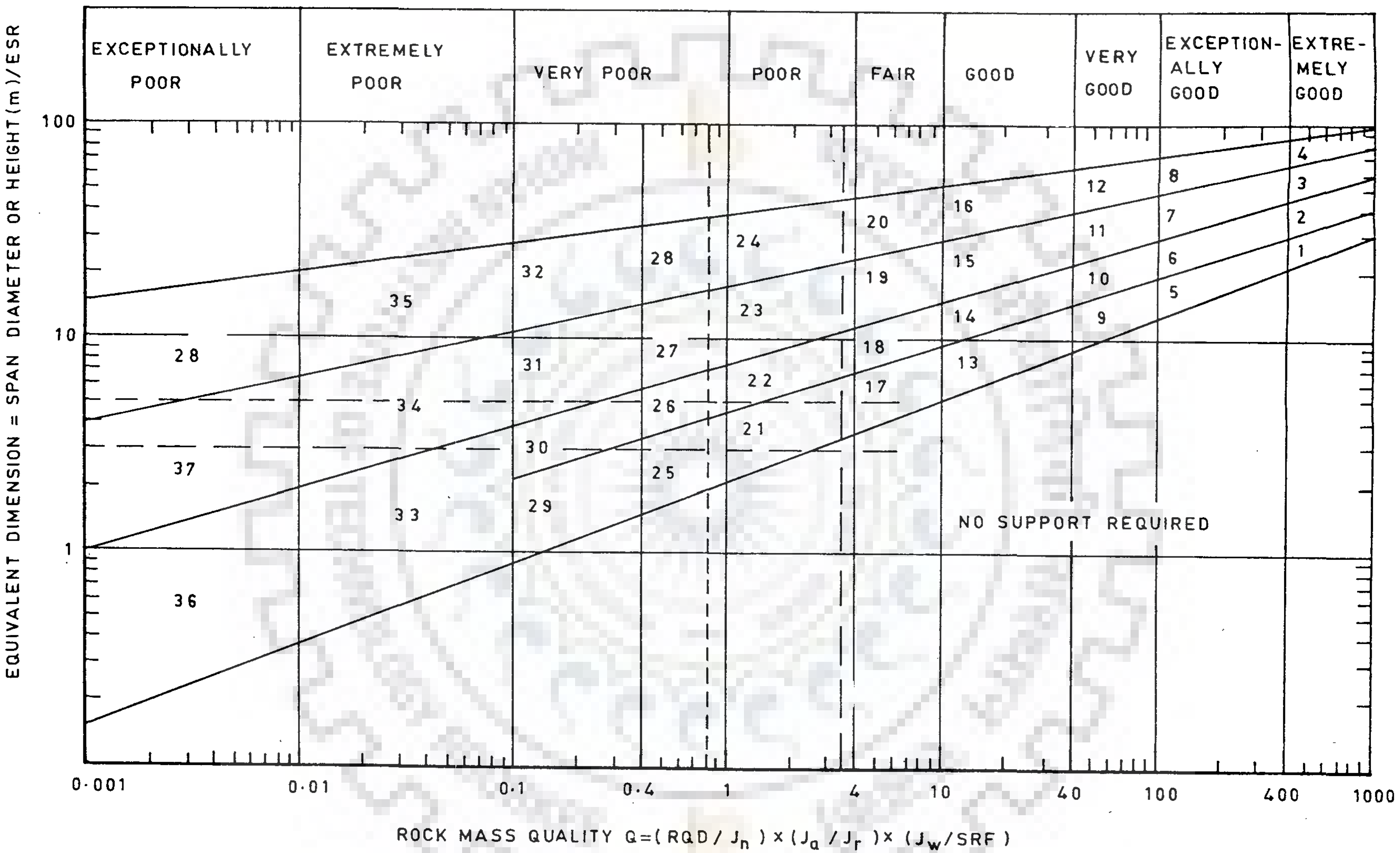


FIG. 2.5 TUNNEL SUPPORT CHART SHOWING THE BOX NUMBERING FOR 38 CATEGORIES OF SUPPORTS

(AFTER BARTON et al, 1974)

Benjamin and Cornell(6) have stated that the first two moments, viz., the mean and the variance alone contain a substantial amount of information on which to base engineering decisions.

2.5.3 Sample size

In sampling experiments, the question of optimal sample size is one of economic importance. On the question of sample size Ostle (109) has stated that the statistician can provide an ' educated guess' after seeking information on several aspects. In some cases fairly simple formulae are available for estimating the required sample size (139). Operating characteristic (OC) curves and tables are also available for finding the sample size (109). Pentico (110) has suggested simple relations to determine optimal sample size for a given difference of means of two samples.

2.5.4 Class interval

There is no generally accepted universal method for determination of number of class intervals (88). However, rules have been suggested for deciding on the class interval. The choice of the length of class interval should be done in such a manner that the main characteristic features of the observed distribution are emphasized and chance variations are obscured (39). Basically there are two concepts for choice of the length of class intervals, viz., equal lengths, and equal probabilities.

Equal lengths of class intervals are extensively used even though there is no theoretical basis for the same and a commonly used thumb rule states that the number of class intervals should be so chosen that the average expected frequency of any class interval is at least five (88). According to

Ostle (109) there should be no fewer than 5 and no more than 15 intervals in the entire population. Walpole and Myers (146)have extended the range of choice between 5 and 20 intervals. Varma (138) has pointed out that the class interval should be chosen so that an optimum combination of smoothness and detail is obtained.

2.5.5 Goodness-of-fit testing

The problem of testing the goodness-of-fit of a hypothesized probability distribution to observed sample distribution was solved first by Pearson (1900) who developed the Chi-square test (88). Later, Fisher (29) contributed the significant idea of ' degrees of freedom' which account for parameters estimated from the observed data while finding the tabulated value of Chi-square. Chi-square test is versatile in as much as any distributional assumption can be tested. However, it has a serious drawback that arrangement of data into arbitrary cells can affect the outcome of the test significantly (38). Moreover, it is difficult to select a suitable probability density function in the event of more than one distributions being found to fit using Chi-square test. Allen Hazen(1914) developed the probability paper. This suitably scaled paper provides a simple means of testing any distributional assumption by using the corresponding probability paper for plotting the data(122). This technique provides: (i) a pictorial representation of the data; (ii) an evaluation of the reasonableness of the assumed probability model; (iii) estimates of the percentiles of the distribution; and (iv) estimates of the distribution parameters. This information may be obtained even with censored data(38).

2.6 Simulation

The origin of modern simulation methods can be traced to the development and highly successful use of Monte Carlo method by Neumann, Ulam and Fermi for dealing with problems related to the shielding of nuclear reactors during World War-II (43,96). The extensive use of simulation started only when the high speed digital computers were introduced in the 1950's. This review is, however, confined to the use of simulation in tunnel excavation process only.

In tunnel excavation the inherent uncertainties which may be accounted for in simulation modelling are those of geological formation and of the performance of various tasks in the tunnel excavation cycle, notable amongst them being: (i) muck generation; (ii) material handling; (iii) roof support; and (iv) environmental conditions (100).

2.6.1 Simulation of geologic formations

The geological predictions may be both subjective and objective (97,98). Use of the Markov chains (43) or the theoretical analysis (150,151) may be made to predict the rock formation along the tunnel alignment. Moavenzadeh et al (98) suggested a decision tree concept for prediction of geological formations assigning probabilities to various parameter states based on subjective judgement of the geologist and through Markov process analysis. Harbaugh and Carter (43) proposed application of statistical distributions for prediction of geologic states. These could be the known theoretical distributions, or empirical distributions could be constructed based on the data.

2.6.2 Random variable

Many dynamic simulation models require variables which are supplied from an external source as exogenous variables. These input variables may be deterministic represented by simple mathematical functions or these may be stochastic which show random behaviour (43,101). The stochastic variables conform to known probability distributions, each characterized by a set of parameters (43). The artificial variable whose statistical behaviour resembles that of the actual variable may be generated through random sampling from the known distribution. The procedures for generation of random numbers and for statistically testing these have been discussed by several investigators(43, 96,101,135). Modern high speed digital computers, however, provide library functions for generation of pseudo-random numbers applicable in simulation experiments.

The variables of interest in simulation experimentation may be generated from the known continuous probability distributions by any of the three basic methods, viz., the inverse transformation method, the rejection method and the composition method (101). For generating variates of an empirical distribution or of a discrete distribution the method suggested by Marsaglia could be used (101).

2.6.3 Simulation of mucking operation

Out of the various operations in tunnel excavation cycle, muck handling has attracted maximum attention. Nelson (102) simulated the working of a mine haulage locomotive to decide its optimum load size to achieve maximum haulage rate. He had, however, not considered the simultaneous deployment of more than one locomotive which is necessary in excavation of long tunnels.

This deficiency was studied by Konya et al (74) and Mutmansky (100) in their models for simulating muck handling in tunnel excavation. Konya et al (74) have applied the simulation model to construction of SEI-KAN tunnel in Japan. They identified the optimal number of trains required for muck removal and the average waiting time for trains. Mutmansky (100) studied material handling in conjunction with TBM seeking to obtain the following information through the application of his model:

i) optimum number of trains to use in a specific tunnelling situation;

ii) optimum location of California switches in the tunnel;

iii) proper size and utilization of the tunnel crew; and

iv) better type of material handling method (cyclic or continuous) for different lengths of the tunnel.

2.6.4 Simulation of overall tunnelling

The effect of various types of delays and breakdowns on tunnel construction progress has been studied by Nesargi(103) in evaluating the effect of concurrent excavation and concrete lining on the completion time of tunnel vis-a-vis the sequential mode of concrete lining and excavation. In the process of simulating the system behaviour, the optimal combination of equipment for least time of construction was also evolved. In his analysis triangular distribution was used for most of the variables and three time estimates were adopted. The breakdowns were, however, simulated through the use of empirical distributions due to availability of limited real world data. Priority rules were set for permitting movement of locomotives between two California switches or rail sidings as also between muck removal and concrete placement.

2.6.5 Tunnel cost model (TCM)

Moavenzadeh et al (97,98) have developed a tunnel cost model for simulating the tunnelling process through the application of three sub-models; the geologic sub-model, the construction sub-model and the tunnel simulator. They have provided options in their model for data to be supplied directly or to be generated within the model itself as needed by the analysis. The result was a scattergram indicating variability of costs and periods in the construction of tunnels.

2.7 Combined Effect of Job and Management Conditions on Tunnelling

Tunnel advance rates and, therefore, the costs are affected as much by the variability in management conditions as by job conditions. This aspect of tunnelling has not been studied by any investigator to the best of author's knowledge. However, in the area of performance of equipment, Nikirk developed factors for scaling down the ideal production of excavators for different job and management conditions (112). All working conditions were divided into four categories of job and four categories of management conditions, viz., excellent, good, fair and poor. Table 2.1 gives the matrix of these factors as suggested by Nikirk.

TABLE 2.1

JOB AND MANAGEMENT FACTORS FOR EXCAVATORS

		Management condition			
		Excellent	Good	Fair	Poor
Job condition	Excellent	0.84	0.81	0.76	0.70
	Good	0.78	0.75	0.71	0.65
	Fair	0.72	0.69	0.65	0.60
	Poor	0.63	0.61	0.57	0.52

2.8 Concluding Remarks

On the basis of this review the following gaps were identified in the area of simulating the tunnel excavation process:

i) For a particular diameter tunnel, the technique of construction is not varied unless there is a significant change in the job conditions. This indicates a strong need for classification of job conditions to suit the significant variations in ground conditions.

ii) The periods for individual operations, and hence, the total cycle time in the tunnel excavation process is affected as much by the management efficiency as by the job condition. This aspect has not been studied yet.

iii) The simulation studies conducted for tunnelling so far have been based on empirical methods or computations of average production estimates for equipment and operations using manufacturer's data. The performance of equipment and personnel in the underground restricted space is adversely affected by changes in working environment. The achievable production in such cases could be assessed much better on the basis of past performance rates for which extensive field data is required.

iv) The analysis of tunnel construction data to discover specific statistical behaviour of the activity performance time has also not been done in the past.

v) Simulation of tunnel excavation based on field data has not been attempted so far.

vi) Factors for prediction of tunnel advance rates under different job and management conditions, such as, through use of job and management factors have not been evaluated yet.

Some of the above listed deficiencies in our knowledge of the behaviour of prominent factors in tunnelling performance will, hopefully, be made good through the results of this study.

CHAPTER 3

COLLECTION OF FIELD DATA

3.1 General

Tunnelling is a complex activity affected by a large number of variables. These variables may be ascribed to the job and/or management conditions. Thus the data pertaining to both these conditions is important in order to study the effect of all the variables on the progress of tunnel excavation. In a simulation study like the present one the formulation of problem and collection of data go together as the experimentation on the model may indicate the need for additional data while lack of data may call for modifying the problem and the model. Thus, the study becomes an iterative process. Hence, the data for the present study was collected in different phases as and when its need was felt.

3.2 Types of Data Needed

Both the descriptive and quantitative data is of interest in this study. The tunnelling rate is affected by both, the job and the management conditions, which are usually difficult to quantify.

The job conditions are affected by the following factors:

i) Geology, such as, type of rock, RQD, jointing system, dip and strike of strata, presence of major fault or thrust zones and uniaxial compressive strength of rock;

ii) Water flow, including probable quantum of water expected to be met with;

iii) Presence of inflammable gases;

iv) Size and shape of tunnel;

v) Whether the construction adits are horizontal or inclined; and

vi) Maximum drilling depth or advance per round which can be adopted.

The management conditions are affected by the following factors for which generally the descriptive data is required to be collected:

i) Overall planning for the job including planning for equipment, manpower and materials;

ii) Training of personnel affecting equipment maintenance, breakdowns of equipment, overbreak in excavation and quality of supervision;

iii) Incentives to workmen;

iv) Co-ordination and rapport;

v) Environmental conditions inside the tunnel; and

vi) Staff punctuality.

Both the above, viz., job conditions and management conditions have a cumulative effect on the tunnel cycle time, which, in turn, governs the progress of excavation. Thus, the cycle time data for tunnel excavation giving details of time taken for each individual operation in the excavation cycle is of utmost importance for simulation. This data is needed for a considerable period so that it covers, by and large, all possible job and management conditions on the project.

Monthly actual progress of excavation for as long a period of construction as possible is another important data needed for this study; as this enables correlation of ideal with real progress or validation of results of the model.

3.3 Identification of the Sources of Data

Collection, sorting, collating and disseminating of construction data is difficult due to the cost and human effort involved in the process. On most construction sites this data is either not recorded and maintained at all, or is poorly recorded. This is due to the lack of awareness of the need for recording data in proper form. The analyst has to sift and painstakingly isolate useful content from a mass of redundant and sometimes scanty information. However, on projects where the management was conscious of this need, the data was properly recorded and fairly well maintained. One such project is the Beas-Sutlej Link project in the state of Himachal Pradesh in India for which extensive recorded data on tunnelling is available.

The following sources of data have been found to exist on the projects and were made use of for the purpose of this study:

i) Records maintained by construction agency in the form of registers, charts, graphs, geological profiles, etc;

ii) Personal discussions with engineers, foremen and other technicians in charge of various construction activities;

iii) Personal recording of data at site by the author;

iv) Papers published in various journals and the proceedings of symposia and conferences; and

v) Personal experience of author on the construction of a tunnelling project in the Himalaya.

3.4 Collection of Data and Its Listing

The data collection was done in more than one stage. As a first step formats for collection of data were devised and sent to various projects for compliance. The data received thus proved to be inadequate and had to be supplemented with information collected through personal visits. Copies of records as maintained by project authorities were obtained, and a scrutiny of the same helped in visualizing the need for discussions with construction personnel. The discussions helped to clarify issues and indicated need for further information which was collected through subsequent visits and/or questionnaires.

The projects visited for the purpose of collection of field data are shown in Table 3.1. Most of these projects were under construction during the period of study. Projects at serial Nos.1 to 6 as listed in the Table were visited more than once to collect necessary data. Eight of the projects pertain to sub-Himalayan region for which the study is primarily aimed. The last of these is located in central part of the country and was visited in order to have a relative idea about the working conditions in the two regions.

The type of data collected from all these projects comprised of the following :

i) geological profile along the tunnel alignment;
ii) equipment performance and its breakdown;
iii) monthly progress for all tunnel headings;
iv) cycle times for each day; and
v) other information considered of interest.

The visits to project sites were made over a period of 4 years from 1978 through 1981. As far as possible on-going projects were given priority in visits although a bulk of the information was obtained on recently completed projects.

The cycle time data from all projects was collected and recorded in the formats devised for the purpose (Appendix I and II).

This data has been stored on a magnetic tape on DEC SYSTEM-20 Computer at University of Roorkee (1).

TABLE 3.1

PROJECTS VISITED FOR DATA COLLECTION

Sl. No.	Name of project	Tunnel excavation	
		Year started	Year completed
1	BSL Project		
	i) Pandoh-Baggi Tunnel	1965	1975
	ii) Sundernagar-Sutlej Tunnel	1967	1975
2	Yamuna Project		
	i) Ichari-Chhibro Tunnel	1967	1973
	ii) Chhibro-Khodri Tunnel	1968	1981
3	Baira-Siul Project Head Race Tunnel	1973	1979
4	Giri Project Head Race Tunnel	1968	1976
5	Loktak Project Head Race Tunnel	1973	1981
6	Salal Project Tail Race Tunnel*	1979	-
7	Lakhwar Dam Project Diversion Tunnels	1980	1981
8	Tehri Dam Project Diversion Tunnels**	1979	1981
9	Pench Project Tail Race Tunnel	1975	1980

*Project in progress
**Only heading excavated

3.5 Processing of Data

The recorded data was processed for the purpose of various analyses given in following chapters. This processing is discussed in Chapters 4 and 5.

CHAPTER 4

CLASSIFICATION SYSTEMS FOR JOB AND MANAGEMENT CONDITIONS

4.1 Need for Classification

Working conditions on tunnelling projects are highly variable, even on the same project, and a uniform rate of progress over the entire period of construction is difficult to maintain. The purpose of the classification system is to divide these working conditions into groups of similar behaviour with respect to the tunnelling rate. This grouping may be done according to the rate of advance made per round and the cycle time for that advance. While the advance in each round will be controlled by job conditions, the cycle time will generally be governed by the quality of management.

Three main time elements in a tunnel excavation cycle are - drilling, muck removal and rock supporting. At present there is no classification system for drillability of rocks and their fragmentation characteristics which affect the time for drilling and mucking. However, a number of classification systems for rock masses in respect of support requirements (5,7,23,76,133,150) have been developed. The geological formations have also been classified according to their lithology, such as, rock type, mineralogy and texture (41), uniaxial compressive strength (24,128) and extent of jointing and type of joint surfaces(5,34).

The adoption of correct drilling pattern for a given rock condition, proper alignment of drill holes and suitable use of explosive charges can ensure high percentage of pull out (actual advance) and good fragmentation of rock from a particular drilling depth in a given rock condition. The control of these factors is governed by the management conditions. Other components in the excavation cycle such as mucking, ventilating,etc. are also affected by management conditions. Therefore, a unified classification system for tunnelling is required which considers the effects of both, job conditions and management conditions, on the tunnelling rate.

4.2 Job Conditions

In tunnelling, variations in underground formations result in variations in the job conditions, at times, even from one cycle to another. Often these variations are significant in affecting the selection of tunnelling method and estimating the rate of progress achieved.

In this study the classification of job conditions has been done into three categories, viz., good, fair and poor. This classification reflects the effect of geologic formations on the job and is shown in Table 4.1. Table 4.2 gives an extract from tunnelling data showing the actual classification of geology made by the author according to the three categories. For each geology the monthly tunnel advance made is also shown.

Job conditions are inherent in the job and have to be faced as they occur. Nothing can be done to improve or alter them. It is only at the planning stage that an alternative alignment for the tunnel may be selected if economically and technically feasible to obviate the adverse geology predicted during the investigations. This was done in the case of tunnels on Giri and Yamuna projects in India(27,63,117). The alignment of tunnel axis with respect to strike and dip of rocks, the presence of water and inflammable gases, the size of opening and the advance to be adopted in a particular geology also affect the tunnelling rate.

TABLE 4.1

CLASSIFICATION OF JOB CONDITIONS

Sl. No.	Parameters	Job conditions		
		Good	Fair	Poor
1	2	3	4	5
1	Geologic structure	Hard, intact, massive stratified or schistose, moderately jointed, blocky and seamy	Very blocky and seamy squeezing at moderate depth	Completely crushed, swelling and squeezing at great depth
2(a)	Point load strength index	>2 MPa	1 - 2 MPa	Index cannot be determined but is usually less than 1 MPa
(b)	Uniaxial compressive strength	>44 MPa	22 - 44 MPa	<22 MPa
3	Contact zones	Fair to good or poor to good rocks	Good to fair or poor to fair rocks	Good to poor or fair to poor rocks
4	Rock Quality Designation (RQD)	60 - 100 %	25 - 60 %	<25 %
5(a)	Joint formation	Moderately jointed to massive	Closely jointed	Very closely jointed
(b)	Joint spacing	>0.2 m	0.05 - 0.2 m	<0.05 m
6(a)	Joint orientation	Very favourable, favourable and fair	Unfavourable	Very unfavourable

1	2	3	4	5
6(b)	Strike to tunnel axis and Dip w.r.t.tunnel driving	(i) Perpendicular 20° to 90° along dip 45° to 90° against dip	i) Perpendicular 20° to 45° against dip	i) Parallel 45° to 90°
		ii) Parallel 20° to 45°	ii) Irrespective of strike 0° to 20°	
7	Inflammable gases	Not present	Not present	May be present
8	Water inflow	None to slight	Moderate	Heavy
9	Normal drilling depth/round	>2.5 m	1.2 m - 2.5 m	<1.2 m
10	Modified bridge action period	>36 hrs.	8 hrs. - 36 hrs.	<8 hrs.

Note: The geologist's predictions based on investigation data and laboratory and site tests include information on parameters at Sl.Nos. 1 to 6. This information is considered adequate for classifying the job conditions.

TABLE 4.2

EXTRACT FROM TUNNELLING DATA

Tunnel heading	Month/year	Geology	Author's job classification	Monthly progress (m)
Pandoh downstream	Jan.,1967	Interbedded phylites and quartzites	Good	67
	March,1968	Granite	Good	111
	May, 1971	Blocky to closely jointed granite with thin kaolinized seams (distressed portion)	Poor	19
	Feb.,1972	Blocky to closely jointed granite with very minor schist lenses and schist seams	Fair	25
	July, 1972	Moderately jointed coarse grained granite	Good	82
Baggi	Aug., 1966	Phylitic quartzites and phylites (low advance rate)	Fair	64
	Jan., 1968	Massive coarse grained porphyritic granite	Good	84
	Nov., 1968	Blocky granite with schist bands	Good	93
	June, 1969	Highly broken granite	Fair	60
	Nov.,1969	Talcase schist	Poor	39

This categorisation of geology into three classes only as against five to nine classes suggested by the earlier investigators in relation to support requirements is found to be adequate due to the following reasons :

1) The proposed classification is simple and its parameters can be assessed during planning stage. Barton's parameters have not been included in this classification because their estimation is difficult in advance of tunnelling.

2) The method of excavation is not affected for rock conditions varying from very good to fair but could vary only when these conditions change from fair to poor. The effect of change in method of excavation is thus adequately accounted for in this classification.

3) Any feasible advance per round may be adopted for good rock conditions as the bridge action period will always be greater than the expected cycle time. For fair and poor rock conditions the advance per round is governed by the bridge action period and has to be so restricted that the rock is supported within this period after blasting.

The basis for classification as given in Table 4.1 is discussed as below :

1) The first parameter (geologic structure) gives qualitative description of the rock mass which is based on Terzaghi's (133) system.

2) The second parameter (point load strength index/uniaxial compressive strength) reflects the strength characteristics of the rock mass and is based on Bieniawski's quantitative

system (7). According to IS 8764-1978 (61), maximum compressive strength is 22 times the point load strength index.

3) The third parameter reflects transition conditions. Whenever there is a change of geology, it may or may not be abrupt. This effect may be classified on the basis of its effect on performance. If the change takes place from poor to good or from fair to good, then the transition is considered as 'good'. On the other hand, when 'good' condition suddenly changes to 'poor', the transition is considered as poor.

4) The fourth and fifth parameters, viz., RQD and joint spacing are inter-related. These have been grouped according to Deere's (23) and Wickham's (150, 151) systems.

5) The sixth parameter, viz., joint orientation, dip and strike are based on Bieniawski's system. Very favourable, favourable and fair orientation of joints are all assumed to fall under proposed 'good' category.

6) The seventh and eighth parameters relate to presence of inflammable gases and underground water. Inflammable gases are generally not expected to exist in good and fair job conditions. The mild to moderate waterflow which can be controlled without affecting the normal working cycle, could, however, be expected under these conditions. The presence of inflammable gases and also heavy inflow of water may significantly affect the working and, therefore, such conditions have been classified as poor.

7) The next parameter, viz., range of normal drilling depth, is based on the actual achievements realized in the field in corresponding rock conditions.

8) The last parameter, viz., modified bridge action period plays a significant role in deciding the rate of advance and has been defined as the period within which no major rock fall would take place before supports are erected. Bieniawski (7) and Lauffer (76) have considered the bridge action period as the time from initiation of blast upto the first fall of a piece of rock. Such marginal detachments of rock pieces are not found to affect the normal working significantly and are, therefore, ignored in the present classification.

4.3 Management Conditions

The management conditions on tunnelling jobs are more difficult to classify than the job conditions since the various management factors affecting the tunnelling rate are not easily quantifiable, and some of these are even interdependent. The concept of quantifying the various factors proposed here is basically a method of describing the quality of management which governs the tunnelling rate. All management factors contribute to or affect in some way the tunnelling rate achieved. Each of them can be considered individually or all of them can be considered collectively combining their relative effect on each other. By assigning a weighted numerical rating to each factor, it is possible to define the management conditions on the basis of the total sum of ratings for all the individual factors. The higher number is reflective of good management yielding higher tunnelling rates while the lower number is indicative of poor management resulting in slow rate of tunnelling. The factors which have been considered to develop the classification system for management conditions are given in Table 4.3.

TABLE 4.3

RATINGS FOR MANAGEMENT FACTORS

Sl. No.	Sub-group	Item	Maximum rating for item	Maximum rating for sub-group	Remarks
1	2	3	4	5	6
1	Overall job planning	i) Selection of construction plant and equipment including estimation of optimal size and number of machines required for achieving ideal progress	7		
		ii) Adoption of correct drilling pattern and use of proper electric delays	6		
		iii) Estimation and deployment of requisite number of workmen and supervisors for ideal progress	5		
		iv) Judicious selection of construction method, adits, location of portals, etc.	4		Horizontal adits sloping @ 7% towards portal to be preferred to inclined adits or vertical shafts
		v) Use of twin rail track	2		
		vi) Timely shifting of California switch at the heading	2	26	

1	2	3	4	5	6
2	Training of personnel	i) Skill of drilling crew in the correct holding, alignment and thrust application on drilling machines	4		Proper control of drilling and blasting will ensure high percentage of advance from the given drilling depth and also good fragmentation of rock which facilitates mucking operation.
		ii) Skill of crew in charging holes	2		
		iii) Skill of muck loader operator	4		
		iv) Skill of crew in support erection	3		A skilled crew should not take more than ½ hr. for erection of one set of support.
		v) Skill of other crews	2	15	
3.	Equipment availability and preventive maintenance	Time lost due to breakdowns of equipment including derailments, etc.;			
		i) upto 1 hr.	12-15		
		ii) 1 - 2 hrs.	9-11		
		iii) 2 - 3 hrs.	6-8		
		iv) >3 hrs.	0-5	15	
4	Operation supervision	i) Supervision of drilling and blasting (effectiveness depends on location, depth and inclination of drill holes, proper tamping and use of blasting delays)	7		Improper drilling may result in producing : i) unequal depth of holes which results in lesser advance per metre of drilling depth,

1	2	3	4	5	6
					ii) wrong alignment of holes which may lead to : a) overbreak due to wrong inclination of periphery holes, and b) secondary blasting due to wrong inclination of other than periphery holes. Improper tamping of blast hole charge and wrong use of blasting delays result in improper blasting effects.
		ii) Supervision of muck loading/ hauling system	3		Especially in rail haulage system in which rapid feeding of mine cars to loading machine at the heading is essential for increasing productivity of loader.
		iii) Supervision of rib erection, blocking and packing	3		
		iv) Other items of supervision such as, scaling, layout etc.	2	15	
5	Incentive to workmen	i) Progress bonus	5		Define the datum monthly progress as that value which delineates good and fair management conditions for a particular job condition. Introduce bonus slabs for every additional 5 m progress and distribute the total

1	2	3	4	5	6
					monthly bonus thus earned amongst the workmen on the basis of their importance, skill and number of days worked during the month. The amount for each slab should be so fixed that these are progressive and each worker should get about 50% of his monthly salary as progress bonus if ideal monthly progress is achieved.
		ii) Incentive bonus	2		This should be given for certain difficult and hazardous manual operations like rib erection, bottom clearance in circular tunnels etc.
		iii) Performance bonus	1		This should be given to the entire tunnel crew equally if the quarterly progress target is achieved.
		iv) Achievement bonus	1	9	It is to be given for completion of whole project on schedule. It should be given to the whole construction crew and should equal one year's interest on capital cost.
6	Co-ordination	i) Co-ordination of activities of various crews inside the tunnel	5		
		ii) Use of CPM for overall perspective and control of the whole job.	4	9	

1	2	3	4	5	6
7	Environmental conditions and house keeping	Proper lighting, dewatering, provision of safety wear to workmen and general job cleanliness	4	4	
8	Punctuality of staff	i) Prompt shift change-over at the heading	4		
		ii) Loss of upto 1/3 hr. in shift change-over	3		
		iii) Loss of more than 1/3 hr. in shift change-over	0-2	4	
9	Rapport	Good rapport at all levels of working including top management and government level including human relations	3	3	

These factors are based on the study of tunnelling jobs done in India and have been listed in the descending order of their effect on the tunnelling rate. Each item has been assigned a numerical rating after discussions with tunnelling experts of long standing and has been further sub-divided for ease in evaluation. The maximum ratings have also been assigned to each sub-group and represent ideal conditions. These will need downward revision depending upon actual working conditions at the site. On the basis of the sum of ratings for individual sub-groups, the management conditions are classified in Table 4.4.

TABLE 4.4

RATINGS FOR DIFFERENT MANAGEMENT CONDITIONS

Sl.No.	Management condition	Rating score
1	Good	80 to 100
2	Fair	51 to 79
3	Poor	50 or below

The ratings for various items and their sub-groups as given in Table 4.3 have been derived on the basis of observations and personal experience of the author on tunnelling works. These have been supplemented with discussions with field officers and crew on major tunnelling projects.

It was observed that the judicious selection of construction plant and equipment, personnel and location of adits played a highly significant role in achieving high tunnelling rates. Next in importance was found skill of workmen. The availability of equipment for use on work as and when the same was needed is the next item in order of importance. This parameter was assessed on the basis of time lost due to non-availability of equipment or its breakdown while on work.

Supervision of all operations particularly drilling is very important as it affects the advance rate, the fragmentation of rock and its overbreak or undercutting.

Incentives to working crew for increased production have been found to be a positive factor. It has been generally observed that mere provision of adequate equipment and personnel did not necessarily result in achieving the planned production on a sustained basis unless the workmen display devotion to the work. The payment of bonus to the crew resulted in increased production with the same equipment (68,117). This increase in cost due to payment of bonus is more than offset by the increased progress of tunnelling resulting in an overall reduction in unit cost.

The effect of application of CPM is not considered significant as the cyclic tunnelling operation is well defined and the effect of different operations on overall time is also well known. The co-ordination takes care of providing resources as and when needed and also to ensure control of single person at various levels of working.

Other factors listed in the table which marginally affect the tunnelling rate are : i) environmental conditions, ii) change-over of shift at the tunnel heading, and iii) the rapport between various levels of management. These parameters have been assigned low ratings due to their relatively lesser importance on the overall achievement of progress. The pictorial representation of the parameters and their ratings is shown in Fig.4.1.

4.4 Application of Classification Systems to Pandoh-Baggi Tunnel

4.4.1 Grouping in job-conditions

The bulk of geological data available from the project is in the form of descriptive information (Fig.4.2). However, the classification system which has been developed here for job conditions can help in grouping this data into three categories on the basis of the descriptive geology as given by geologist and the actual rate of advance achieved in different tunnel segments for excavation. The different rocks encountered along the Pandoh-Baggi tunnel alignment are classified into the three categories viz., good, fair and poor, and listed in Table 4.5. After classifying the entire tunnel length into three job conditions, these rock categories were reviewed vis-a-vis the advance achieved in respective ground conditions on a monthly basis. The ranges of advance per round for the three job conditions were adopted on the basis of the following criteria :

i) The minimum value of 2.5 m for advance observed under good job condition and the maximum value of 1.2 m for that observed under poor job condition are those which experienced the highest frequency of occurrence.

ii) The general range of values of advance achieved under fair job condition is between 2.5 m and 1.2 m

iii) Certain stray values of advance per round falling outside the ranges defined above may also occur due to random causes under all the three job conditions.

It was observed in a few cases that the rock category and job classification for a certain tunnel length based on achieved rate of advance did not match with rock classification as defined in Table 4.5. Although the classification indicated good or fair

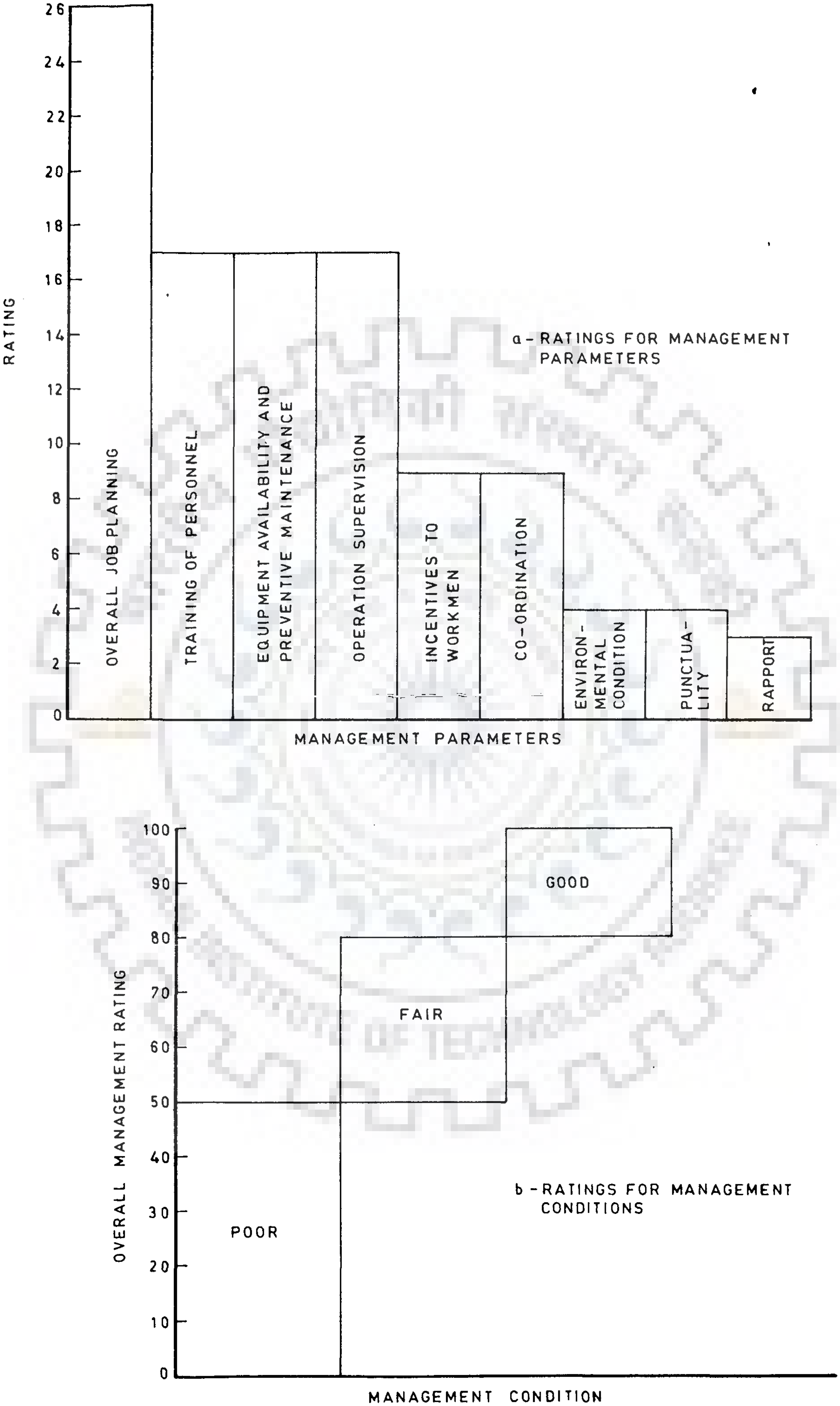


FIG. 4·1 QUANTITATIVE ASSESSMENT OF RATINGS FOR MANAGEMENT

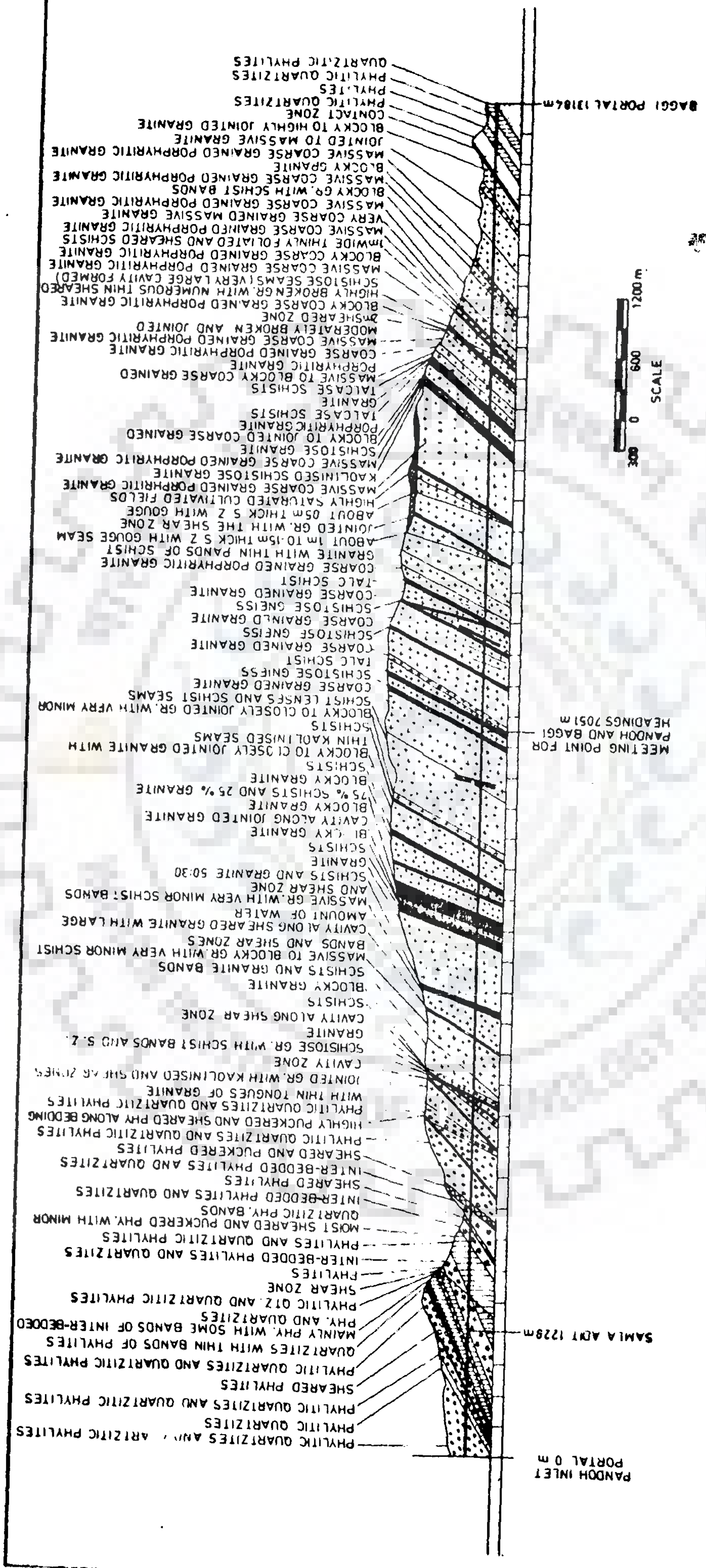


FIG. 4·2 GEOLOGICAL PROFILE ALONG PANDOH-BAGGI TUNNEL

(AFTER KRISHNASWAMY et al, 1974)

TABLE 4.5

GROUPING OF GEOLOGICAL DATA OF PANDOH-BAGGI TUNNEL INTO JOB CONDITIONS

Job conditions		
Good	Fair	Poor
Granite: massive, coarse grained, porphyritic, blocky, and moderately broken and jointed.	Blocky to highly jointed granite	Talc schist
Schistose granite with schist bands and shear zones	Blocky to closely jointed granite with thin kaolinized seams and/or shear zones	Kaolinized schistose granite
Massive to blocky granite with very minor schist bands and shear zones	Moderately jointed granite with thin bands of schists and kaolinized seams	Highly broken granite with numerous thin sheared schistose seams
Jointed granite with kaolinized and shear zones	Sheared to crushed gneiss/schistose gneiss	Shear zones
Schists	Thinly foliated and sheared schists	Cavity portions
Schists with granite bands	Sheared and puckered phylite	Distressed tunnel length
Schistose gneiss	Contact zones between good to fair and poor to fair rocks	Contact zones between good to poor, and fair to poor rocks
Phylites, quartzites, phylitic quartzites and quartzitic phylites, interbedded phylites and quartzites		
Contact zones between fair to good, and poor to good rock		

job condition, lower advance had been recorded. In such cases, the rock categories have been considered to belong to the next lower category, to conform to the criterion of advance per round. For example, the 'good' classification has been changed to 'fair' and 'fair' to 'poor', depending on the advance achieved. The listing of lengthwise rock formations, corresponding monthly progress rates, actual working time and actual breakdown time for Pandoh (Samla-adit, downstream) and Baggi tunnel headings are given in Appendices III and IV respectively.

When more than one job condition was faced during the same month, the equivalent monthly progress (EMP) was evaluated for each job condition separately as if it existed during the whole month. The sample calculations to compute EMP in two job conditions faced during one month are shown in Table 4.6. However, in majority of the cases, the job condition is the same during a month.

Wherever some working days were lost due to existence of cavities or drilling of extra, exploratory holes, the recorded progress was increased proportionately to account for these lost days. This is also shown in Table 4.6.

4.4.2 Grouping in management conditions

The actual monthly progress and actual working time for 124 months for Pandoh-Baggi tunnel of Beas-Sutlej Link project (65 months for Pandoh Heading and 59 months for Baggi Heading) have been listed in Appendices III and IV. The equivalent monthly progress (EMP) for the three job conditions has been computed and recorded (Column 9) against given job condition (Column 5). The EMP values for each job condition are then taken from these appendices and are grouped together in class intervals of 15 m

TABLE 4.6

SAMPLE COMPUTATIONS OF EQUIVALENT MONTHLY PROGRESS (EMP) FOR ONE MONTH

Chainage From (m)	Chainage To (m)	Geological description	Job condition	Actual progress in job condition (m)	Actual working time in job condition (Hrs.)	Total working time during the month (Hrs.)	Days lost during the month	Total no.of days in the month	EMP in job condition (m)
3058	3076	Talcase schist	Poor	18	368.67	500.42	3	31	27*
3076	3094	Blocky to jointed coarse grained porphyritic granite	Good	18	131.75				76**

$$* \quad \frac{500.42}{368.67} \times 18 \times \frac{31}{28} = 27$$

$$** \quad \frac{500.42}{131.75} \times 18 \times \frac{31}{28} = 76$$

each after arranging in the ascending order. The relative frequency (RF) and cumulative relative frequency (CRF) have then been computed (Table 4.7) and plotted (Figs. 4.3, 4.4 and 4.5). The categorization of EMP into good, fair and poor management conditions has been done based on points of inflexion on the CRF curves for the respective job conditions. It is presumed that a change in the slope of the curves represents a different management condition. Thus the matrix of EMP in different job and management conditions has been obtained and is shown in Table 4.8. On the basis of this matrix the months falling under the three management conditions for a given job condition have been identified. The cycle time data for the months falling in the same cell is then isolated for further analysis which is discussed in the next chapter.

4.5 Elimination of Unrepresentative Values from Data

In the field data in certain months there are some stray observations of actual advance rate which are significantly different from that normally expected progress. These low values are due to change in job condition in most cases. The number of such observations, if very small (viz.,less than 5) does not represent the existence of a distinct job condition for the purpose of computation of EMP in that job condition for that month. These values have, therefore, not been considered in the study.

During the months of February, 1969, September, 1970 and December 1971 on Pandoh downstream heading, the advance rates achieved were not found to be consistent with the type of rock encountered. The data for these months was not considered

TABLE 4.7

FREQUENCY DISTRIBUTION OF EQUIVALENT MONTHLY PROGRESS (EMP)

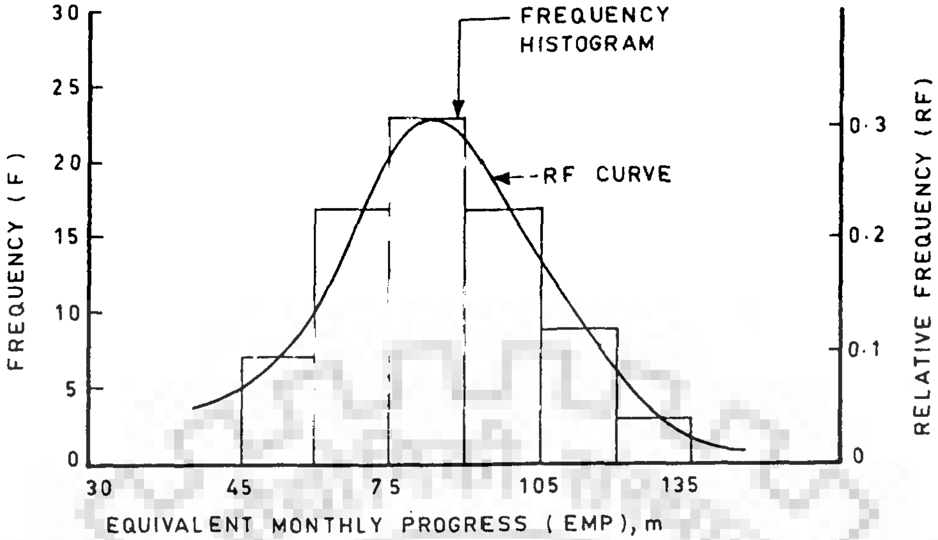
Class interval (m)	Frequency (F)	Relative frequency (RF)	Cumulative relative frequency (CRF)
A - Good Job Condition			
45 - 60	7	0.092	0.092
60 - 75	17	0.224	0.316
75 - 90	23	0.303	0.619
90 - 105	17	0.224	0.843
105 - 120	9	0.118	0.961
120 - 135	3	0.039	1.000
B - Fair Job Condition			
15 - 30	4	0.100	0.100
30 - 45	13	0.325	0.425
45 - 60	13	0.325	0.750
60 - 75	7	0.175	0.925
75 - 90	2	0.050	0.975
90 - 105	1	0.025	1.000
C - Poor Job Condition			
0 - 15	3	0.125	0.125
15 - 30	12	0.500	0.625
30 - 45	8	0.333	0.958
45 - 60	1	0.042	1.000

TABLE 4.8

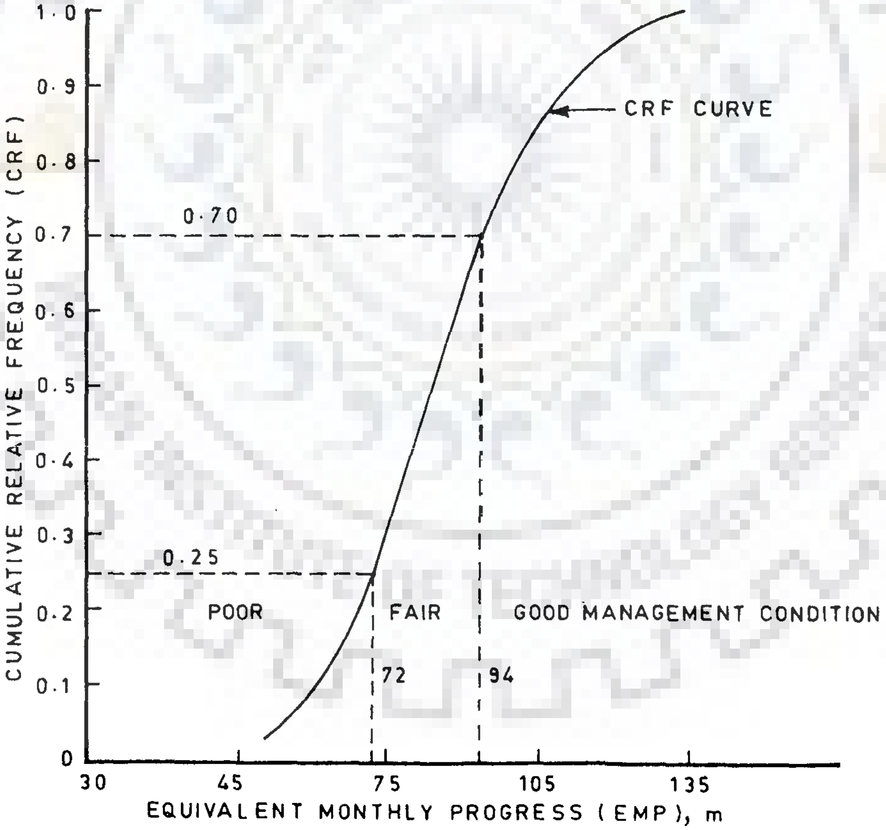
PRODUCTION BASED CATEGORIZATION OF MANAGEMENT CONDITIONS*

		Management condition		
		Good	Fair	Poor
Job condition	Good	> 94	72 - 94	≤ 72
	Fair	> 60	30 - 60	≤ 30
	Poor	> 36	21 - 36	≤ 21

*Values are for equivalent monthly progress (EMP) in metres

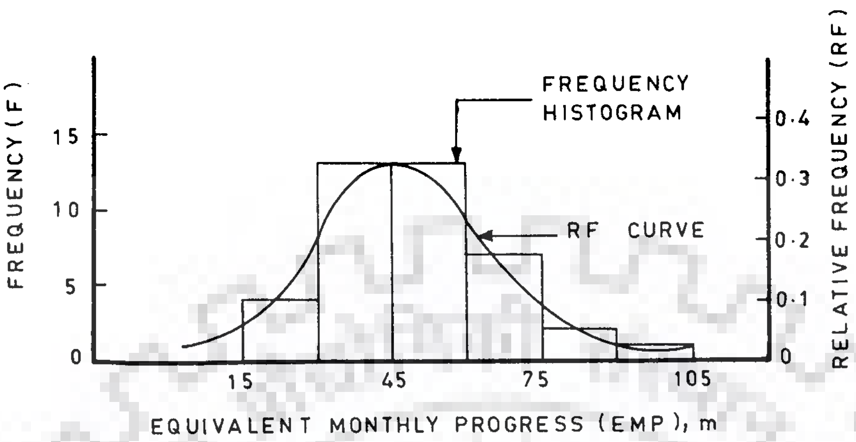


a-RELATIVE FREQUENCY (RF) CURVE

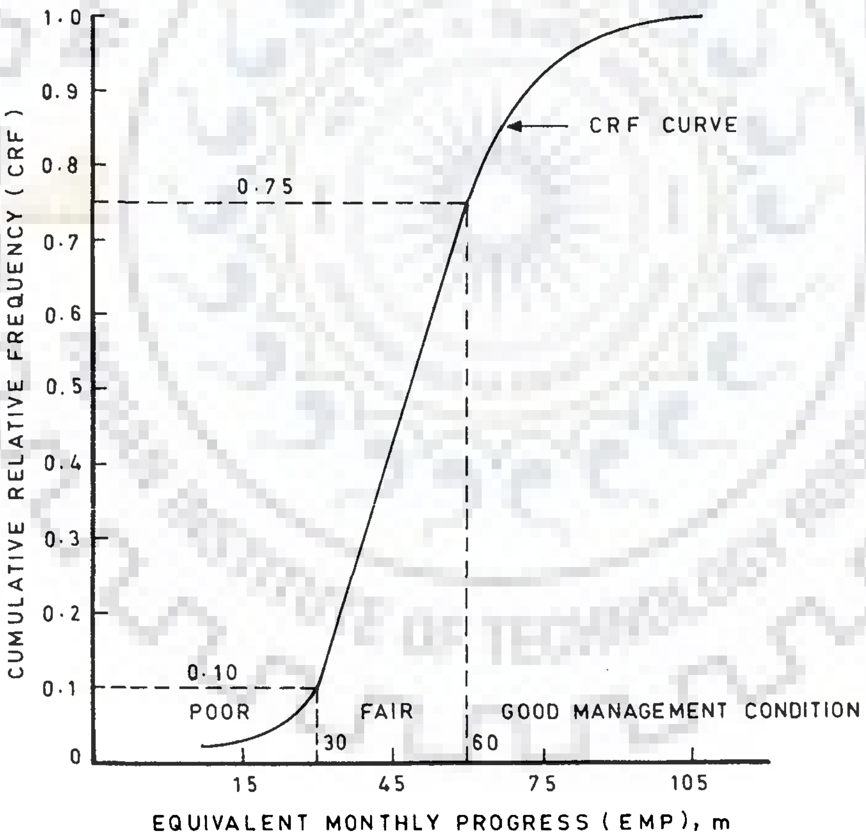


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 4.3 FREQUENCY DISTRIBUTION CURVES FOR EQUIVALENT MONTHLY PROGRESS (EMP) UNDER GOOD JOB CONDITION

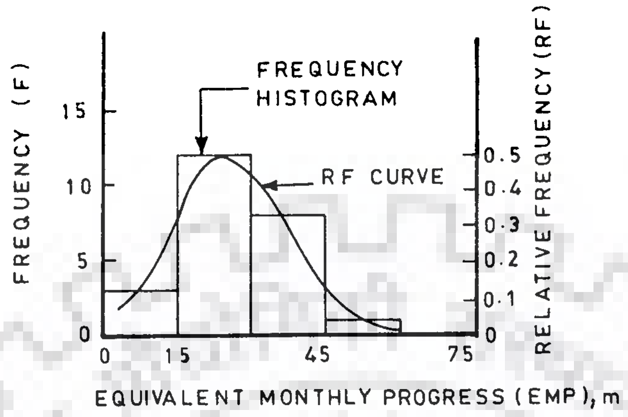


a - RELATIVE FREQUENCY (RF) CURVE

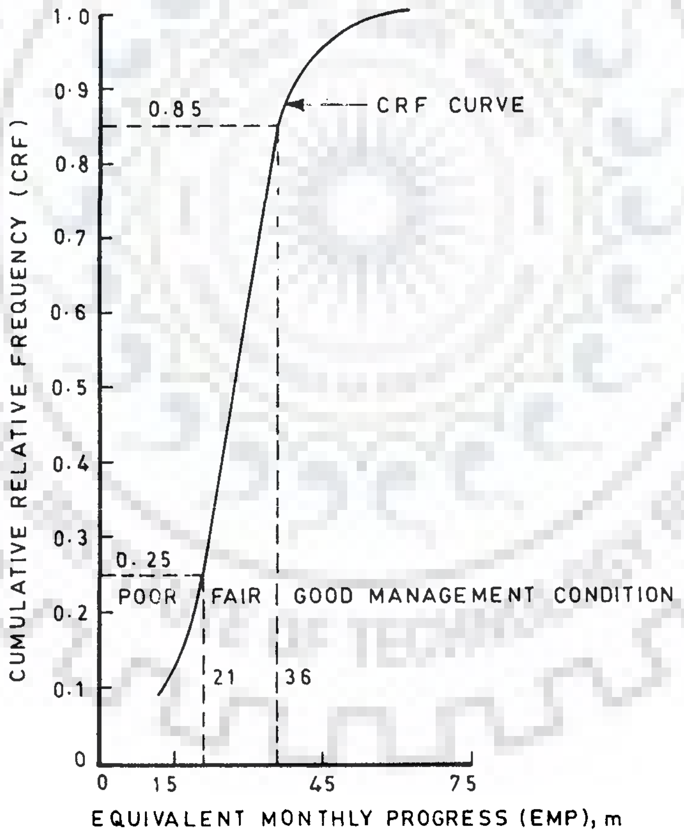


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 4·4 FREQUENCY DISTRIBUTION CURVES FOR EQUIVALENT MONTHLY PROGRESS (EMP) UNDER FAIR JOB CONDITION



a - RELATIVE FREQUENCY (RF) CURVE



b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 4·5 FREQUENCY DISTRIBUTION CURVES FOR EQUIVALENT MONTHLY PROGRESS (EMP) UNDER POOR JOB CONDITION reliable and was not considered for the analysis. Similarly, on Baggi heading the data for months of June,1972 and January,1974 was not included in the analysis.

4.6 Job and Management Factors

Job and management factor for a particular combination of job condition and management condition is defined as the ratio of expected rate (or actual rate achieved) of tunnel advance to the ideal (or achievable) rate. The ideal rate of advance could be estimated with fair degree of accuracy on the basis of best advance rates attained as recorded in field data. For this purpose the following analytical procedure has been adopted.

The field data considered for this analysis consists of total cycle time (sum of actual working time and breakdown time) under good job and good management condition. This data is presented in Table 4.9. The relative frequency and cumulative relative frequency distribution curves based on this data are plotted in Fig. 4.6. The principle of point of inflexion showing a change in management condition is considered to segregate the excellent or ideal from the normal condition. The lower point of inflexion on the CRF curve of Fig. 4.6 shows a total cycle time of 12.8 hours which has been observed to occur for at least 11% of the total period. The mean advance per round for this set of conditions was found to be 2.576 m. This is also shown in Table 5.5.

The ideal monthly advance rate has been computed as discussed below.

During the execution of Pandoh-Baggi tunnel 15 holidays per year were observed on an average. The work was carried out

TABLE 4.9

TOTAL CYCLE TIME(TCT) FREQUENCY DISTRIBUTION UNDER GOOD JOB AND GOOD MANAGEMENT CONDITION

Class interval (Hrs.)	Frequency (F)	Relative frequency (RF)	Cumulative relative frequency (CRF)
<8	1	0.001	0.001
8-10	7	0.010	0.011
10-12	40	0.059	0.070
12-14	137	0.203	0.273
14-16	181	0.268	0.541
16-18	143	0.212	0.753
18-20	64	0.095	0.848
20-22	41	0.061	0.909
22-24	21	0.031	0.940
24-26	19	0.028	0.968
26-28	8	0.012	0.980
28-30	1	0.001	0.981
30-32	3	0.004	0.985
>32	10	0.015	1.000

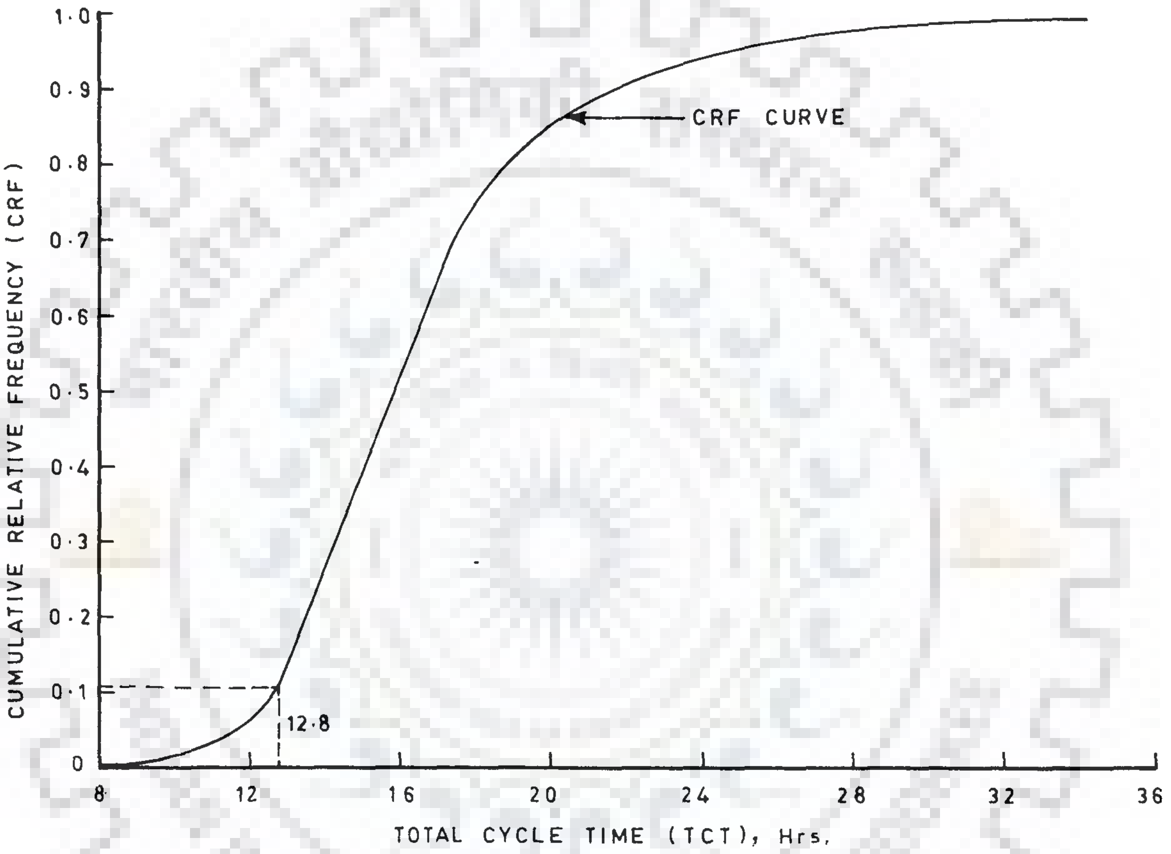


FIG. 4·6 FREQUENCY DISTRIBUTION CURVE FOR TOTAL CYCLE TIME (TCT) UNDER GOOD-JOB AND GOOD-MANAGEMENT CONDITION for the remaining 350 days in the three shifts by staggering the weekly holidays of workmen and supervisory personnel. Thus, the ideal monthly advance rate works out to $\frac{24}{12.8} \times 2.576 \times \frac{350}{12} = 140$ m.

The average achieved rate of tunnel advance for each combination of job condition and management condition is derived from the analysis of actual recorded rate of progress achieved on Pandoh-Baggi tunnel based on field data collected. The ratio of this expected rate to the ideal rate of tunnel advance is defined as job and management factor for the related condition of job and management. The computation of these factors is shown in Table 4.10.

TABLE 4.10

COMPUTATION OF JOB AND MANAGEMENT FACTORS
(Based on ideal monthly progress of 140 m)

Job condition	Management condition	Average monthly advance achieved (m)	Job and management factor $\left[\frac{\text{Col.3}}{140}\right]$
1	2	3	4
Good	Good	108.8	0.78
	Fair	84.4	0.60
	Poor	61.0	0.44
Fair	Good	74.5	0.53
	Fair	45.3	0.32
	Poor	25.7	0.18
Poor	Good	42.2	0.30
	Fair	29.9	0.21
	Poor	17.5	0.13

CHAPTER 5

PROBABILITY DISTRIBUTIONS FOR CYCLE TIMES

5.1 General

In tunnel excavation a number of operations have to be performed sequentially in each cycle. The time taken for the performance of any individual operation is random in nature and is affected by a variety of causes. The effect of these causes on progress of tunnelling operation could be studied through statistical analysis and simulation. Unfortunately, the field data does not reflect the specific effect of such random causes. However, the cumulative effect of these random causes may be studied through the consideration of some major factors such as job and management conditions. The duration of any individual operation within a given set of job and management conditions could be considered random in nature. In turn the total cycle time would also be a random variable. Thus, the whole process of tunnel excavation needs to be studied by simulation modelling instead of by deterministic modelling.

In the present study the total cycle time is divided in two parts. These are the actual working time (AWT) and the breakdown time (BDT). Both these components of the total cycle time which are of significance in simulating the tunnelling activity are also amenable to statistical analysis.

The major concern in such a study is to ensure that the selected statistical model not only fits well in the data under investigation, but also represents the physical phenomenon under study. As such the whole tunnel excavation cycle may be considered to consist of only two components discussed earlier, viz., the AWT and the BDT. The first component is the summation of the actual working times for various operations in the cycle whereas the second component is the sum of the breakdown time which may have occurred during the operation in the same cycle. Statistical models for individual operations could also be developed but this is not considered necessary for this study.

5.2 Choice of Sample Size

The number of observations both for AWT and BDT for each cell of the job and management matrix are given in Table 5.1. These observations are for Pandoh-Baggi tunnel of Beas-Sutlej Link project and have been derived by listing the values of AWT and BDT for each cycle for the months falling in a given cell of job and management matrix. As can be observed from the values in the matrix, the sample sizes for this study are very large and can be considered to represent the universe. The statistical tests based on the concept of confidence interval and confidence co-efficient indicate that much smaller samples would give a confidence level of as high as 95%.

TABLE 5.1

NUMBER OF OBSERVATIONS IN JOB-MANAGEMENT MATRIX

		Management condition			Total
		Good	Fair	Poor	
Job condition	Good	676	1034	475	2185
	Fair	346	660	86	1092
	Poor	114	156	148	418
	Total	1136	1850	709	3695

5.3 Testing of Distributional Assumptions

Suitability of the statistical distribution model for the given data may be ascertained through the application of statistical tests. The following two approaches are available for such testing :

i) probability plotting, and

ii) statistical tests

5.3.1 Probability plotting

This technique is simple and highly reliable if a true linear plot is obtained on the probability paper for the selected probability distribution. For a given distributional model the data is plotted on a special graph paper (122) designed for that distribution. The plotting coordinates are the ordered observation and the expected value of an ordered observation. The plotting positions are thus determined by finding the expected values of ordered observations. The specially scaled graphs obviate the necessity for actually calculating the expected values for many distributions. This paper is scaled in such a way that the ordered observations can be plotted directly against $\frac{(i-d)x100}{n-2d+1}$, where i is the ordered observation, d is a constant and n is the total number of observations (38). The value of d as equal to 0.5 has been found to be generally acceptable. The plotting position (PP) is thus given by $\frac{(i-\frac{1}{2})x100}{n}$. If the assumed model is correct, the plotted points will tend to fall in a straight line. Some deviations due to random sampling fluctuations are, however, inevitable. But the systematic departures from linearity are indications that the model is inadequate.

It is a subjective method because the determination of whether the data contradict the assumed model or not is based on a visual examination rather than on a statistical calculation.

5.3.2 Statistical tests

Statistical tests for testing the distributional assumptions on the other hand are more objective than the probability plots and provide a probabilistic framework to evaluate the adequacy of a model. These tests may be used to supplement the probability plots if the plots fail to provide a clear cut decision.

One of the most common statistical test is the Chi-square test which has been used to evaluate the adequacy of any distributional model. Another test is the W-test which has been found to be quite effective in evaluating the normal, log-normal and exponential distribution assumptions (38).

The Chi-square test requires grouping of the data into arbitrary cells which affect the outcome of the test to a great extent. Further, in the event of validation of two or more distributions by this test it is difficult to select the best fit distribution (75). This procedure permits us to reject a model as inadequate, but it never allows us to prove that a model is correct (38). Another important condition to be satisfied before applying the Chi-square test is that the frequency distribution within each class interval should almost be uniform. This assumption in case of the data under study (viz., AWT & BDT) is not satisfied. Therefore, only the method of probability plotting has been adopted for statistical testing in this study.

5.4 Probability Distribution for Actual Working Time (AWT)

The actual working time studied here is the sum of actual times taken for performance of the various operations in the cycle of excavation. Whereas the performance times for some of the operations are almost constant, sometimes even irrespective of the existing job conditions, those for others are variable and dependent upon the working conditions. Generally the constant time operations are the loading and blasting, defuming, jumbo-shifting, scaling and rail-extension. All other operations like drilling, muck loading and haulage, erection of supports and initial concreting are distinctly affected by the job and management conditions.

5.4.1 Choice of interval size for AWT

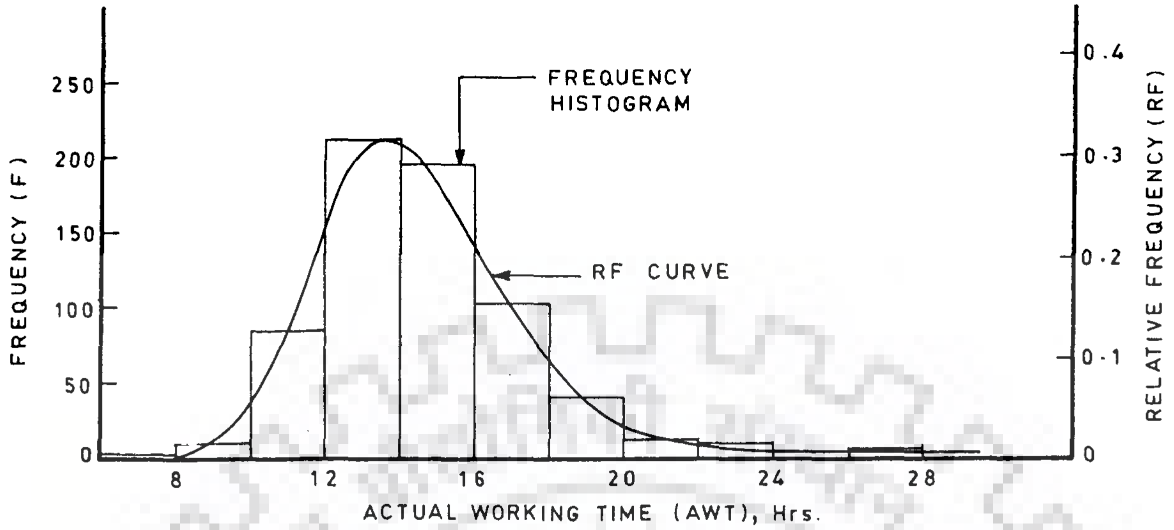
The selection of interval size for analysis of the data is based on judgement. Too narrow an interval will result in irregularities in the distribution associated with sampling fluctuations, while too wide an interval will cover up too much of detail needed to confidently establish the general pattern of the universe (138). An interval size of 2 hours has been selected for studying the statistical behaviour of AWT and provided a near optimum combination of smoothness and detail.

A sample of AWT data has been presented in Table 5.2 for all management conditions under good job condition. For fair and poor job conditions this data is presented in Appendices V and VI respectively. The frequency histograms and curves based on the relative frequencies and cumulative relative frequencies are presented in Fig. 5.1 to Fig. 5.9 for the nine cells of job and management matrix.

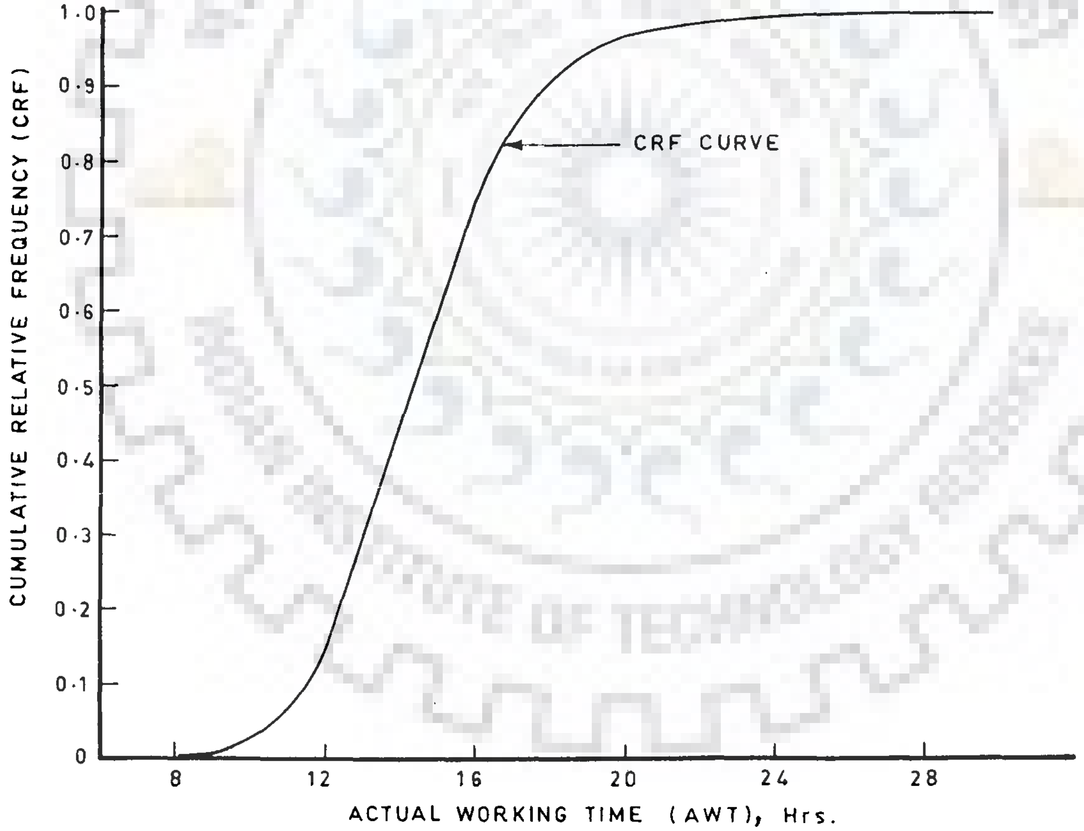
TABLE 5.2

ACTUAL WORKING TIME (AWT) FREQUENCY DISTRIBUTION UNDER GOOD JOB CONDITION

Class interval (Hrs.)	Management conditions								
	Good			Fair			Poor		
	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
≮ 8	1	0.001	0.07	0	0.000	0.00	0	0.000	0.00
8-10	12	0.018	1.85	2	0.002	0.14	1	0.002	0.10
10-12	85	0.126	14.42	18	0.017	1.88	0	0.000	0.10
12-14	212	0.314	45.78	87	0.087	10.30	18	0.038	3.89
14-16	194	0.287	74.48	196	0.189	29.25	51	0.107	14.63
16-18	103	0.152	89.72	144	0.139	43.18	48	0.101	24.74
18-20	39	0.058	95.49	210	0.203	63.49	76	0.160	40.74
20-22	13	0.019	97.41	172	0.166	80.13	83	0.175	58.21
22-24	10	0.015	98.89	106	0.102	90.38	63	0.133	71.47
24-26	2	0.003	99.19	47	0.045	94.92	46	0.097	81.16
26-28	3	0.004	99.63	24	0.023	97.24	32	0.067	87.89
28-30	2	0.003	99.93	7	0.007	97.92	20	0.042	92.10
30-32	0	-	-	5	0.005	98.40	11	0.023	94.42
32-34	0	-	-	8	0.008	99.18	9	0.019	96.32
34-36	0	-	-	2	0.002	99.37	6	0.013	97.58
> 36	0	-	-	6	0.006	99.95	11	0.023	99.89

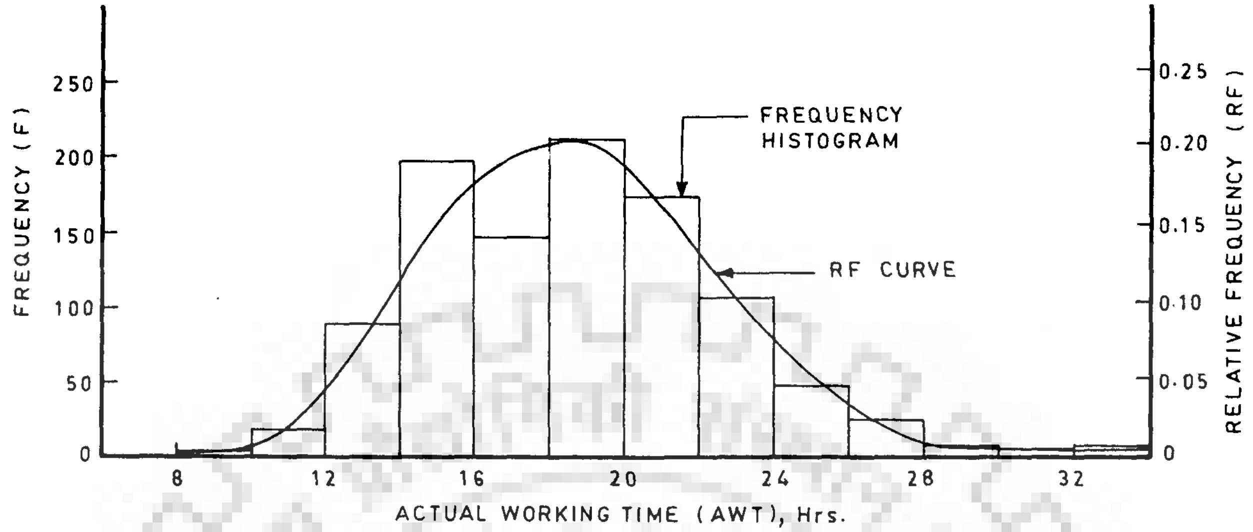


a - RELATIVE FREQUENCY (RF) CURVE

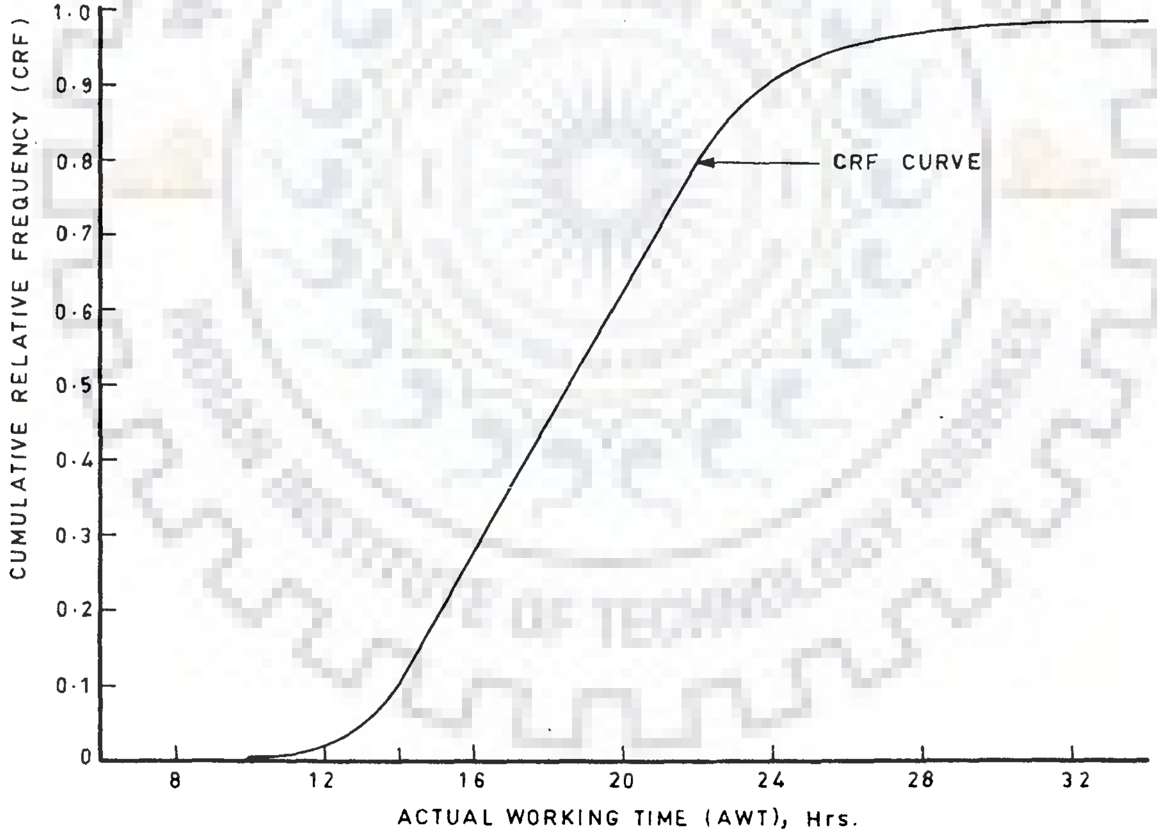


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5.1 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER GOOD-JOB AND GOOD-MANAGEMENT CONDITION

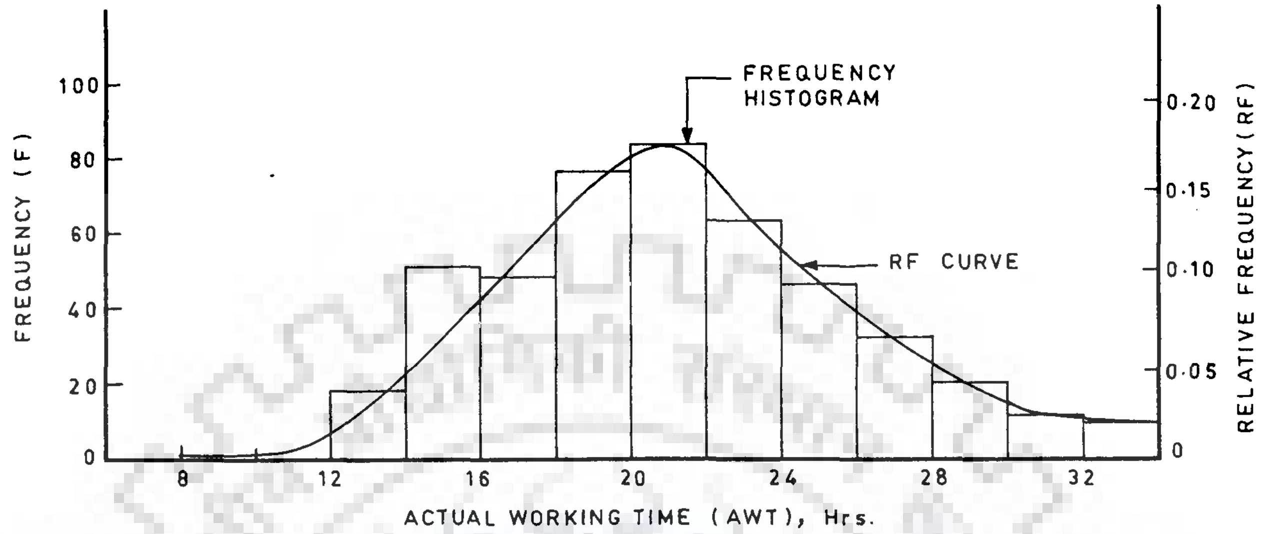


a - RELATIVE FREQUENCY (RF) CURVE

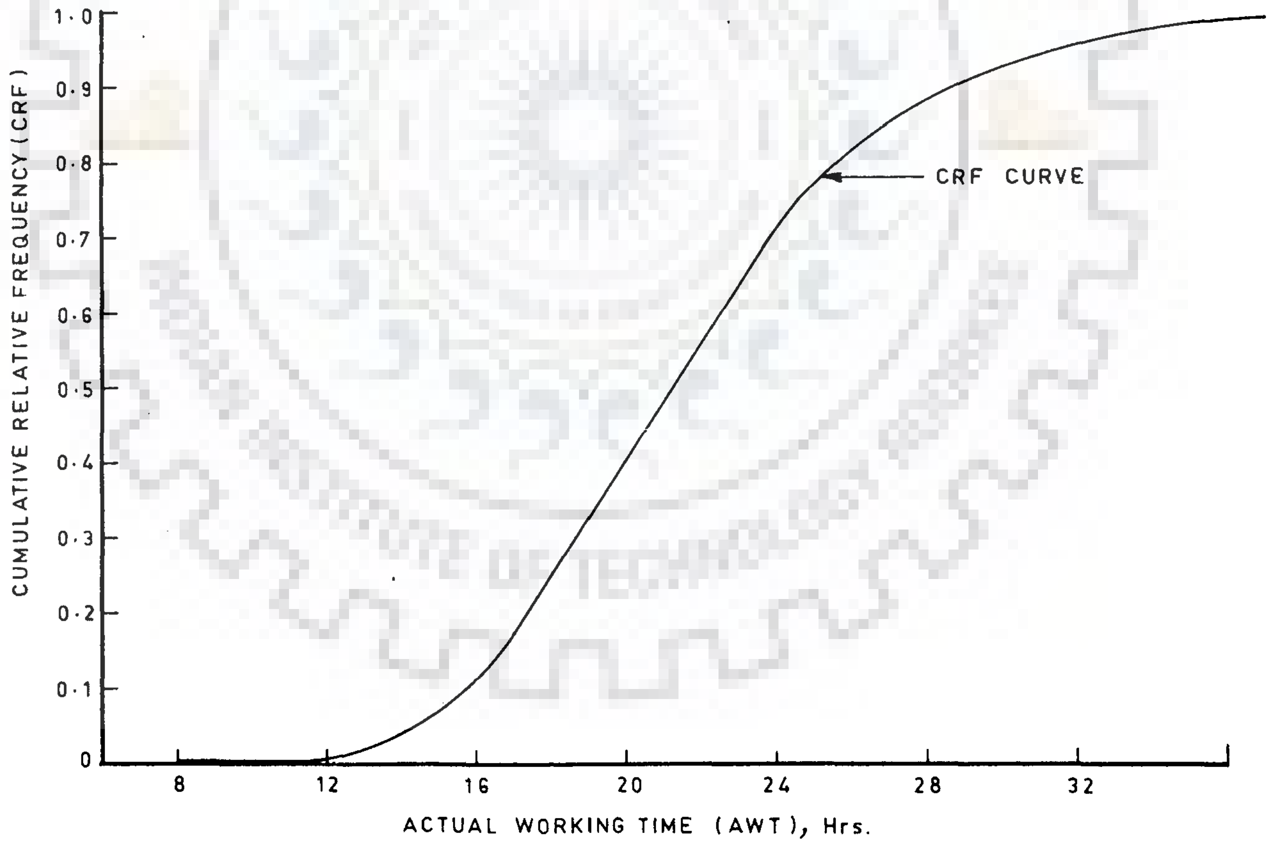


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5.2 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER GOOD-JOB AND FAIR-MANAGEMENT CONDITION

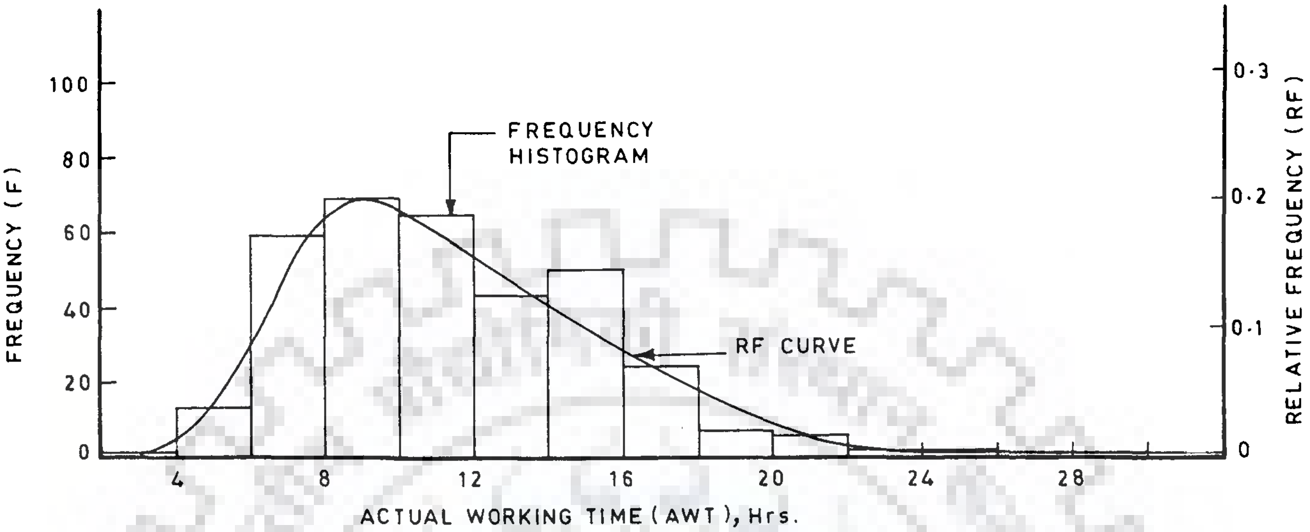


a - RELATIVE FREQUENCY (RF) CURVE

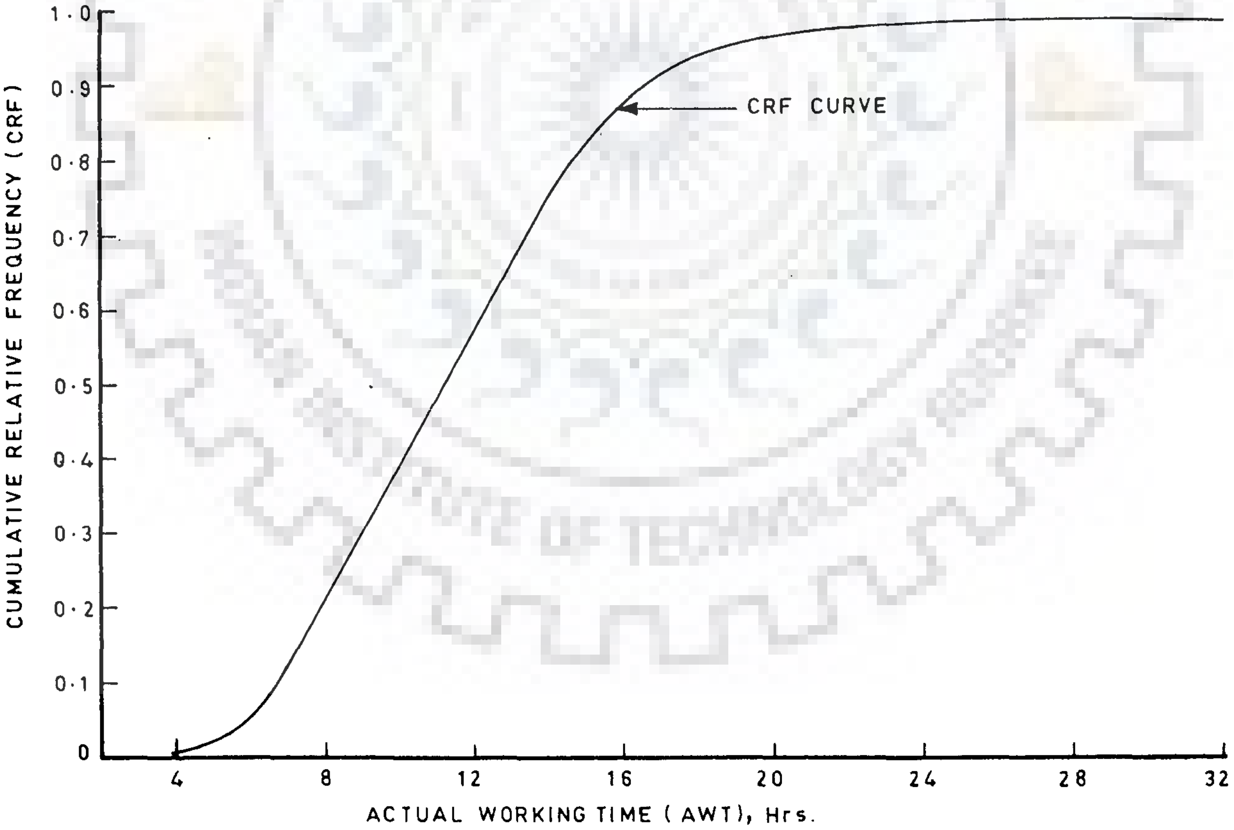


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5·3 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER GOOD-JOB AND POOR-MANAGEMENT CONDITION

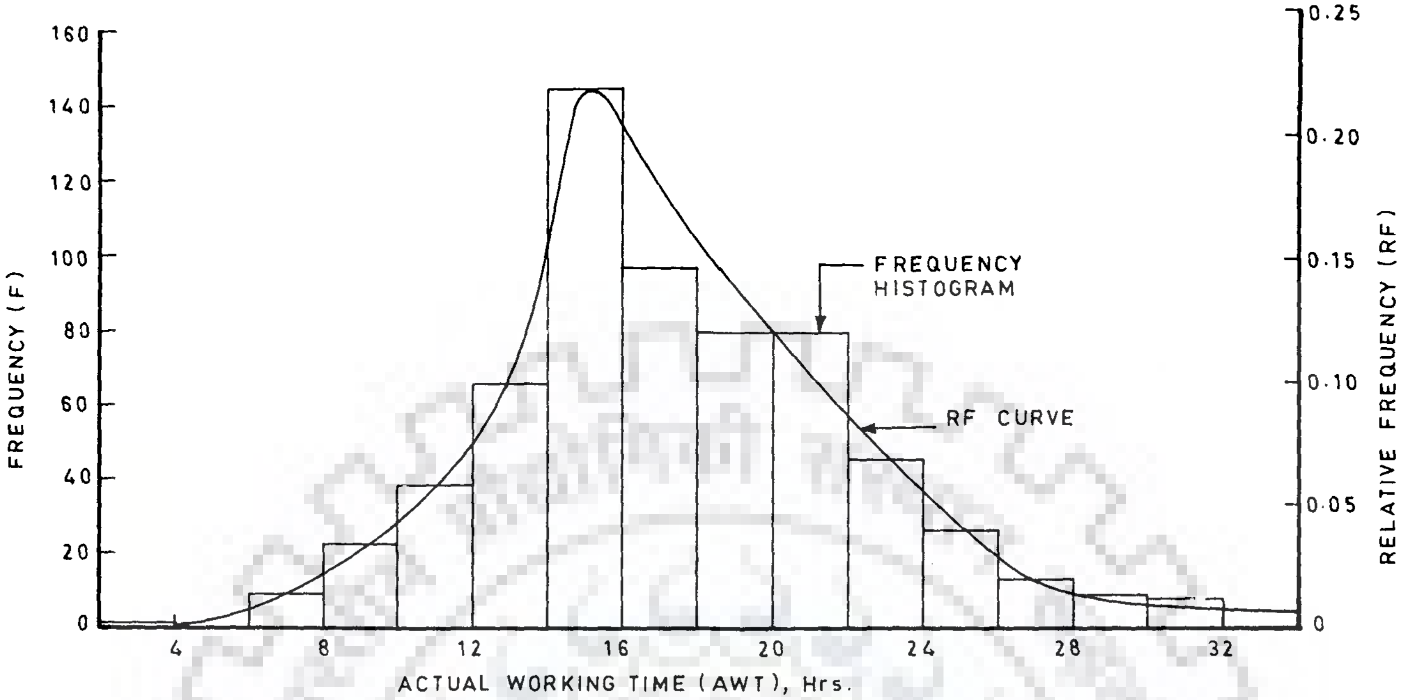


a - RELATIVE FREQUENCY (RF) CURVE

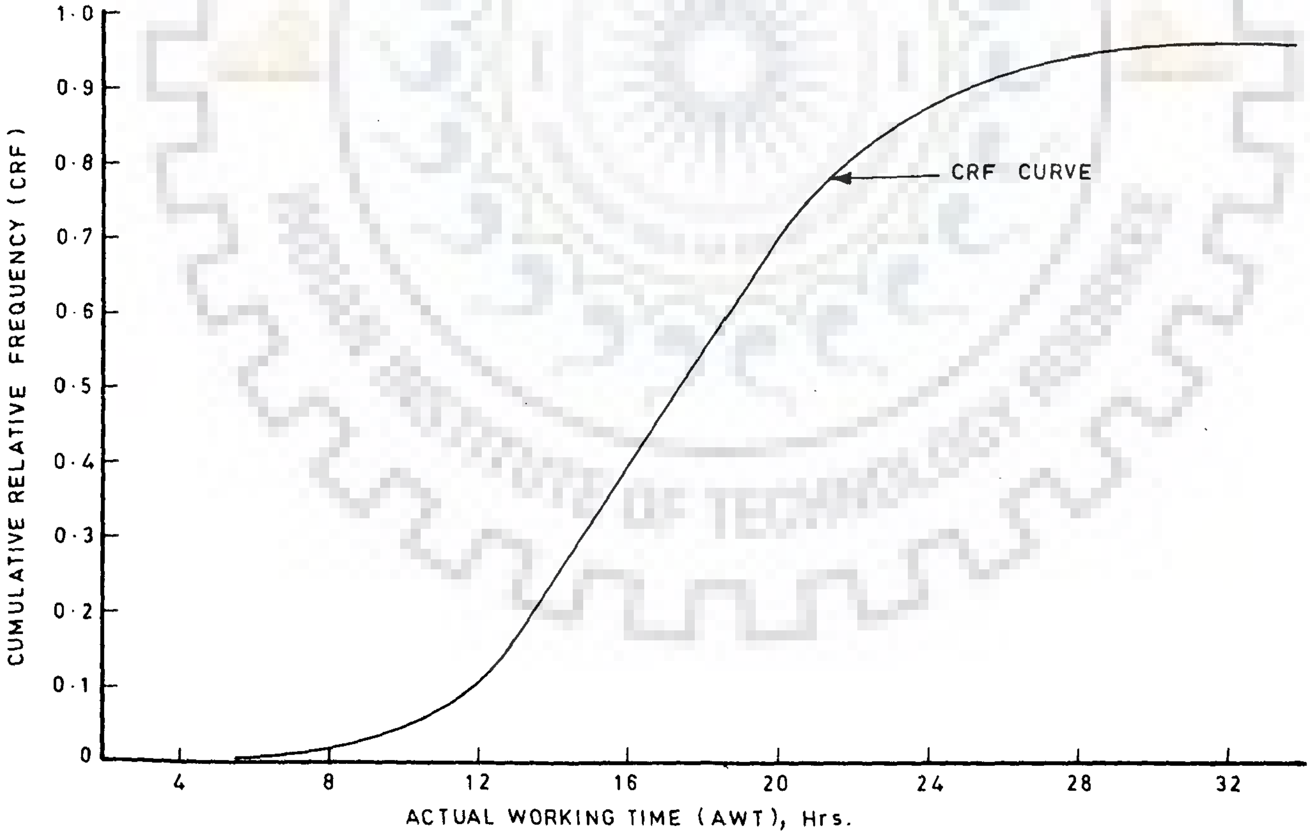


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5·4 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER FAIR-JOB AND GOOD-MANAGEMENT CONDITION

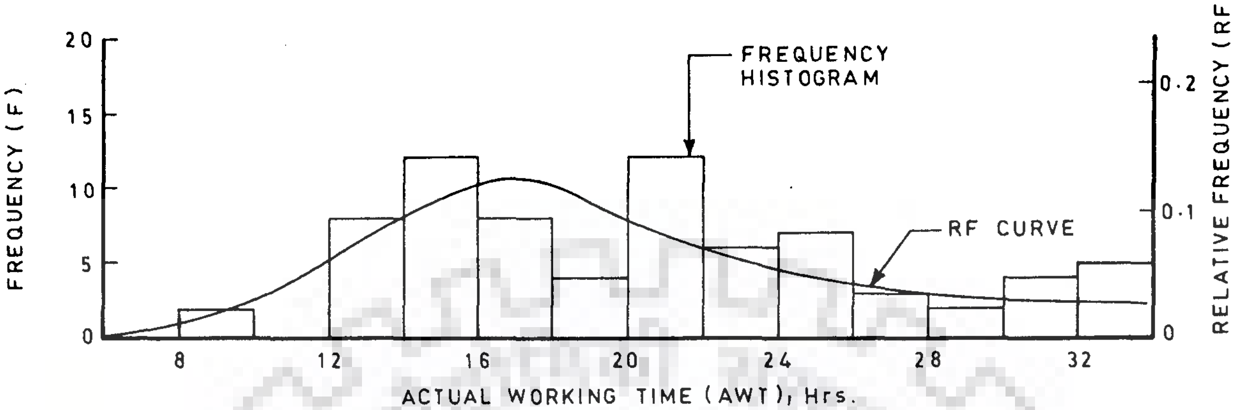


a - RELATIVE FREQUENCY (RF) CURVE

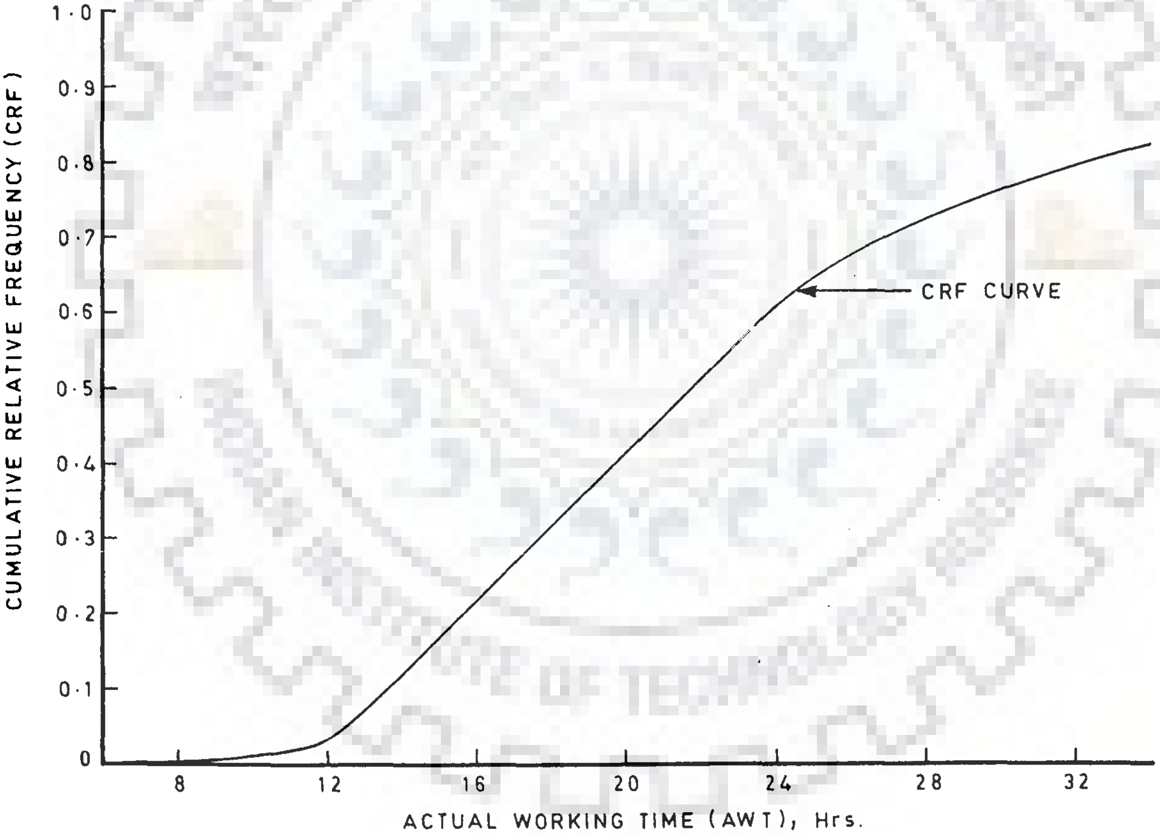


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG 5 5 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER FAIR-JOB AND FAIR-MANAGEMENT CONDITION

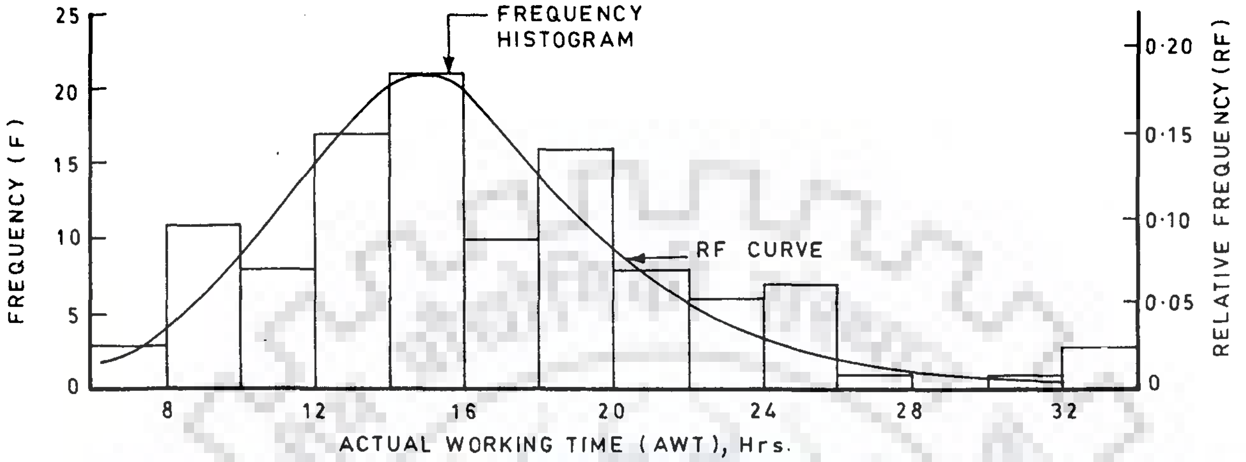


a-RELATIVE FREQUENCY (RF) CURVE

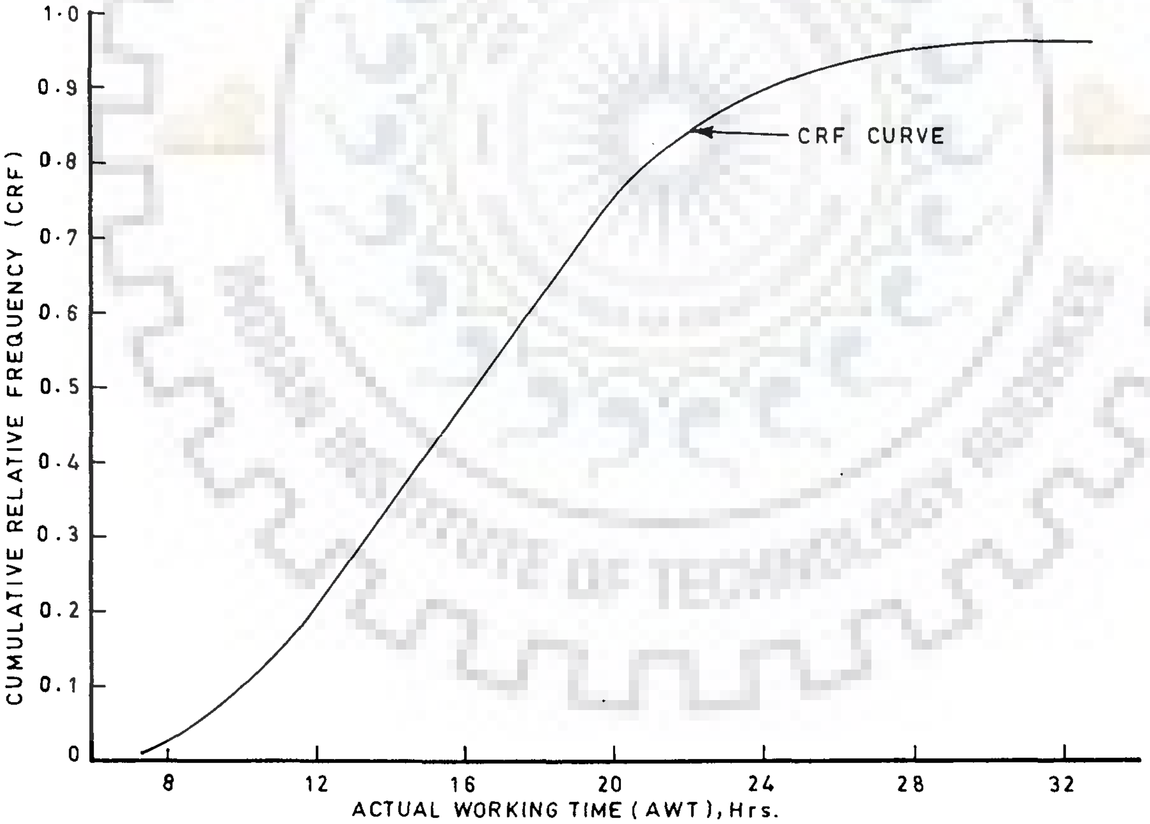


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5.6 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER FAIR-JOB AND POOR-MANAGEMENT CONDITION

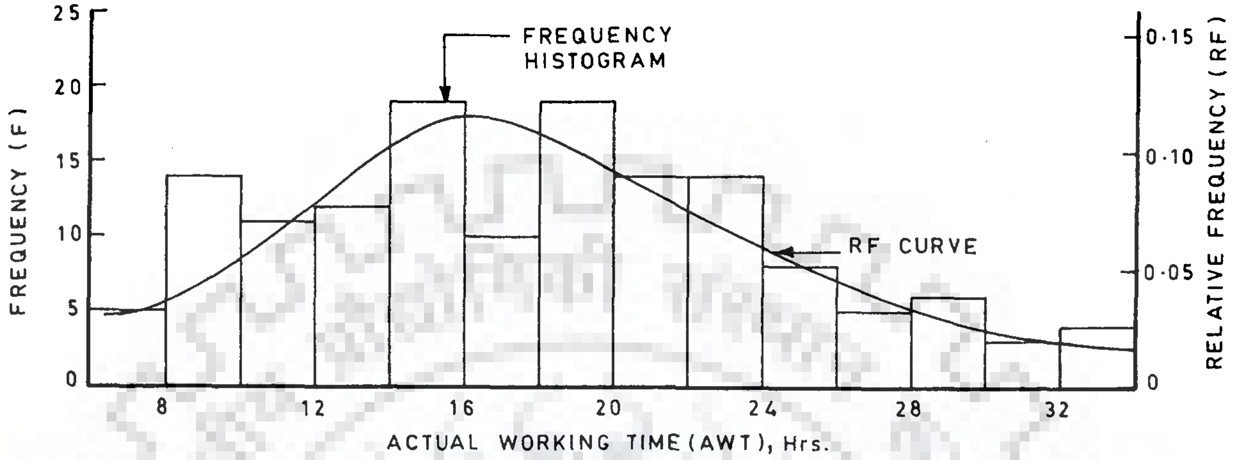


a - RELATIVE FREQUENCY (RF) CURVE

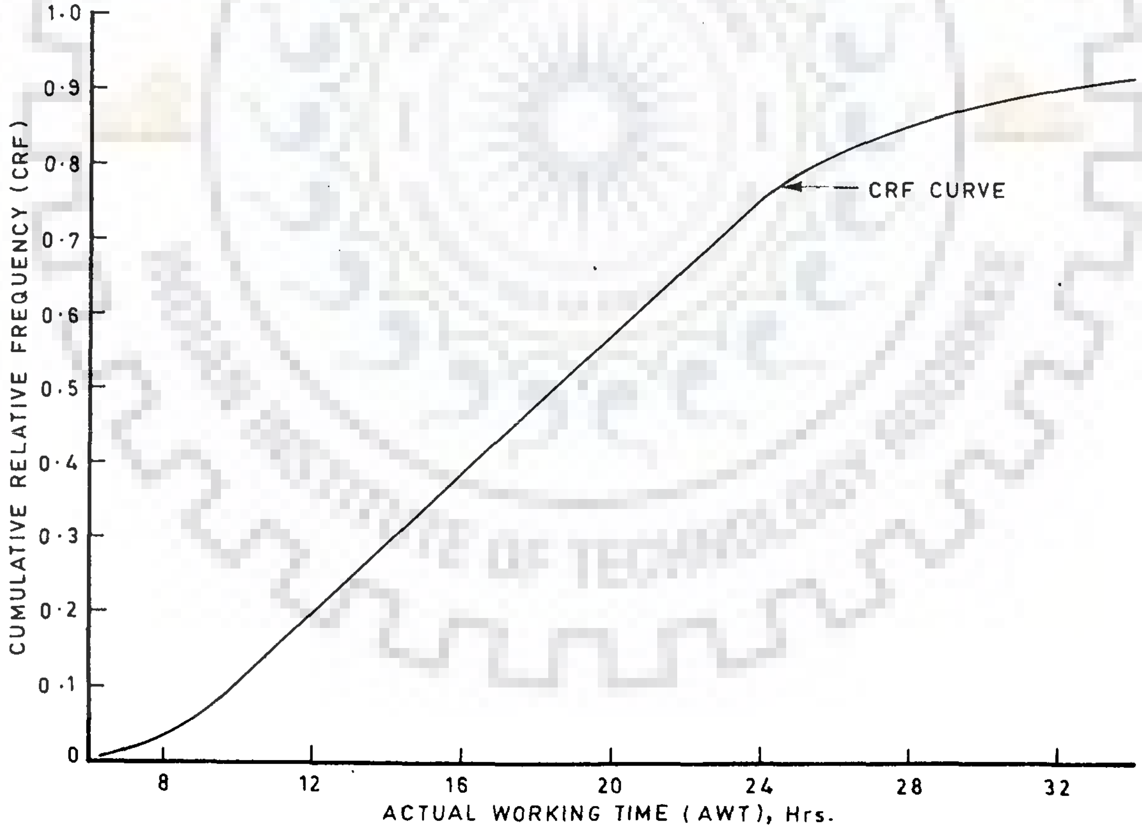


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5·7 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER POOR-JOB AND GOOD-MANAGEMENT CONDITION

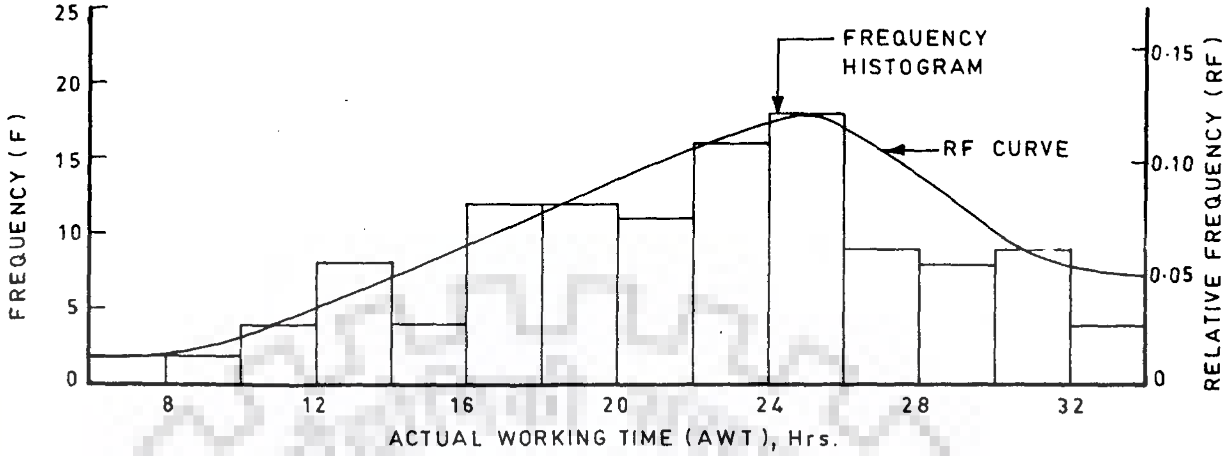


a - RELATIVE FREQUENCY (RF) CURVE

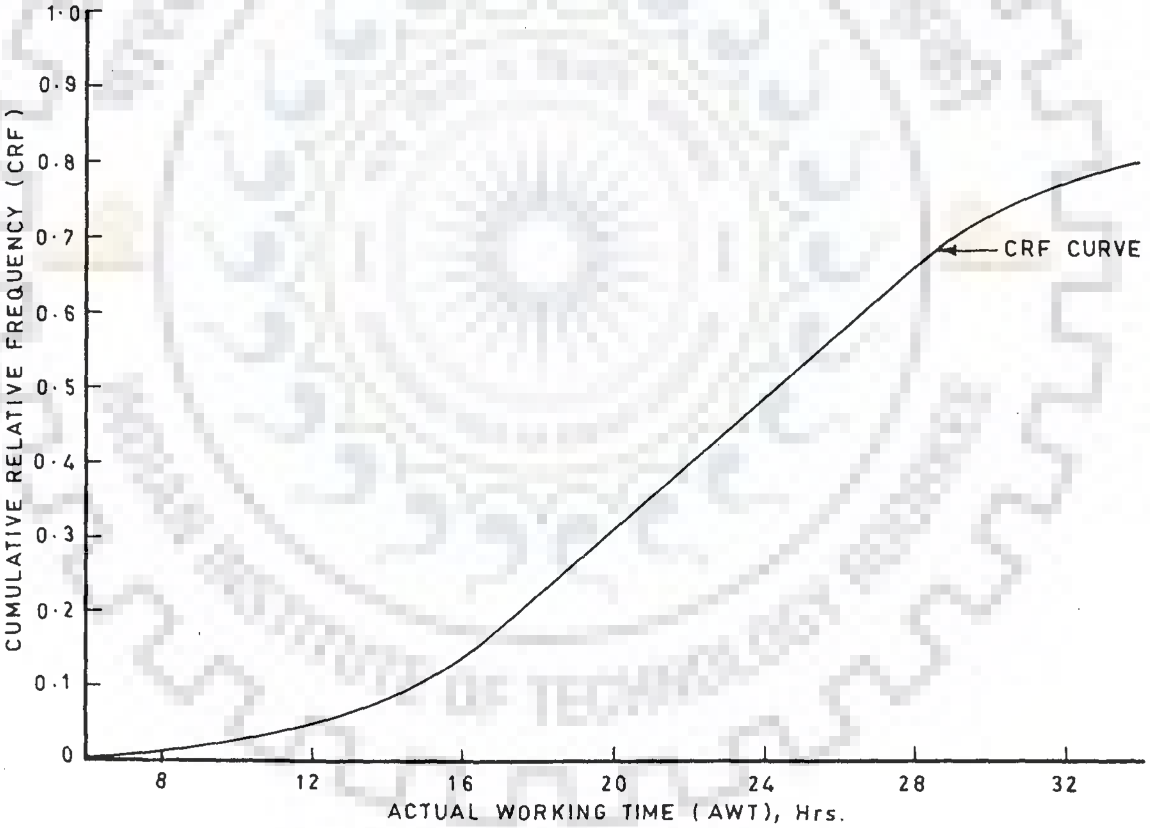


b - CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5·8 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER POOR-JOB AND FAIR-MANAGEMENT CONDITION



a-RELATIVE FREQUENCY (RF) CURVE



b-CUMULATIVE RELATIVE FREQUENCY (CRF) CURVE

FIG. 5.9 FREQUENCY DISTRIBUTION CURVES FOR ACTUAL WORKING TIME (AWT) UNDER POOR-JOB AND POOR-MANAGEMENT CONDITION

It is seen from the curves that the distribution is fairly smooth for all management conditions under the good job condition and also for good and fair management in fair job condition. Though the curves are not smooth for the remaining cells of job and management conditions, yet the points show a uniform scatter about the centrally plotted curves. The general assessment of the shape of curve was also made by the computer regression analysis.

5.4.2 Test for suitable probability distribution function for AWT

It is observed from the frequency distribution curves that the distribution is continuous and skewed. In most of the cases it also shows a tendency for peaking. These features of the curves indicate that log-normal distribution is the most suitable probability density function for studying the behaviour of AWT. The log-normal distribution arises in physical problems when the domain of the variable x is greater than zero and its histogram is markedly skewed. This skewing occurs when x is affected by random causes that produce small effects that are proportional to the variate x. Further, the outcome of these random causes, each producing a small constant effect, is normally distributed.

It is interesting to note that the probability plots for AWT for all the sets of job and management conditions showed a linear fit on the log-normal probability paper (Fig.5.10 to Fig. 5.12). These plots on probability papers for other continuous probability distributions did not show linearity except in some cases on Weibull probability paper. But the AWT may not conform to Weibull distribution and should rather conform to log-normal distribution due to the following reasons :

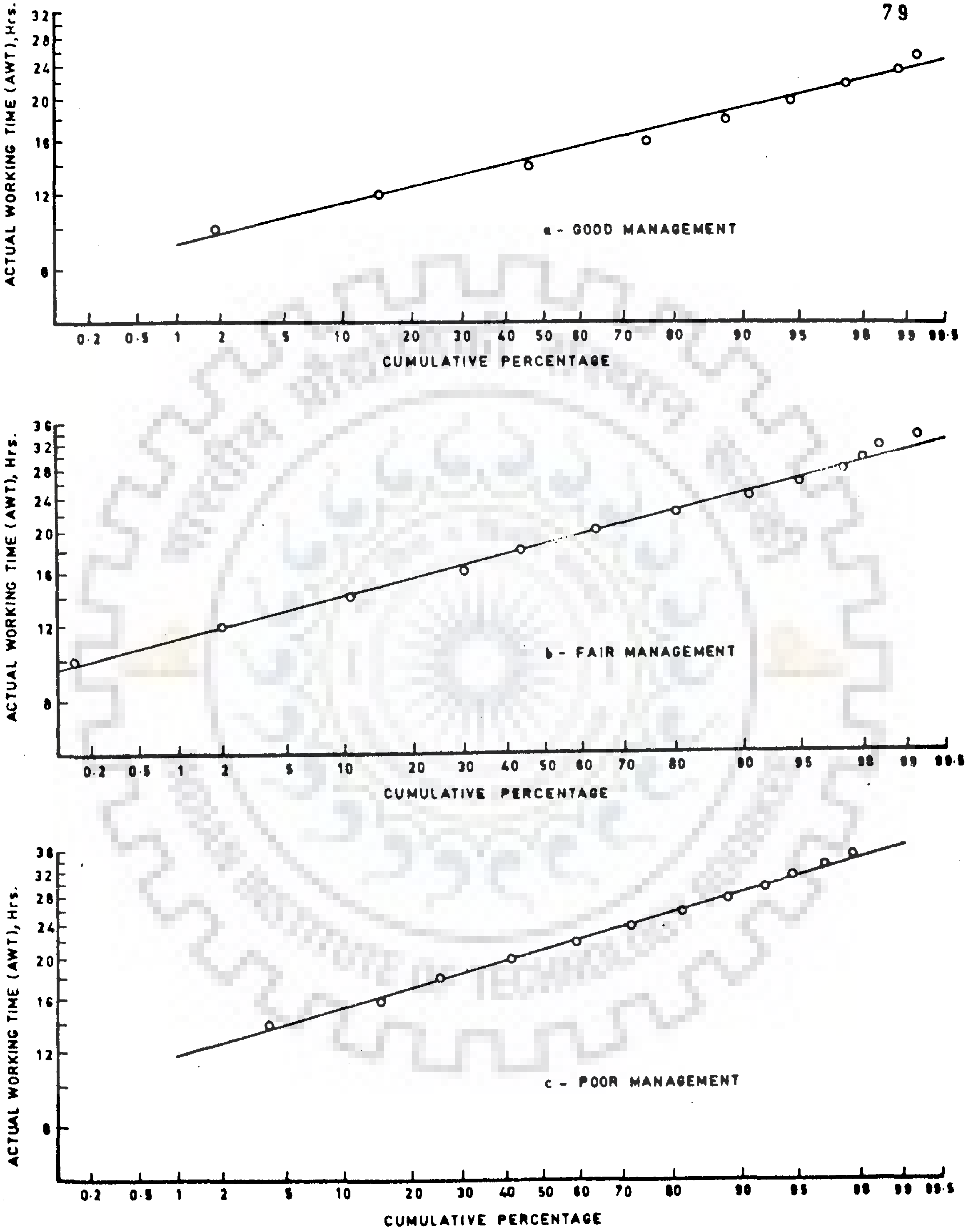


FIG. 5·10 LOG-NORMAL PROBABILITY PLOT OF ACTUAL WORKING TIME (AWT) UNDER GOOD JOB CONDITIONS.

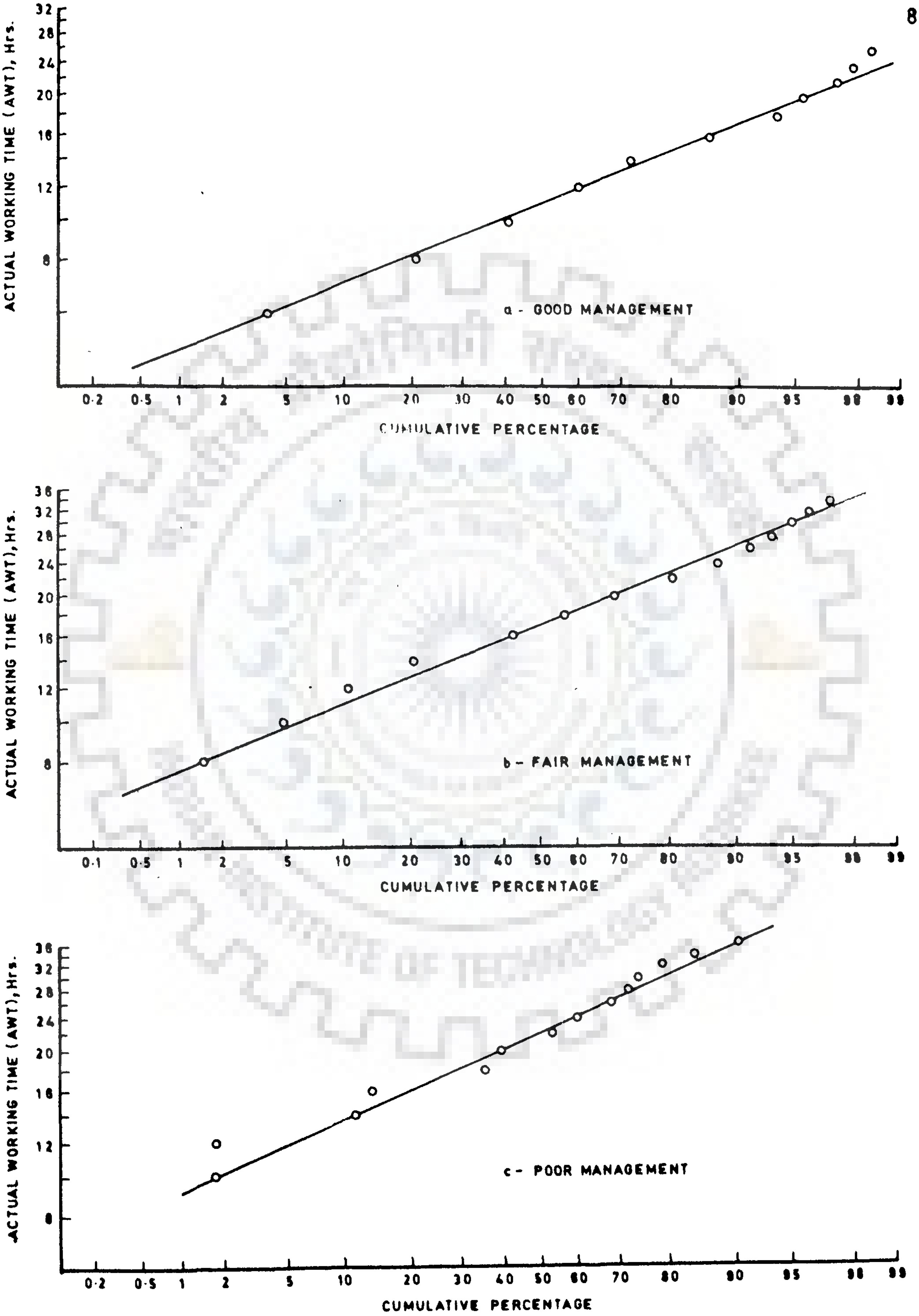


FIG. 5·11 LOG-NORMAL PROBABILITY PLOT OF ACTUAL WORKING TIME (AWT) UNDER FAIR JOB CONDITIONS.

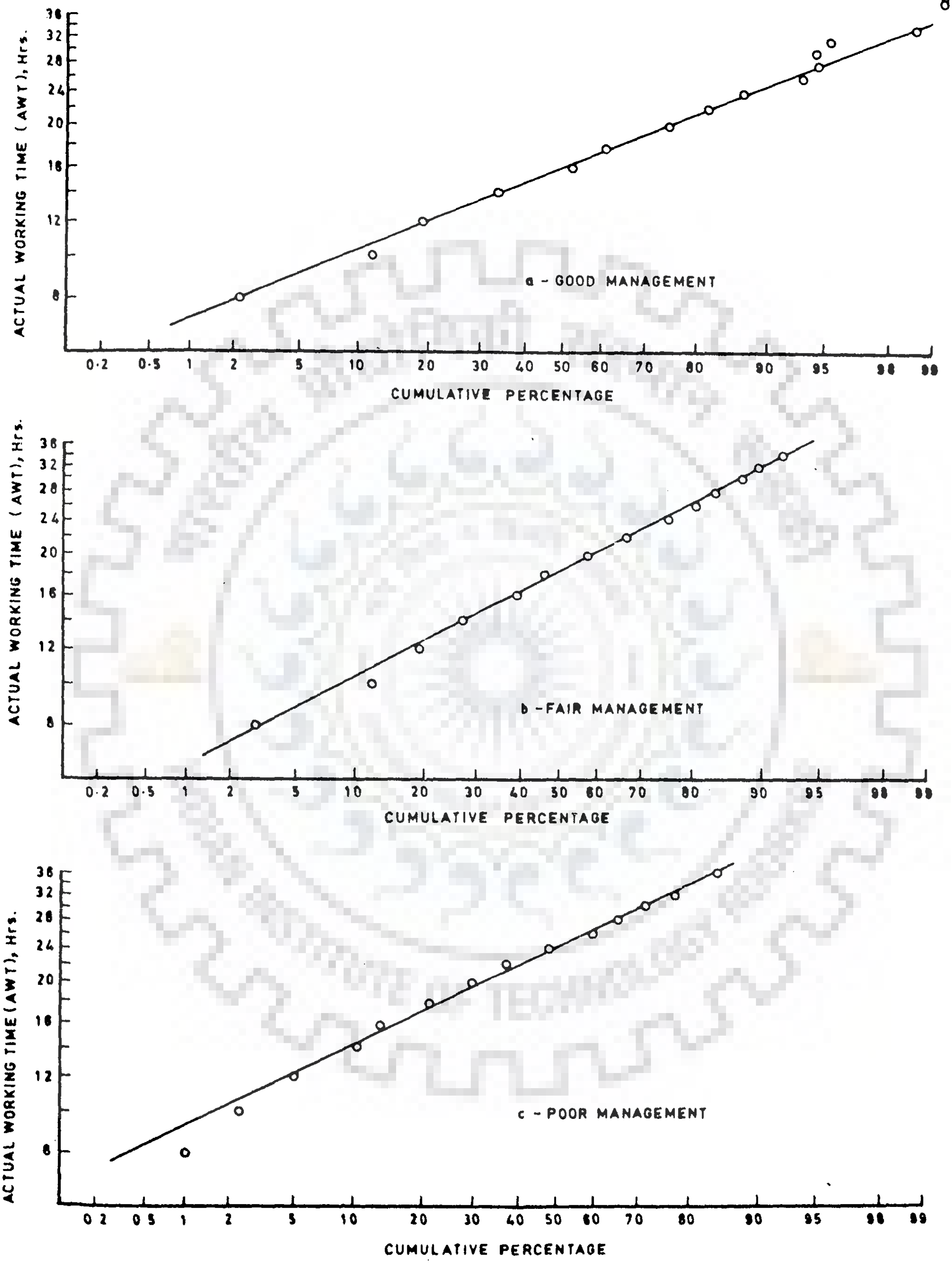


FIG. 5·12 LOG-NORMAL PROBABILITY PLOT OF ACTUAL WORKING TIME (AWT) UNDER POOR JOB CONDITIONS.

i) AWT can not be characterised as a failure function which is the basic requirement for Weibull function.

ii) Log-normal distribution is unbounded at both the ends whereas the Weibull distribution is bounded at one end either having a value of zero or equal to location parameter.

iii) The location parameter will have a single specific value for a particular situation whereas AWT is a random variable and cannot attain any single minimum value.

The probability plots on log-normal probability paper are shown in Figs. 5.10, 5.11 and 5.12 for good, fair and poor job conditions respectively. Each figure includes plots for all the three management conditions in that job condition. The values for ordered observation, viz., AWT and the plotting position (PP) have been taken for the purpose of probability plotting from Table 5.2 and Appendices V and VI for the different sets of job and management conditions.

The data fits well into the log-normal distribution and satisfies all necessary requirements. Thus, it is felt that there is no necessity of carrying out any statistical tests. It is, however, noted that there is variance of some points at the tails. Since these are rare occurrences, they do not affect significantly the results of the study.

5.5 Probability Distribution for Breakdown Time (BDT)

A variety of breakdowns of equipment or services and hold-ups in the work occur during tunnel excavation cycle. These may be mechanical in nature, such as, the breakdown of drilling equipment, breakdown of muck loading and/or hauling equipment, derailments, etc. or these may be electrical breakdowns caused by failure of electric supply or failure of the electrical components of the tunnelling equipment. Some of the hold-ups may be of a mixed nature. These include minor mishaps, non-availability of a particular piece of equipment when needed, rock falls, change-over in working shift, tunnel maintenance, extension of service lines, survey and preventive maintenance, etc. Recording of the nature of breakdowns and hold-ups and their durations for all types has not been done on any project for the total construction period. However, the total time lost in all kinds of hold-ups in each cycle has been recorded and forms the basis for further analysis in this study. As expected the breakdown time (BDT) in many cycles is observed to be zero. Total number of observations in each cell of the matrix is the same as for AWT since the basic record for both the components of total cycle time is the same (Table 5.1).

5.5.1 Choice of interval size for BDT

For the same reasons as discussed under AWT, the interval size for BDT giving optimum combination of smoothness and detail has been found to be one hour (138). The sample frequency data of BDT for good job condition is presented in Table 5.3. For fair and poor job conditions this data is presented in Appendices VII and VIII respectively. The relative frequency distribution curves are shown in Figs. 5.13, 5.14 and 5.15 for good, fair and poor job conditions respectively. All management conditions are covered under a particular job condition in each figure.

5.5.2 Test for suitable probability distribution function for BDT

The shapes of curves in Figs. 5.13, 5.14 and 5.15 indicate a J-shaped probability distribution. Such a shape of the curves is common to the exponentially distributed variates and the break-

TABLE 5.3

BREAKDOWN TIME (BDT) FREQUENCY DISTRIBUTION UNDER GOOD JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position
(Hrs.)	(F)	(RF)	(PP)	(F)	(RF)	(PP)	(F)	(RF)	(PP)
0-1	379	0.560	55.99	358	0.346	34.57	127	0.267	26.63
1-2	110	0.163	72.26	213	0.206	55.17	74	0.156	42.21
2-3	73	0.108	83.06	153	0.148	69.97	64	0.135	55.68
3-4	33	0.049	87.94	84	0.081	78.09	54	0.114	67.05
4-5	22	0.032	91.20	84	0.081	86.22	29	0.061	73.16
5-6	13	0.019	93.12	42	0.041	90.28	26	0.055	78.63
6-7	5	0.007	93.86	26	0.025	92.79	27	0.057	84.31
7-8	9	0.013	95.19	18	0.017	94.53	11	0.023	86.63
8-9	7	0.010	96.23	12	0.012	95.70	13	0.027	89.37
9-10	1	0.001	96.37	12	0.012	96.86	8	0.017	91.05
10-11	6	0.009	97.26	5	0.005	97.34	2	0.004	91.47
11-12	6	0.009	98.15	5	0.005	97.82	5	0.010	92.53
> 12	12	0.018	99.93	22	0.021	99.95	35	0.074	99.89

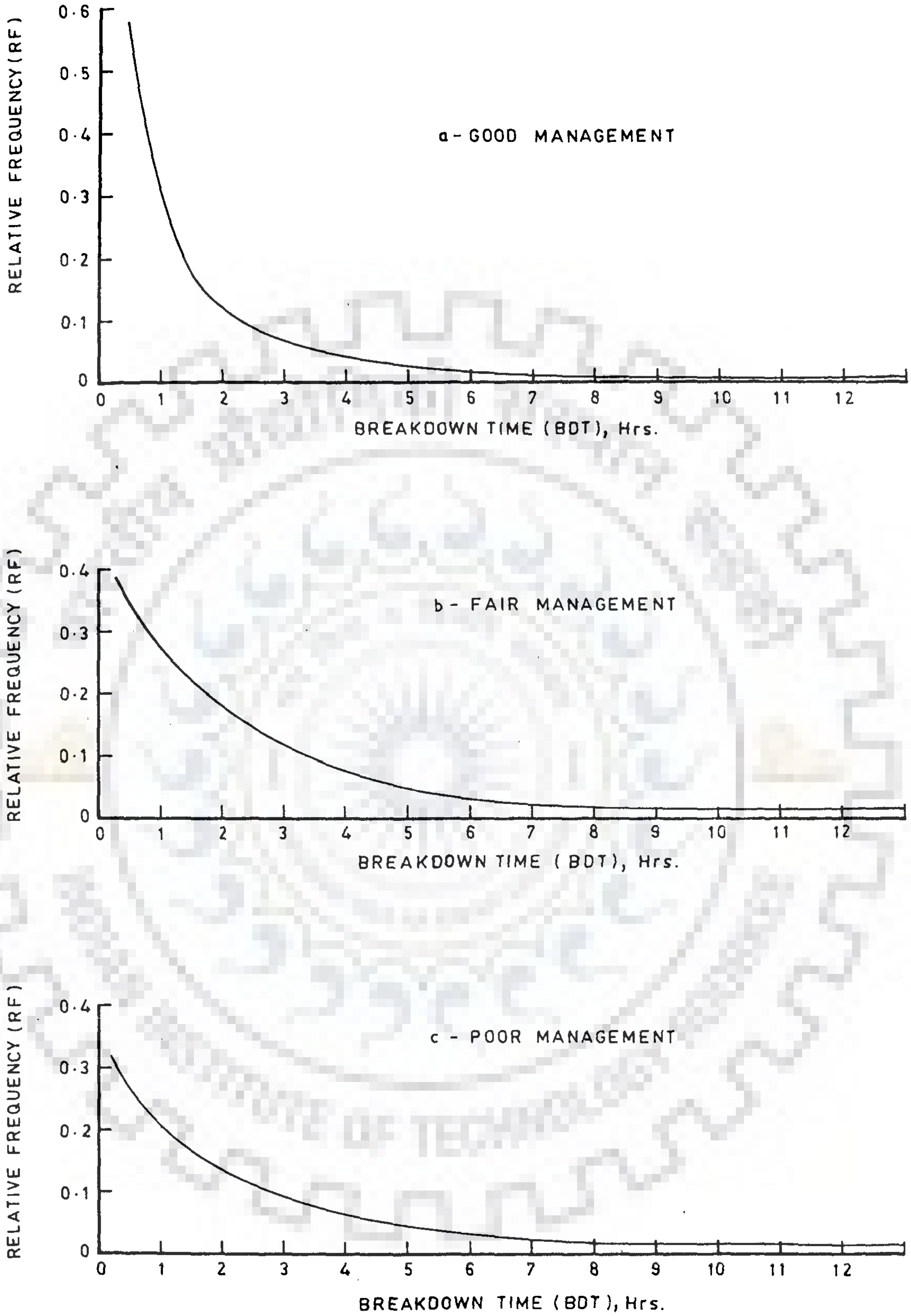


FIG. 5·13 RELATIVE FREQUENCY DISTRIBUTION CURVES FOR BREAKDOWN TIME (BDT) UNDER GOOD JOB CONDITIONS.

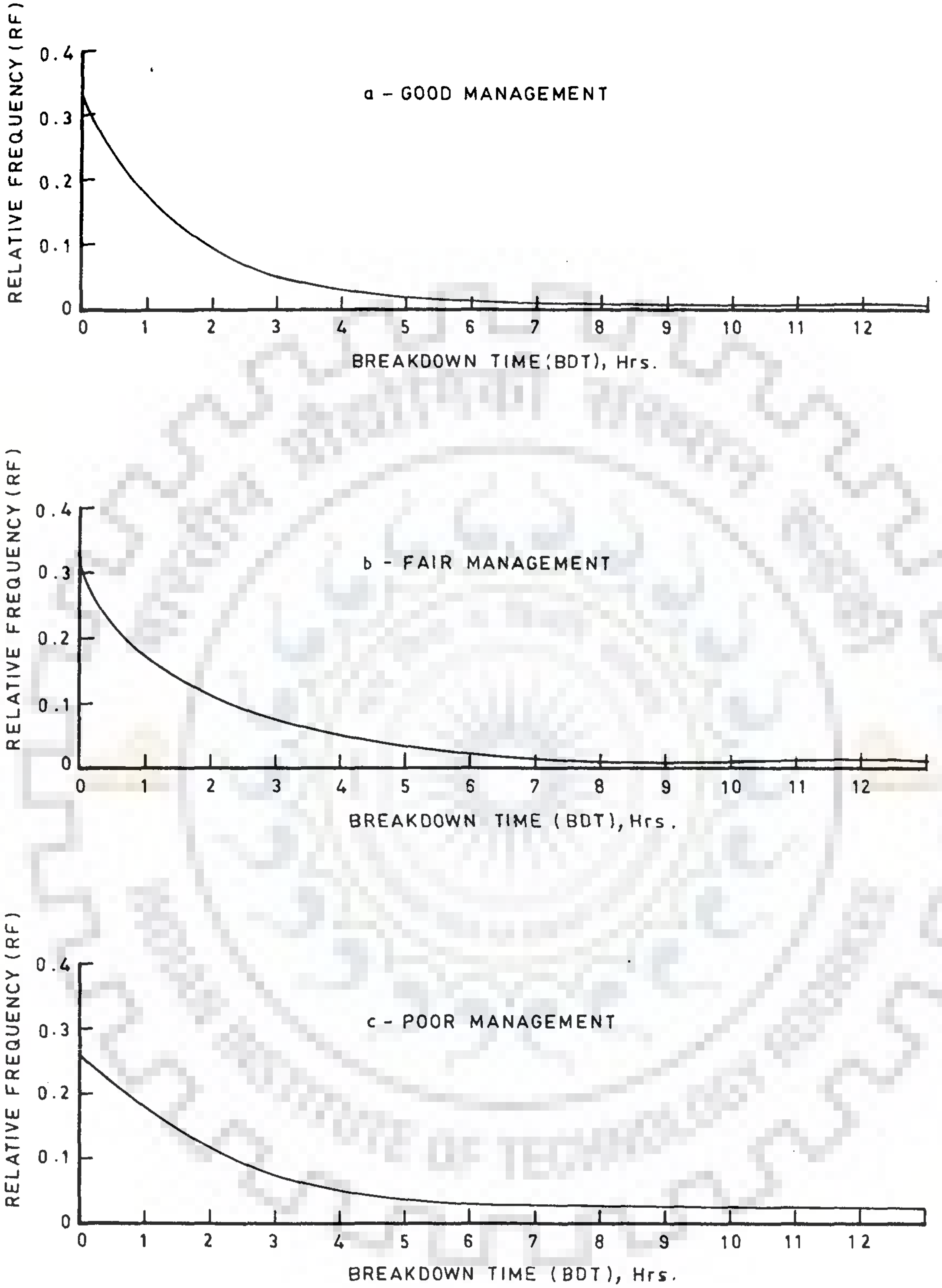


FIG. 5·14 RELATIVE FREQUENCY DISTRIBUTION CURVES FOR BREAKDOWN TIME (BDT) UNDER FAIR JOB CONDITIONS.

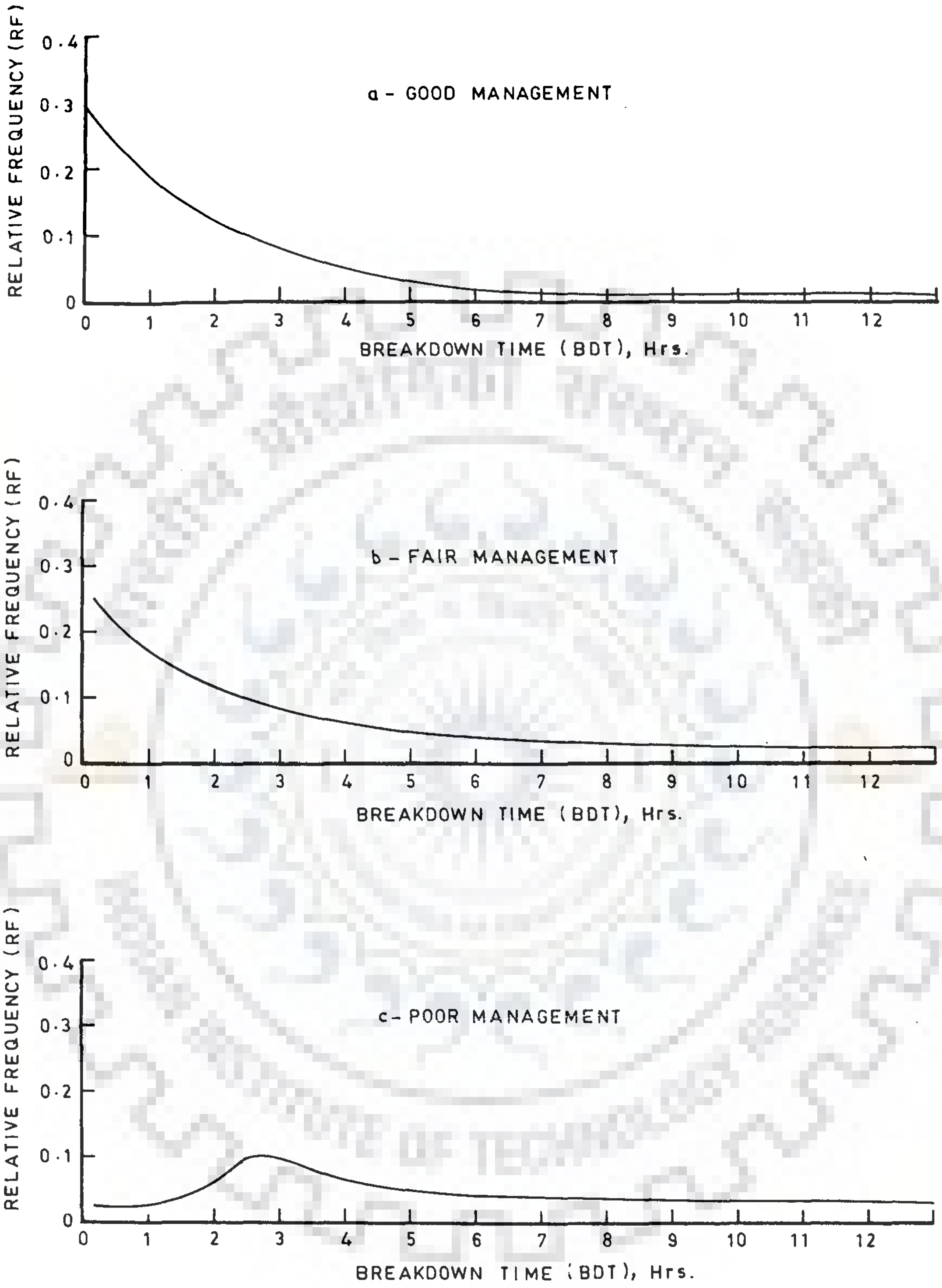


FIG. 5·15 RELATIVE FREQUENCY DISTRIBUTION CURVES FOR BREAKDOWN TIME (BDT) UNDER POOR JOB CONDITIONS.

downs being failure functions belong to this family of probability distributions. Behaviour of a number of time dependent processes conforms to exponential distribution (6,136,146). The special classes of exponential distribution are the two-parameter exponential and three parameter Weibull distributions. The Weibull distribution gives more refined representation taking into account the effect of all parameters in the probability distributions such as the location, scale and shape parameters. This has, therefore, been considered for testing the fitness of the BDT data. In this case the Weibull distribution is found to be best fit due to the following reasons :

Weibull distribution is applicable as a failure function whenever a system under study consists of more than one component. Complete failure occurs due to the most serious defect only out of a large number of defects that may be present in the system(136, 148). This is precisely the case in the tunnel excavation process in which all subsequent operations might be stalled due to hold up in any one of the preceding operations.

The probability plots of BDT for all the conditions are presented in Figs. 5.16, 5.17 and 5.18 for good, fair and poor job conditions respectively. These plots reveal an exceptionally good fit of the data into Weibull distribution for all the conditions. The need for statistical tests is, therefore, not felt due to the good fit indicated by the probability plotting.

5.5 Probability Distribution for Advance Per Round (APR)

The advance achieved in different excavation cycles is a function of both the controlled and uncontrolled factors. The advance may be controlled by adoption of a predefined drilling

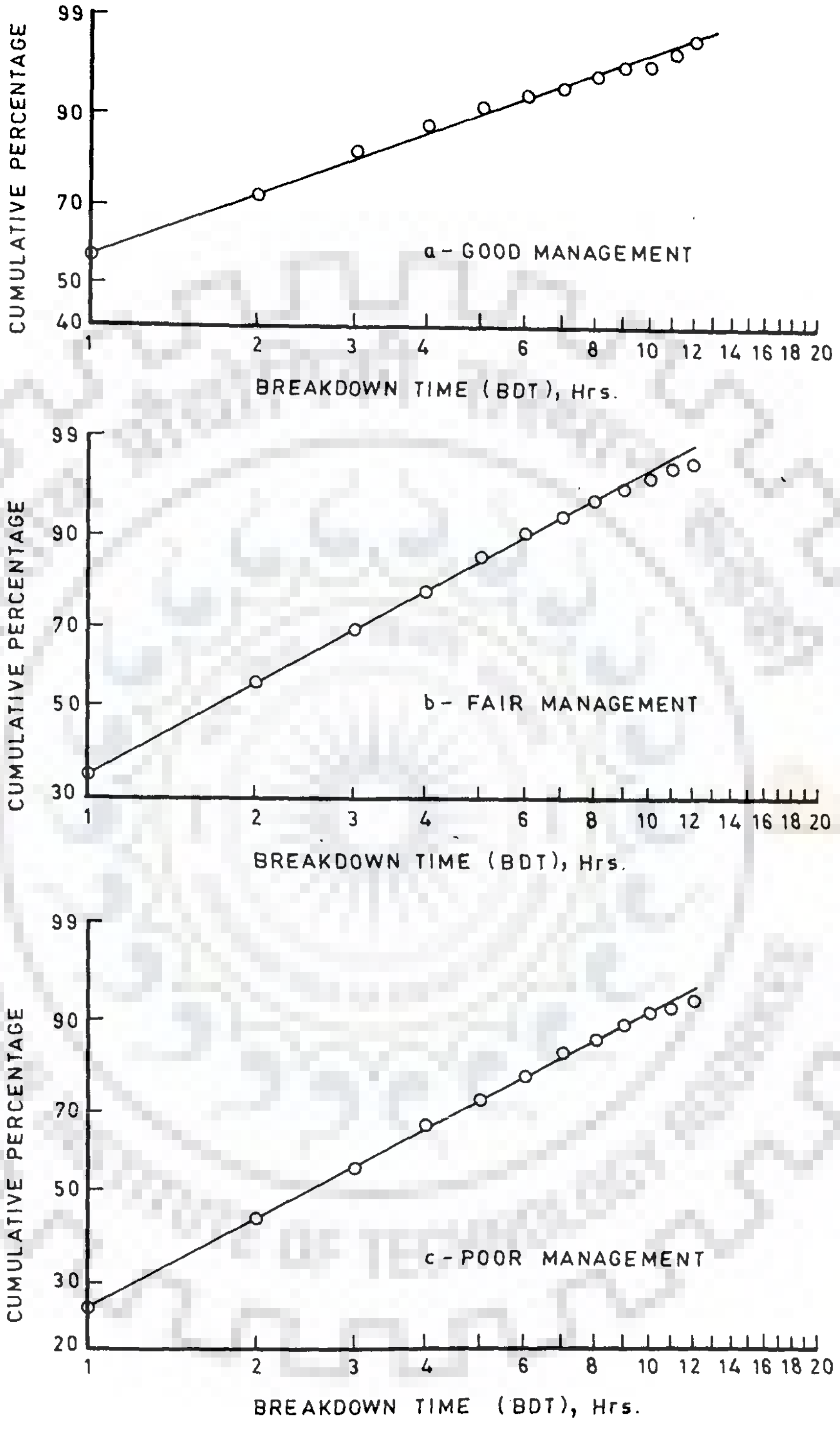


FIG. 5.16 WEIBULL PROBABILITY PLOT OF BREAKDOWN TIME (BDT) UNDER GOOD JOB CONDITIONS.

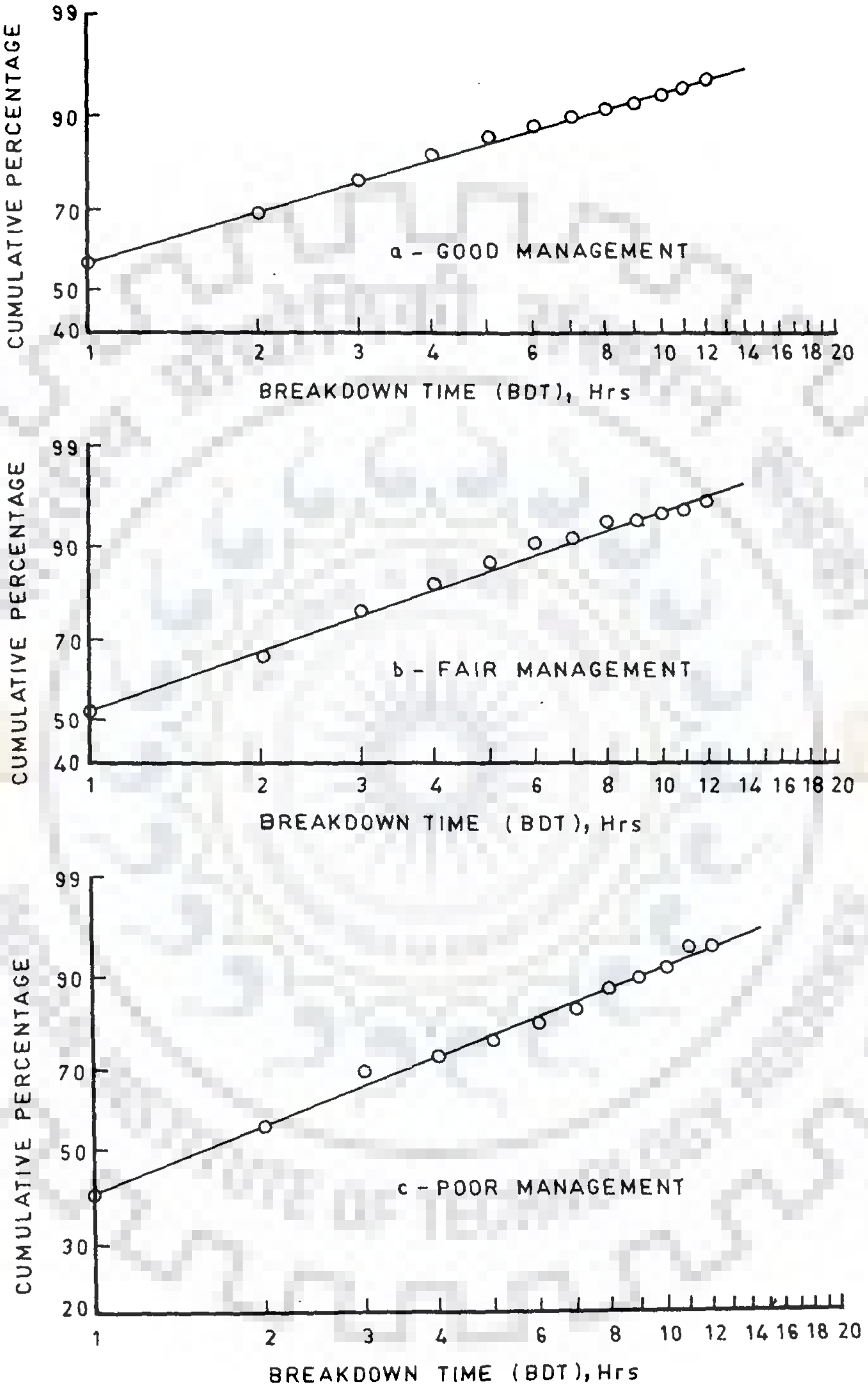


FIG. 5·17 WEIBULL PROBABILITY PLOT OF BREAKDOWN TIME (BDT) UNDER FAIR JOB CONDITIONS.

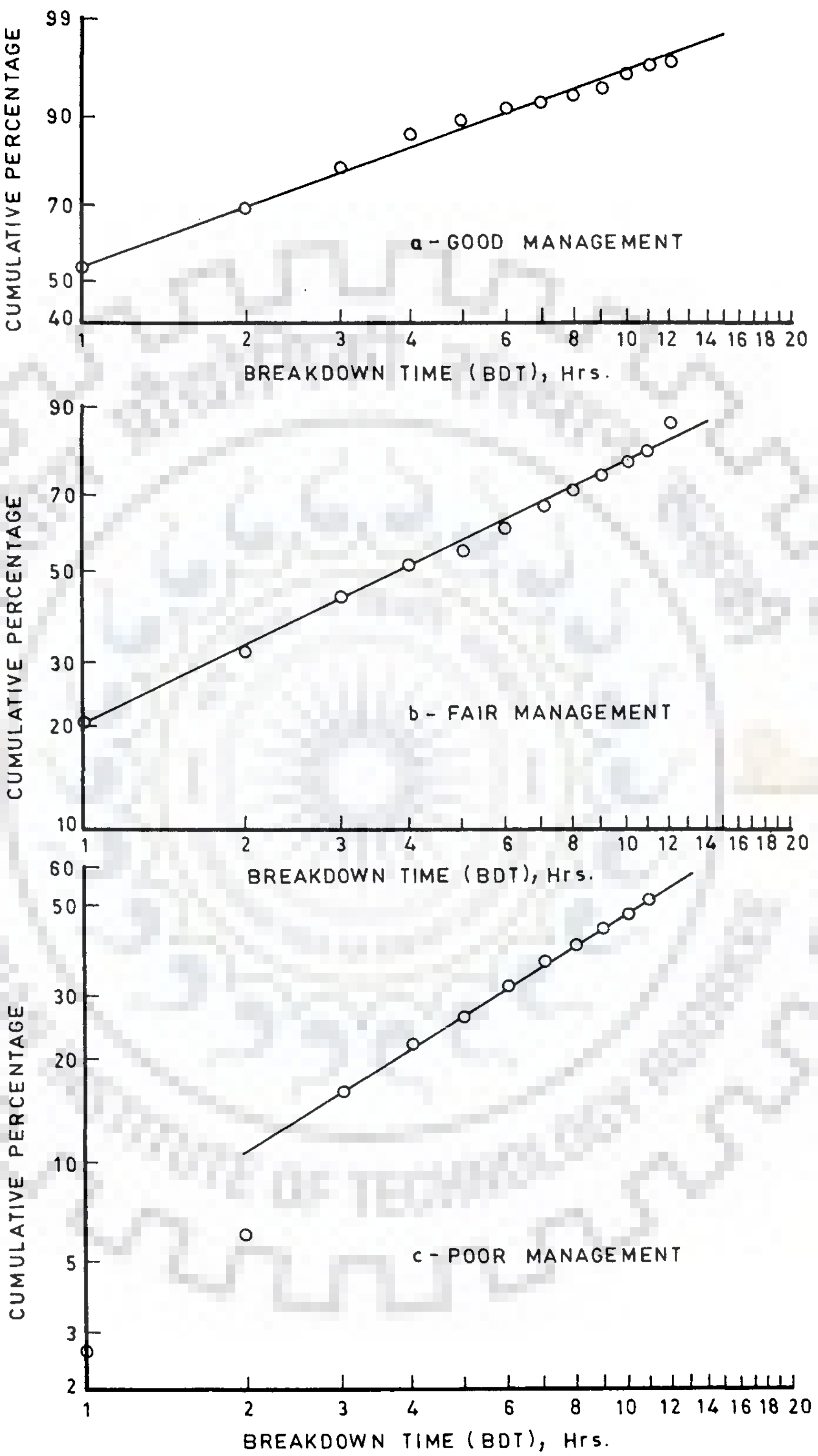


FIG. 5·18 WEIBULL PROBABILITY PLOT OF BREAKDOWN TIME (BDT) UNDER POOR JOB CONDITIONS.

depth and the control of actual drilling operation. The loading of explosive charges in the various holes at the tunnel face may also be controlled. However, the fragmentation characteristics of the rocks will be governed by the jointing, dip and strike of rock formations apart from the above mentioned controllable factors. This may affect the actual advance under a given set of conditions.

The scrutiny of data (Figs. 5.19, 5.20 and 5.21) collected for tunnel under study reveals that an advance of 2.44 m was achieved for over 46% of the cycles and of 3.05 m for over 24% of the cycles under good job condition. The actual advance achieved under this job condition is shown in Table 5.4. Similar tables for fair and poor job conditions are presented in Appendices IX and X respectively. The relative frequency curves are shown in Figs. 5.19, 5.20 and 5.21 for good, fair and poor job conditions respectively. The curves show that the data is unevenly scattered for most cases and does not indicate a definite trend for any known probability distribution. This is further confirmed by plotting the data on the probability papers for various distributions. Since none of the plots showed a linear fit, it was decided not to use the probability model for advance per round but to adopt a weighted average value for the advance from the processed data for all the cycles under each job and management condition. These weighted values are shown in Table 5.5.

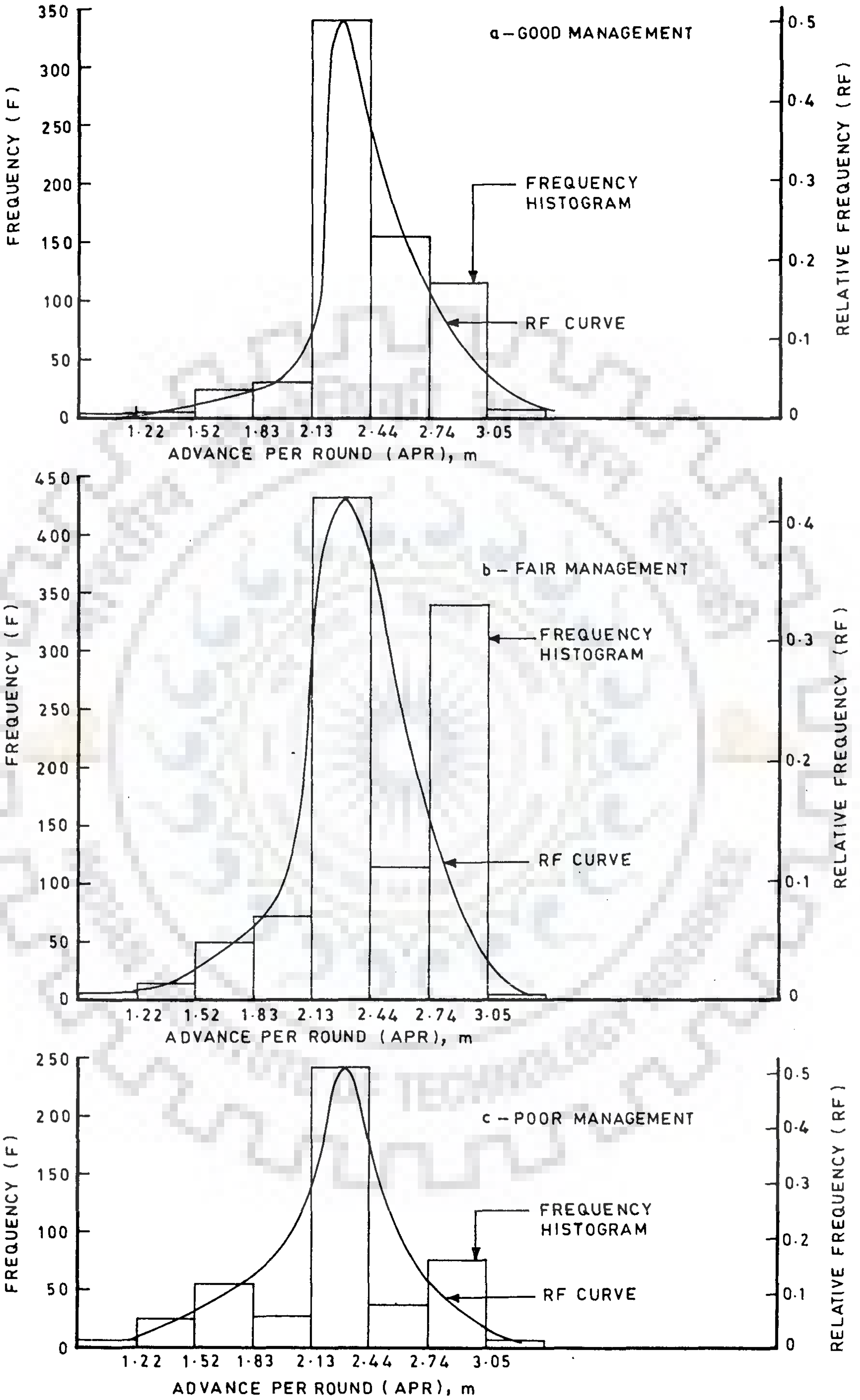


FIG. 5.19 FREQUENCY DISTRIBUTION CURVES FOR ADVANCE PER ROUND (APR) UNDER GOOD JOB CONDITIONS.

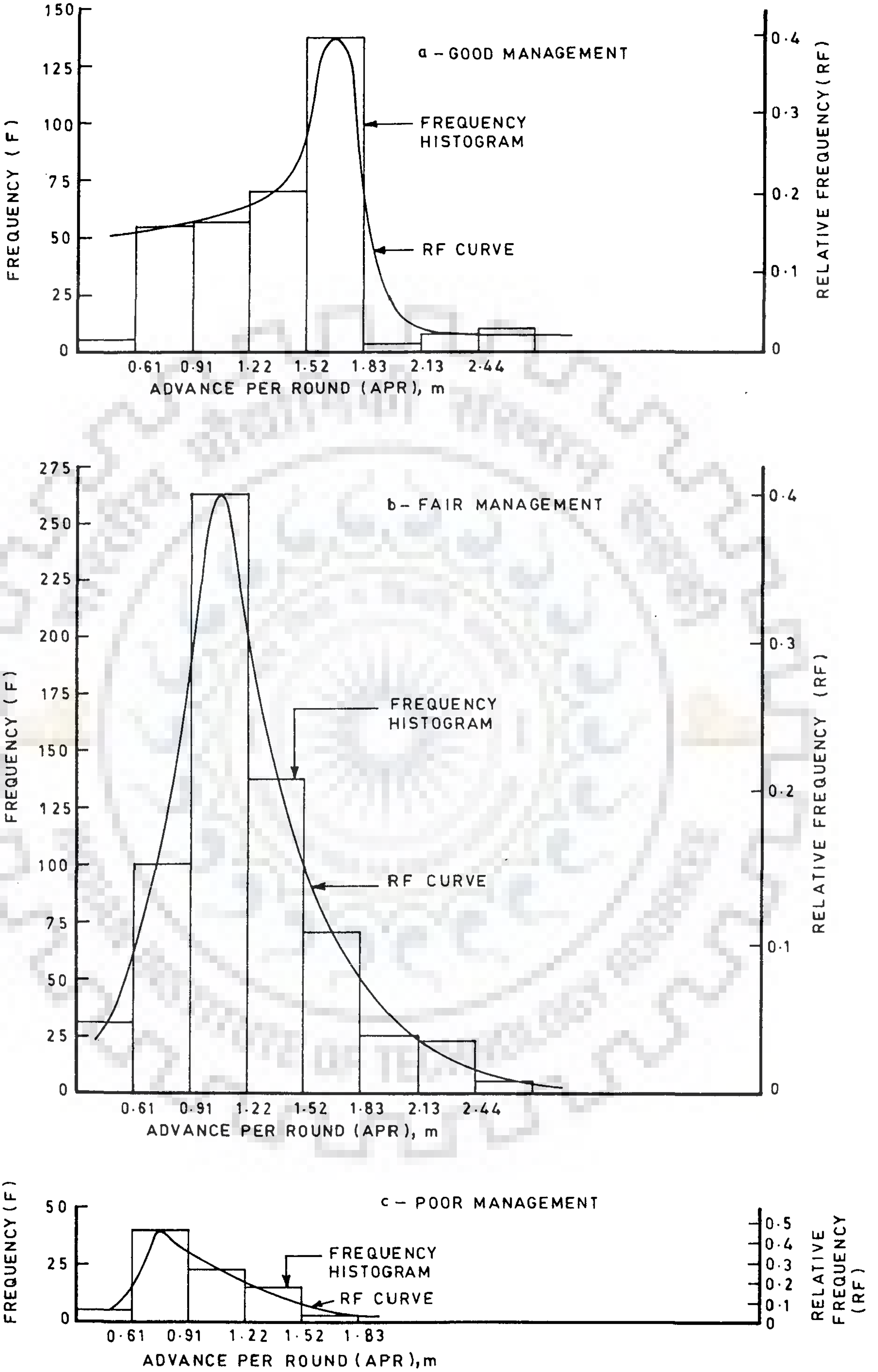


FIG. 5·20 FREQUENCY DISTRIBUTION CURVES FOR ADVANCE PER ROUND (APR) UNDER FAIR JOB CONDITIONS

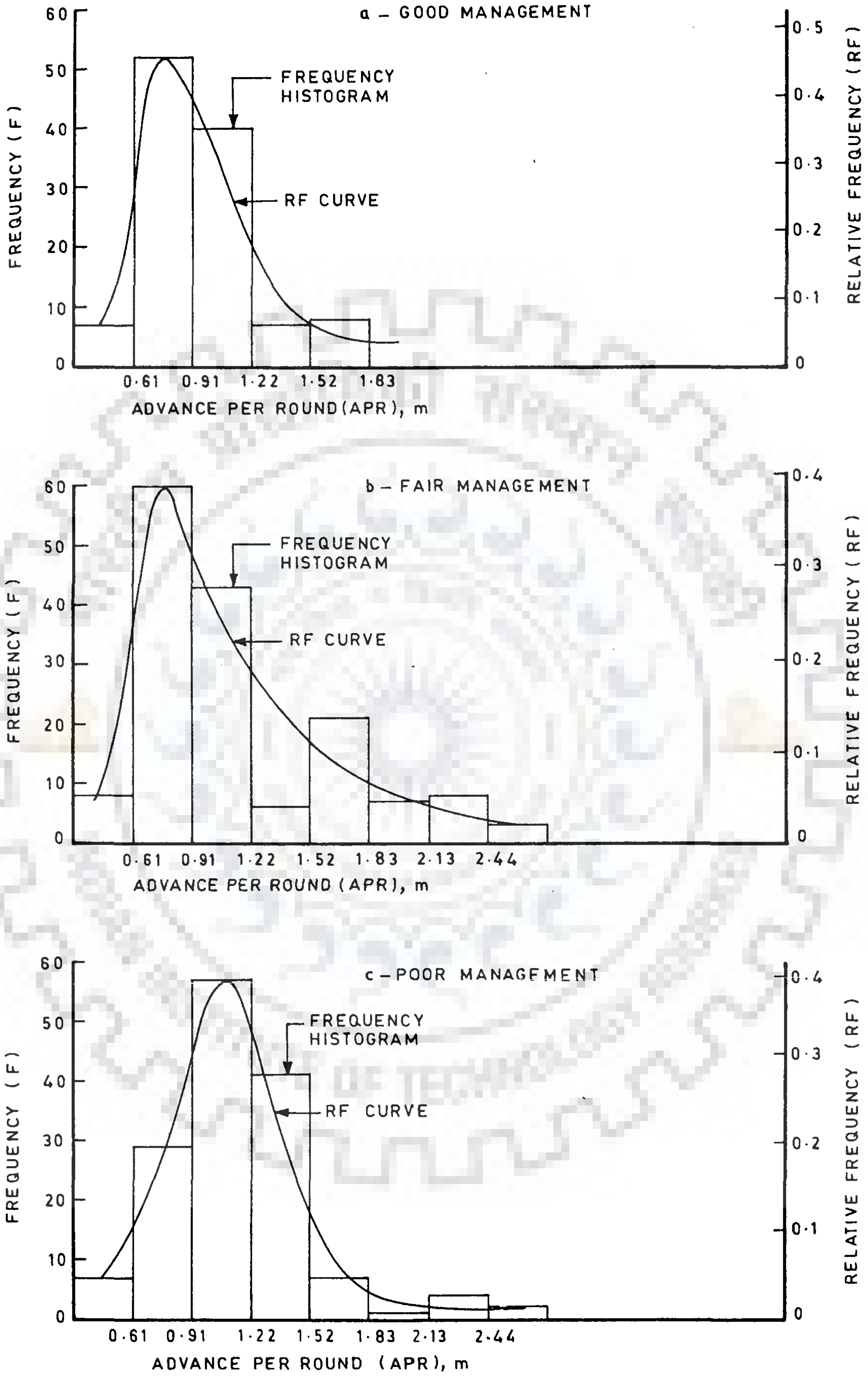


FIG. 5·21 FREQUENCY DISTRIBUTION CURVES FOR ADVANCE PER ROUND (APR) UNDER POOR JOB CONDITIONS.

TABLE 5.4

ADVANCE PER ROUND (APR) FREQUENCY DISTRIBUTION UNDER GOOD JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position
(m)	(F)	(RF)	(PP)	(F)	(RF)	(PP)	(F)	(RF)	(PP)
⩽ 1.22	3	0.004	0.37	6	0.006	0.53	6	0.013	1.16
1.22-1.52	5	0.007	1.11	14	0.013	1.88	25	0.053	6.42
1.52-1.83	23	0.034	4.51	49	0.047	6.62	55	0.116	18.00
1.83-2.13	30	0.044	8.95	72	0.070	13.59	27	0.057	23.68
2.13-2.44	338	0.500	58.95	433	0.419	55.46	243	0.512	74.84
2.44-2.74	154	0.228	81.73	115	0.111	66.59	37	0.078	82.63
2.74-3.05	116	0.172	98.89	341	0.330	99.56	76	0.160	98.63
> 3.05	7	0.010	99.93	4	0.004	99.95	6	0.013	99.89

TABLE 5.5

WEIGHTED AVERAGE VALUES OF ADVANCE PER ROUND IN METRES

		Management condition		
		Good	Fair	Poor
Job condition	Good	2.576	2.608	2.424
	Fair	1.519	1.376	1.069
	Poor	1.088	1.305	1.306

CHAPTER 6

COMPUTER SIMULATION OF TUNNEL EXCAVATION

6.1 General

Planning for tunnel construction is a complex exercise. Due to the stochastic nature of this activity, the deterministic conventional approach is inadequate. Tunnelling involves grappling with uncertainties at all stages and for such situations, stochastic simulation offers the best solution. Specifically simulation may be used where analytical solutions are impracticable. Through the use of simulation one may experiment on the real system, i.e., the performance of real work may be imitated. With the availability of computers, endless permutations and combinations can be experimented with and appropriate decisions taken based on the results of these experiments. These experiments have to be carefully planned and performed so as to conceptualize the essence of the whole process and also to take into account the effect of various exogenous variables and parameters on the performance of the system. The actual field performance data chosen with the analyst's experience and adoption of statistical methods and probability functions for analysis give an insight into the working of stochastic phenomenon like tunnelling.

There are two types of effects to be studied in simulation. These are, the main effects and the interaction effects (101). In the present study only the main effects (AWT and BDT) have been studied and it is presumed that the effects of interactions (performance times for individual operations) are taken care of by these main effects.

6.2 Flow Chart for Simulation Experiments

The general outline for planning simulation experiment for tunnel excavation is given in the flow chart shown in Fig. 6.1. Out of the nine steps listed in the figure, the first three have been discussed in the preceding chapters of this study. The remaining six steps are evaluated and discussed in this chapter.

6.3 Estimation of Parameters of Probability Distributions

Statistical analyses of cycle time data has revealed that the log-normal distribution is the best fit for AWT and Weibull distribution for BDT (Fig. 5.10 to Fig. 5.12 and Fig. 5.16 to Fig. 5.18). The generation of values for these components of the cycle time requires the estimation of parameters of these distributions. This is discussed here.

6.3.1 Estimation of parameters for log-normal distribution

The variate of interest in this case is the actual working time in hours. If it is designated as x and its logarithm (to base e) has a density function f(y) given by

$$f(y) = \frac{1}{\sigma_y \sqrt{2\pi}} \exp\left[(-1/2) \left\{ \frac{y-\mu_y}{\sigma_y} \right\}^2 \right] \qquad \ldots (6.1)$$

$$-\infty < y < \infty$$

where log x = y, and $x \geq 0$, then x follows the log-normal distribution.

The parameters, μ_y and σ_y^2 correspond to the mean and variance of y in Eq.6.1.

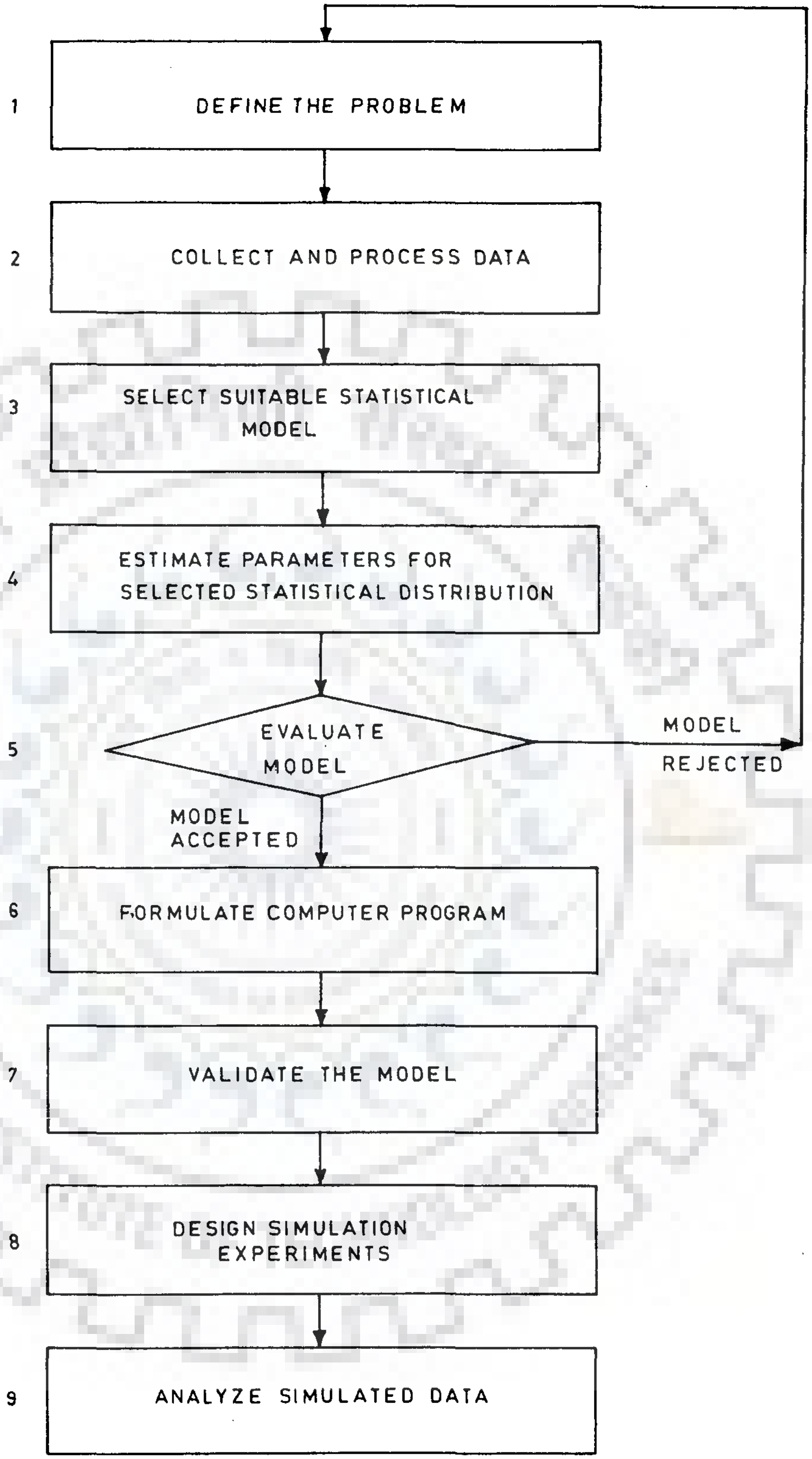


FIG. 6·1 FLOW CHART FOR SIMULATION EXPERIMENTS

The expected value (EX) and the variance (VX) of the log-normally distributed variate x are given by the following relations.

$$EX = \exp\left[\mu_y + \frac{\sigma_y^2}{2}\right] \qquad \ldots (6.2)$$

$$VX = \exp\left[2\mu_y + \sigma_y^2\right]\left[\exp(\sigma_y^2) - 1\right]$$

$$VX = (EX)^2\left[\exp(\sigma_y^2) - 1\right] \qquad \ldots (6.3)$$

Since the values of EX and VX, are known from the observed data, μ_y and σ_y^2 can be expressed in terms of EX and VX and evaluated.

From Eq.6.3

$$\frac{VX}{(EX)^2} = \exp(\sigma_y^2) - 1 \qquad \ldots (6.4)$$

$$\exp(\sigma_y^2) = \frac{VX}{(EX)^2} + 1$$

$$\sigma_y^2 = \log\left[\frac{VX}{(EX)^2} + 1\right] \qquad \ldots (6.5)$$

From Eq. 6.2,

$$\log(EX) = \mu_y + \frac{\sigma_y^2}{2}$$

or $$\mu_y = \log(EX) - 1/2 \log\left[\frac{VX}{(EX)^2} + 1\right] \qquad \ldots (6.6)$$

The values of σ_y^2 and μ_y can be computed using Eq. 6.5 and Eq. 6.6 respectively knowing the values of EX and VX.

The parametric estimates for log-normal distribution for all the nine cells of job and management matrix are given in Table 6.1.

TABLE 6.1

ESTIMATES OF PARAMETERS OF LOG-NORMAL DISTRIBUTION FOR AWT IN HOURS

		Management condition		
		Good	Fair	Poor
Job condition	Good	14.683 2.880 2.680 0.1152	18.917 4.448 2.934 0.1111	22.006 6.009 3.085 0.1111
	Fair	11.777 6.117 2.545 0.2077	18.605 8.192 2.912 0.1529	24.756 12.454 3.199 0.1418
	Poor	17.260 7.035 2.837 0.1528	19.995 9.025 2.984 0.1494	28.049 17.938 3.323 0.1501

INDEX

EXA	STDX
EY	STDY

i) EXA is mean of AWT,
ii) STDX is standard deviation of AWT,
iii) EY is mean of log (AWT), and
iv) STDY is standard deviation of log (AWT)

6.3.2 Estimation of parameters for Weibull distribution

The breakdown time in hours is the variate under study here which is derivable from Weibull distribution function. Weibull's distribution is an extension of exponential distribution. Its density function f(x) is given as,

$$f(x) = \frac{c}{b}\left[\left(\frac{x-a}{b}\right)^{c-1}\right] \exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \qquad \ldots(6.7)$$

and the cumulative density function F(x) is given as

$$F(x) = 1-\exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \qquad \ldots(6.8)$$

for $x \geq a$, $a \geq 0$, $b > 0$ and $c > 0$.

Here a is the location parameter which is zero for BDT since the origin for the density function of BDT is taken at zero. Thus, only two parameters are left for evaluation. These are : the scale parameter (b), and the shape parameter (c). If c is equal to unity, Eq. 6.7 becomes identical to the density function for an exponential distribution. If $c > 1$, the distribution is bell shaped and if $c < 1$ it is J-shaped like the exponential. The expected value (EX) and variance (VX) for Weibull density function f(x) are given by the following expressions.

$$EX = b\,\Gamma\left(\frac{1}{c} + 1\right) \qquad \ldots (6.9)$$

$$VX = b^2\,\Gamma\left(\frac{2}{c} + 1\right) - (EX)^2 \qquad \ldots (6.10)$$

From Eq. 6.9 and Eq. 6.10, b and c may be expressed in terms of EX and VX and may be evaluated as follows :

$$b = \frac{c.EX}{\Gamma\left(\frac{1}{c}\right)} \qquad \ldots (6.11)$$

$$1 + \frac{VX}{(EX)^2} = \frac{2c\,\Gamma\left(\frac{2}{c}\right)}{\left[\Gamma\left(\frac{1}{c}\right)\right]^2} \qquad \ldots (6.12)$$

Eq. 6.11 and Eq. 6.12 involve evaluation of Gamma function whose values may be taken from the tables (94) and used in Eq. 6.12. This equation may be satisfied for a given accuracy (0.5% in this case) to yield a value for c, and then b can be evaluated from Eq. 6.11. The values of b and c for this study have been determined by a computer program (Appendix - XI) and are given in Table 6.2.

TABLE 6.2

ESTIMATES OF PARAMETERS OF WEIBULL DISTRIBUTION FOR BDT IN HOURS

		Management condition		
		Good	Fair	Poor
Job condition	Good	1.924 11.228 1.2916 0.6046	2.932 35.015 1.6688 0.5390	4.746 89.830 2.7353 0.5433
	Fair	3.099 70.124 1.185 0.4396	2.805 64.365 0.9818 0.4237	3.853 54.169 2.339 0.5620
	Poor	3.028 111.697 0.7605 0.3759	10.147 385.500 6.0686 0.5565	24.230 1335.437 18.651 0.6816

INDEX

EXB	VX
b	c

i) EXB is mean of BDT,
ii) VX is variance of BDT,
iii) b is scale parameter, and
iv) c is shape parameter.

6.4 Evaluation of the Model

This step of simulation represents the first stage of testing the simulation model prior to actual computer runs (Fig.6.1). Initial value judgement concerning the adequacy of the model is made. The operating characteristics in this model take the form of probability distributions for which the tests of goodness of fit have been made and suitable probability distributions satisfying the statistical criteria have been identified. In this step the following aspects of model study are taken care of :

i) Variables not pertinent to the study are not included.

ii) All exogenous variables which are likely to influence the behaviour of endogenous variables are included.

iii) The functional relationships have been accurately formulated. This entails selection of the suitable probability distribution functions satisfying the physical phenomenon under study.

iv) Estimation of parameters of operating characteristics has been correctly done.

v) The endogenous variables conform to the historical data or production records on the basis of hand computations.

6.5 Computer Simulation Model

The computer program developed for simulation is given in Appendix XII. The simulation of tunnel excavation activity entails generation of AWT and BDT for each cycle along the entire tunnel length. The values of AWT and BDT have been generated using subroutines for this purpose and random numbers for generation of the values have been adopted from the library function available in DEC SYSTEM-20, as R = RAN(X), where R is the random number between 0.0, 1.0, and X is any real integer number like 4, 5, ..., 36, 37 etc. The computer program has been developed in FORTRAN language and is equipped with suitable switches for availing options in the selection and use of a particular probability distribution function for generating values of both AWT and BDT.

6.5.1 Input data for simulation

The input to computer simulation model is in the form of lengths to be excavated in each job condition and % of the length falling in each management condition for that particular job condition for Pandoh-Baggi Tunnel. The lengths for each job condition are derived from the geological profile (Fig.4.2) and the job classification (Table 4.5, and Appendices III and IV).

These lengths for the three job conditions, viz., good, fair and poor have been found to be 9584 m, 791 m and 908 m respectively totalling to 11283 m. They cover the tunnel length excavated between January, 1966 and December, 1973, except 123 m length which experienced cavity formation.

The lengths excavated during the year 1965 and 1974 were not included for simulation since the initial period in 1965 was used for arrangements, training and acclimatisation; while in the year 1974 attention had been diverted to concrete lining of the tunnel. However, the length for which simulation is done covers 85.7% of the total length of the tunnel (which comes to 11283 m), while the field data for analysis was available for 57.9% of the total tunnel length (which came to 7625 m).

The field data covering lengths excavated in different job and management conditions and the percentage of length and cumulative % length in different management conditions for each job condition are shown in Table 6.3. The cumulative % lengths under different sets of job which have been derived on the basis of tunnel profile (Fig.4.2) and the classification system described in Table 4.5, have been used as input data for simulation and are shown in Table 6.4.

The values for parameters of log-normal and Weibull distributions are input as shown in Tables 6.1 and 6.2 respectively. The advance per round has been input as shown in Table 5.5.

TABLE 6.3

PERCENTAGE LENGTHS EXCAVATED IN EACH JOB AND MANAGEMENT CONDITION (Based on field data)

Job condition	Management condition	Length excavated (m)	Total length in job condition (m)	% of total in job condition	Cumulative % in each job condition
Good	Good	1744	5589	0.3121	0.3121
	Fair	2693		0.4818	0.7939
	Poor	1152		0.2061	1.0000
Fair	Good	526	1516	0.3470	0.3470
	Fair	898		0.5923	0.9393
	Poor	92		0.0607	1.0000
Poor	Good	124	520	0.2385	0.2385
	Fair	204		0.3923	0.6308
	Poor	192		0.3692	1.0000
Total			7625		

TABLE 6.4

CUMULATIVE LENGTHS AND PERCENTAGES IN EACH JOB AND MANAGEMENT CONDITION

Job condition	Cumulative length (m)	Cumulative percentage length in management condition		
		Good	Fair	Poor
Good	9584	0.3121	0.7939	1.000
Fair	10375	0.3470	0.9393	1.000
Poor	11283	0.2385	0.6308	1.000

6.5.2 Generation of log-normal variates

The log-normal variate x to be generated may be found from the equation of the standard normal variate z given as,

$$z = \frac{\log x - \mu_y}{\sigma_y} \qquad \ldots (6.13)$$

or

$$\log x = \mu_y + \sigma_y . z \qquad \ldots (6.14)$$

and

$$x = \exp\,(\mu_y + \sigma_y . z) \qquad \ldots (6.15)$$

where

$$z = \frac{\sum_{i=1}^{K} r_i - \frac{K}{2}}{\sqrt{\frac{K}{12}}} \qquad \ldots (6.16)$$

and r_i is the random number generated. The value of K is chosen such that the computational efficiency is balanced against the accuracy. If one chooses K equal to 12 there is a computational advantage since (K/12) becomes 1.

Thus, x is given by

$$x = \exp\left[\mu_y + \sigma_y\left(\sum_{i=1}^{12} r_i - 6.0\right)\right] \qquad \ldots (6.17)$$

The subroutine for generating log-normally distributed variates is given as follows;

```
      SUBROUTINE LOGNOR (EY,STDY,AWT)
      SUM=0.0
      DO 1 I=1,12
      R = RAN(4)
  1   SUM=SUM + R
      AWT=EXP[EY+STDY*(SUM-6.0)]
      RETURN
      END
```

Here R is the random number generated by the library function in DEC SYSTEM-20 Computer for generation of random numbers.

6.5.3 Generation of Weibull variates

The variate x which follows the Weibull distribution may be generated if we use the inverse transformation of the cumulative density function of x which is given by Eq.6.8, that is,

$$F(x) = 1-\exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \quad \ldots (6.18)$$

For BDT the scale parameter a is zero

$$\therefore \quad F(x) = 1-\exp\left[-\left(\frac{x}{b}\right)^{c}\right] \quad \ldots (6.19)$$

$$\text{or} \quad 1-F(x) = \exp\left[-\left(\frac{x}{b}\right)^{c}\right] \quad \ldots (6.20)$$

But $1-F(x) = r$ where r is the random number such that $0 < r < 1$

$$\therefore \quad x = b(-\log r)^{1/c} \quad \ldots (6.21)$$

For generating BDT the subroutine is given below :

```
SUBROUTINE WEIBUL (BBDT,CBDT,BDT)
R = RAN(6)
BDT = BBDT*(-ALOG(R)**(1./CBDT))
RETURN
END
```

Again, R is the random number generated by the library function.

6.6 Job and Management Factors Based on Computer Simulation

Computer simulation model generates values of AWT and BDT for each excavation cycle based on input parameters of statistical distributions for a particular condition of job and management. For the same condition the APR values for each cycle are adopted as given in Table 5.5. Total cycle time (TCT) is computed as sum of AWT and BDT for each cycle. APR and TCT are cumulatively added until TCT adds upto total hours in a month which is 720. The corresponding cumulative value for APR is the advance made during the month. When the tunnel length under a particular set of job and management condition is completed, new set of data for the next set of conditions is used for generating monthly advance rates as discussed above. This is done for all the nine sets of job and management conditions. The computer prints out values of APR, AWT, BDT and TCT for each cycle and also their monthly averages.

The average monthly advance rate is then computed for each set of conditions and job and management factors computed as shown in Table 6.5.

TABLE 6.5

JOB AND MANAGEMENT FACTORS BASED ON SIMULATION RESULTS
(Based on ideal monthly progress of 140 m)

Job condition	Management condition	Average expected monthly advance (m)	Job and management factor $\left[\frac{\text{Col. 3}}{140}\right]$
1	2	3	4
Good	Good	112.0	0.80
	Fair	87.2	0.62
	Poor	64.1	0.46
Fair	Good	78.2	0.56
	Fair	44.9	0.32
	Poor	26.1	0.19
Poor	Good	39.2	0.28
	Fair	31.2	0.22
	Poor	17.7	0.13

CHAPTER 7

DISCUSSION OF RESULTS

7.0 This study is based on extensive field data which has been statistically analysed and used to simulate the tunnel excavation activity. The results of various aspects of the study are discussed in this chapter.

7.1 Development of a Classification System

7.1.1 Job classification

The first finding of this study is that the job conditions for tunnelling may be grouped into three categories as against five or more suggested by various investigators for the purpose of providing rock supports. Moreover, this categorization may be done on the basis of the knowledge of six simple parameters (Table 4.1). All these parameters can be known from the investigations which are normally carried out before planning for construction of the project. Thus the job classification can be done in advance of the actual planning and construction. This will result in precise estimation of total time for tunnel excavation in the planning stage, since tunnel advance rates in different rock formations falling in different sets of job conditions can be computed on the basis of this study.

It has been observed that the type of rock along with the jointing pattern plays the most significant role in tunnelling and affects job classification. While the phylites were found by the author to be generally a good tunnelling media on most Indian projects, talc schists were found to be poor. Further, the formation of cavities can not be ruled out even in good job conditions and this prediction at the investigation stage is difficult. Therefore, the prediction of tunnel advance rate either by computer or with manual computation can not be done for this exceptional job condition.

According to this classification system 74% of the total length of Pandoh-Baggi tunnel passed through good, 17% through fair and 8% through poor job conditions. The remaining 1% length involved cavity formations.

The comparison of job conditions as predicted by the proposed classification to that adopted by project geologist is shown in Table 7.1.

TABLE 7.1

COMPARISON OF GEOLOGIST'S AND AUTHOR'S CLASSIFICATION SYSTEMS (percentages of total tunnel length)

Basis	Rock category*		
	Good	Fair	Poor
Pre-construction (1964) forecast by geologist (77)	35	51	14
Post-construction (1974) observations by geologist (77)	69	22	9
Author's classification based on pre-construction forecast(Table 4.1)	74	17	9

*The geologist had named his three rock categories as good to satisfactory, satisfactory to fair and fair to poor.

Table 7.1 clearly shows that the classification as developed in this study (Table 4.1) agrees well with the actual ground conditions as observed by the geologist.

7.1.2 Management classification

The deviation in tunnelling progress from month to month in the same job condition is a pointer to the management to gauge its own effectiveness. The causes for fair or poor management may be easily identified from the study of rating parameters in Table 4.3. It is significant to note that there is a very close interrelationship among and interdependence of various parameters. The improvements in some of the items would automatically improve conditions in certain other allied activities. For example, the training of drilling and blasting crew will help to reduce overbreak and avoid any need for secondary blasting in addition to saving of some time in the performance of these operations. Similarly the training of mechanics and operators will help in reducing the breakdowns in addition to improved productivity from equipment.

The points of inflexion on the cumulative relative frequency curves for equivalent monthly progress (Figs.4.3 to 4.5) were considered to indicate the changes in management conditions. This fact was confirmed from the study of the values of actual working time which were listed in different class intervals for each month, while the months themselves were arranged in the descending order of their effective monthly progress values. The values of AWT for those months which fell in a different management condition as indicated by the point of inflexion principle showed a distinctly different trend having peak frequency for different values of actual working time than that for the previous management condition.

The development of parameter ratings is an iterative process. The values proposed here may need slight modifications when the sample size for data to compute these values is larger.

7.1.3 Job and management factors based on field data

Job and management factors based on field data were computed using an achievable production of 140 m per month under good job and good management condition as the reference. These values are tabulated in Table 4.10.

7.2 Ascertaining Distribution Patterns for Cycle Time

7.2.1 Statistical analysis

In order to simulate the tunnel excavation activity, the input statistical parameters to the model are the advance per round, and means and standard deviations of actual working time and breakdown time. These values, as derived from the present study are shown in Tables 7.2 and 7.3.

It is observed from Table 7.2 that under the good job condition the mean advance per round does not vary significantly for the three management conditions. It has varied significantly under the fair and poor job conditions. It is felt that the advance of 1.07 m for poor management under fair job condition is rather low. On the other hand the advance of 1.31 m for fair and poor management under poor job condition is on the high side. These values should be within the ranges suggested in Table 4.1. The optimal advance for a particular job condition could, however, be computed through optimisation analysis (18).

In general the advance should be so selected that either a maximum total cycle time of 24 hours or of 16 hours is maintained.

TABLE 7.2

SUMMARY OF RESULTS OF STATISTICAL ANALYSIS FOR ACTUAL WORKING TIME (AWT)

Job condition	Management condition	Average advance per round (Table 5.5) (m)	Actual working time (AWT)		
			Mean ($\bar{x}$) (Table 6.1) (hrs.)	Standard deviation (σ) (Table 6.1) (hrs.)	COV(%) $\left[\frac{\sigma}{\bar{x}} \times 100\right]$
Good	Good	2.58	14.68	2.88	19.62
	Fair	2.61	18.92	4.45	23.51
	Poor	2.42	22.01	6.01	27.31
Fair	Good	1.52	11.78	6.12	51.94
	Fair	1.38	18.61	8.19	44.01
	Poor	1.07	24.76	12.45	50.28
Poor	Good	1.09	17.26	7.04	40.76
	Fair	1.31	19.99	9.03	45.14
	Poor	1.31	28.05	17.94	63.95

TABLE 7.3

SUMMARY OF RESULTS OF STATISTICAL ANALYSIS FOR BREAKDOWN TIME (BDT)

Job condition	Management condition	Average advance per round (Table 5.5) (m)	Breakdown time (BDT)		
			Mean ($\bar{x}$) (Table 6.2) (hrs.)	Standard deviation (σ) (Table 6.2) (hrs.)	COV(%) $\left[\frac{\sigma}{\bar{x}} \times 100\right]$
Good	Good	2.58	1.92	3.35	174.48
	Fair	2.61	2.93	5.92	202.05
	Poor	2.42	4.75	9.48	199.58
Fair	Good	1.52	3.10	8.37	270.00
	Fair	1.38	2.80	8.02	286.43
	Poor	1.07	3.85	7.36	191.17
Poor	Good	1.09	3.03	10.57	348.84
	Fair	1.31	10.15	19.63	193.40
	Poor	1.31	24.23	36.54	150.82

This will instill confidence and urgency in the working crew to control the cycle time within the shift period and hence increase the tunnelling rate.

The probability plots of actual working time on log-normal probability paper show a linear fit thereby validating the assumption of log-normal distribution applicable for actual working time.

Similarly, the probability plots of breakdown time on Weibull probability paper also show an exceptionally linear fit. The breakdown time, thus, follows the Weibull distribution as is well known for such phenomenon (67,136).

7.2.2 Computer simulation

The excavation of Pandoh-Baggi tunnel was started in June, 1965 from Pandoh heading and was completed in December, 1974. For the purpose of present study the simulation has been carried out for the period from January, 1966 to December 1973. The initial few months of the year 1965 which were used in training and acclimatization, and the year 1974 when attention had been diverted to concrete lining, were not considered for this simulation. In addition, the cavity reaches (exceptional job conditions) were also not considered for analysis and simulation as these did not involve cyclic operations. The simulation has been carried out to compute calender time of excavation. The holidays falling during the construction period have, therefore, to be separately considered. Percentage lengths for each job condition and under different management conditions were computed for months identified by points of inflexion in Figs. 4.3 to 4.5. The lengths in each job condition were derived on the basis of job classification (Table 4.1). The results of simulation indicated a variation of only

4.68% with the actual construction period as shown below :

1) Total calendar construction period from January, 1965 to December, 1973 for both Pandoh and Baggi headings taken together is 192 months.

2) Period lost in tackling cavity portions for both the headings is 13 months.

3) Period lost due to holidays for both the headings @ 15 days/year/heading is 8 months. Thus, the calendar period actually spent in excavation is 171 months (192-13-8 = 171).

4) Period indicated by computer simulation is 163 months.

5) Deviation in completion time comes to $\frac{171-163}{171} \times 100 = 4.68\%$.

This shows that probability distributions for AWT and BDT and proposed job classification system are excellent representation of actual tunnelling activity.

7.3 Comparison of Values Derived from Field Data and from Simulation Data

A comparison of values of job and management factors derived from field data and those derived on simulated data is shown in Table 7.4. It is found that the two sets of factors compare well with each other.

The factors based on simulation results are only marginally higher than those obtained from real data. The difference is not significant since the probability distributions selected for AWT and BDT inherently account for these variations. All values of factors based on simulated data except one of them are either greater than or equal to the counterpart obtained from analysis of field data. It is felt that the factors should be given in range of values rather than single values in view of the non-uniformity of conditions even within the same job and management condition. The recommended values of the factor ranges are also shown in Table 7.4. The range covers the values in the two sets of factors and is, in itself, quite narrow. If prudently used, these values could provide a good guide to a planner in his estimation of rates of achievable progress on a tunnelling project.

TABLE 7.4

COMPARISON OF JOB AND MANAGEMENT FACTORS EVOLVED FROM FIELD DATA AND SIMULATION RESULTS

Job condition	Management condition	Job and management factors based on		Factor range recommended for use on projects
		Field data	Simulation	
Good	Good	0.78	0.80	0.76 - 0.81
	Fair	0.60	0.62	0.58 - 0.63
	Poor	0.44	0.46	0.42 - 0.47
Fair	Good	0.53	0.56	0.53 - 0.58
	Fair	0.32	0.32	0.30 - 0.35
	Poor	0.18	0.19	0.16 - 0.21
Poor	Good	0.30	0.28	0.28 - 0.33
	Fair	0.21	0.22	0.19 - 0.24
	Poor	0.13	0.13	0.10 - 0.15

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This study is based on large volume of field data collected from several Indian tunnelling projects. Extensive use was made of data collected for Pandoh-Baggi tunnel of Beas-Sutlej Link project and successful computer simulation was also done.

8.1 Conclusions

The conclusions presented below will generally apply to all tunnels using conventional drill and blast method with full face excavation.

The job and management classification of tunnelling conditions indicates that :

i) All tunnelling conditions are adequately represented by the proposed job classification system (Table 4.1).

ii) The quantification of factors affecting the quality of management (Table 4.3) gives an insight into the whole process of tunnelling. It could provide a handy tool for control of various operations during actual construction.

iii) The points of inflexion on the cumulative relative frequency curves of equivalent monthly progress (Figs. 4.3 to 4.5) appear to provide basis for significant changes in management conditions. Alternatively, the management conditions may be evaluated from Table 4.3 which gives numerical ratings for various parameters.

It has also been established in this study that the behaviour of prominent components in the tunnelling cycle is statistically well defined for all tunnelling situations. The analysis of cycle time data revealed that :

i) The data for actual working time (AWT) and break-down time (BDT) which are two components of the total cycle time conforms to log-normal and Weibull probability distributions respectively, for all sets of job and management conditions;

ii) The testing for distributional assumptions has been done by probability plotting method which has been found to be quick and reliable;

iii) The statistical parameters for actual working time(AWT) are its mean (EXA)and its standard deviation (STDX) and the mean (EY) and the standard deviation (STDY) of its logarithmic values. Similarly, the statistical parameters for break down time (BDT) are its mean (EXB), variance (VX), scale parameter (b) and the shape parameter (c). These eight parameters for all the nine job and management conditions have been evaluated from the field data (Tables 6.1 and 6.2);

iv) The data for advance per round (APR) did not fit into any of the known probability distributions. Therefore, the weighted average values have been adopted for each job and management condition which are realistic. The best advance rate for any job condition could be evaluated through optimisation;

v) The methodology of simulation as used for the study is proved adequate due to the similarity of values of job and management factors as obtained from field data and as obtained from simulated data;

vi) In view of the validity provided by the field data on production actually achieved, the range of values proposed for job and management factors appear to be reasonable and could be used in planning a tunnelling job.

8.2 Recommendations for Further Work

The study has exposed other problem areas where further investigations seem to be indicated. These are listed below under two distinct headings.

8.2.1 Collection of data

i) The present state of recording of data on projects is unsatisfactory. Accuracy and proper detailing of the field data in its recording are highly important. A format for recording cycle time data has been suggested in Appendix I.

ii) The upkeep of data and its availability after a project is completed is not assured on most projects at present. This aspect needs attention of construction managers.

iii) Geological information during construction needs to be compared and correlated with pre-construction information on all major projects.

iv) Data files for tunnel construction should be created on computer peripherals.

8.2.2 Analysis of data

i) Statistical analysis of time of each principal operation in the tunnelling cycle should be made so that the model could be improved.

ii) The effect of improving management quality in each job condition should be separately evaluated.

iii) A serious study of breakdown time patterns should be made to assess the effect of different types of breakdowns on production rates.

iv) Analysis for different advance rates per round may be made.

v) Management parameters as adopted in the study have subjective overtones and could perhaps be improved with greater expert opinion.

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INDEX FOR ABBREVIATIONS IN REFERENCES

AIIE	American Institute of Industrial Engineers
AIME	American Institute of Mining, Metallurgical and Petroleum Engineers
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Materials
CBI and P	Central Board of Irrigation and Power
CE and PWR	Civil Engineering and Public Works Review
CSIR	Council of Scientific and Industrial Research
IE	Institution of Engineers
IS	Indian Standard
ISRM	International Society of Rock Mechanics
JIE(I)	Journal of Institution of Engineers (India)
JOCD	Journal of Construction Division
N	Number
NARETC	North American Rapid Excavation and Tunnelling Conference
NATM	New Austrian Tunnelling Method
T & T	Tunnels and Tunnelling
V	Volume

APPENDIX I

FINAL FORMAT FOR RE-RECORDING DATA OF TUNNELS FOR BEAS SUTLEJ LINK (BSL) PROJECT

Cycle number	Chainage (m)	Advance achieved (m)	Number of drill holes	Number of muck cars	Time taken for various activities in hours						
					Drilling	Loading and blasting	Defuming	Mucking	Scaling	Rail extension	Moving jumbo
1	2	3	4	5	6	7	8	9	10	11	12

Time taken for various activities in hours									
Secondary blasting	Fixing rib and packing	Initial concreting	Worker's rest	Total working time (sum of cols.6 to 16)	Mechanical breakdowns	Electrical breakdowns	Miscellaneous breakdowns	Total breakdown time (sum of cols. 18,19 and 20)	Gross cycle time (sum of cols. 17 and 21)
13	14	15	16	17	18	19	20	21	22

APPENDIX II

FINAL FORMAT FOR RE-RECORDING DATA OF OTHER THAN BEAS-SUTLEJ LINK (BSL) TUNNELS

Cycle number	Chainage (m)	Advance achieved (m)	Time taken for various activities in hours						
			Drilling	Loading and blasting	Defuming	Mucking	Rail extension	Fixing ribs and packing	Worker's rest
1	2	3	4	5	6	7	8	9	10

Time taken for various activities in hours		
Total working time (sum of cols. 4 to 10)	Total break-down time	Gross cycle time (sum of cols. 11 and 12)
11	12	13

APPENDIX III

CHAINAGEWISE GEOLOGICAL AND MONTHLY PROGRESS DATA FOR PANDOH HEADING OF PANDOH-BAGGI TUNNEL

(BEAS-SUTLEJ LINK PROJECT)

Year and month	Chainage		Geology	Job condition data					Remarks
	From (m)	To (m)		Job classification	Progress (m)	Actual working time (Hrs.)	Breakdown time (Hrs.)	Equivalent monthly progress (EMP) (m)	
1	2	3	4	5	6	7	8	9	10
1966									
April	170	216	Interbedded phylites and quartzites	Good	46	627.00	55.17	46	1 holiday
May	216	282	-ditto-	Good	66	604.80	113.94	66	1 holiday
June	282	361	-ditto-	Good	79	666.50	44.00	79	
July	361	381	-ditto-	Good	20	704.00	35.84	82	
	381	393	Shear zone*	Good	12				
	393	443	Phylites and quartzitic phylites	Good	50				
Nov.	715	777	-ditto-	Good	62	422.40	233.04	62	2 holidays
Dec.	777	855	-ditto-	Good	78	627.00	138.60	78	
1967									
Jan.	855	922	Interbedded phylites and quartzites	Good	67	631.80	39.25	67	2 holidays
Feb.	922	1013	-ditto-	Good	91	583.45	29.05	91	2 holidays

1	2	3	4	5	6	7	8	9	10
March	1013	1037	Interbedded phylites and quartzites	Good	24				
	1037	1067	Sheared phylites*	Good	30	707.25	51.25	112	
	1067	1125	Interbedded phylites and quartzites	Good	58				
April	1125	1191	-ditto-	Good	66	622.44	60.76	66	1 holiday
May	1191	1276	Sheared and puckered phylite*	Good	85	678.40	85.75	85	
June	1276	1370	Phylitic quartzites and quartzitic phylites	Good	94	614.33	88.65	94	1 holiday
July	1370	1468	-ditto-	Good	98	666.24	68.25	98	
Aug.	1468	1553	-ditto-	Good	85	651.20	61.05	85	2 holidays
Sept.	1553	1649	-ditto-	Good	96	603.20	91.30	99	1 day's strike
Oct.	1649	1749	-ditto-	Good	100	601.42	79.00	100	3 holidays
Nov.	1749	1861	-ditto-	Good	112	590.33	69.00	116	Started on Nov.2. 1 holiday
Dec.	1861	1936	Phylitic quartzites and quartzitic phylites with thin tongues of granite	Good	75	670.08	81.67	124	
	1936	1985	Jointed granite with kaolinized and shear zones	Good	49				
1968									
Jan.	1985	2023	-ditto-	Good	38	274.75	29.75	87	2 holidays
	2043	2046	-ditto-	Good	3				
	2026	2043	Jointed granite with kaolinized and shear zones	Fair	17	138.50	19.58	72	Low advance per round (APR)
	2023	2026	Cavity						9 days lost in cavity

*Advance per round (APR) and cycle time have not been affected, hence considered under good category.

1	2	3	4	5	6	7	8	9	10
Feb.	2046	2070	Schistose granite with schist bands and shear zones	Fair	24	161.25	11.25	88	Low APR
	2070	2149	-ditto-	Good	79	431.33	41.58	109	2 holidays
March	2149	2177	-ditto-	Good	28	631.75	101.75	111	1 holiday
	2177	2226	Granite	Good	49				
	2226	2241	Schists	Good	15				
	2241	2260	Granite	Good	19				
April	2260	2297	Blocky granite	Good	37	235.33	45.17	97	
	2314	2317	Blocky granite	Good	3				
	2297	2309	Cavity zone	Poor	12	128.50	28.67	54	11 days lost in cavity
	2309	2314	Cavity						
May	2317	2357	Blocky granite	Good	40	633.00	105.00	124	
	2357	2441	Schists and granite bands	Good	84				
June	2441	2456	-ditto-	Good	15	267.67	106.50	95	
	2463	2481	-ditto-	Good	18				
	2495	2508	Massive to blocky granite with very minor schist bands and shear zones	Good	13				
	2456	2458	Cavity zone	Poor	2**	152.00	1.00	7	Not included in analysis
	2458	2463	Massive to blocky granite with very minor schist bands and shear zones	Fair	5	129.25	52.33	81	Low APR
	2481	2495	-ditto-	Fair	14				
Nov.	2784	2831	-ditto-	Good	47	359.00	110.25	67	1 holiday 9 days lost in cavity
	2831	2849	Cavity						

1	2	3	4	5	6	7	8	9	10
1969									
March	2880	2965	Massive granite with minor schist bands and shear zones	Good	85	643.92	91.00	85	
April	2965	3046	-ditto-	Good	81	620.45	90.55	81	
May	3046	3126	Schists and granite	Good	80	532.60	95.25	91	
	3126	3131	Schists and granite	Fair	5**	73.58	45.17	41	Low APR
June	3131	3172	Schists and granite	Good	41	489.00	63.25	87	
	3179	3207	Schists and granite	Good	28				
	3172	3179	Schists and granite	Poor	7	130.00	24.75	33	Very low APR
Sept.	3384	3476	Granite	Good	92	622.50	72.60	92	1 holiday
Oct.	3476	3518	Granite	Good	42	472.00	48.42	85	2 holidays. 5 days lost in cavity
	3523	3544	Granite	Good	21				
	3518	3523	Poor rock	Poor	5**	63.00	-	51	
Nov.	3544	3617	Granite	Good	73	566.00	86.00	73	2 holidays
1970									
Jan.	3701	3783	Granite	Good	82	576.00	85.50	82	2 holidays
Feb.	3783	3793	Granite	Good	10	521.00	136.17	53	1 holiday
	3793	3836	Schists	Good	43				
March	3836	3854	Schist	Good	18	257.33	36.42	93	Work upto March 12.
	3854	3872	Block granite	Good	18				
	3872	3886	Cavity						Cavity tackled till April 3.
April	3886	3939	Blocky granite	Good	53	446.08	148.67	61	Work upto April, 29. 1 holiday.
Oct.	4279	4312	Blocky to closely jointed granite with shear zones (DTS-I)	Poor	33	408.50	251.75	33	3 holidays (DTS-I distressed tunnel segment - 1)

**Not considered for analysis due to very few observations under the category during the month.

1	2	3	4	5	6	7	8	9	10
Nov.	4312	4336	Blocky to closely jointed granite with shear zones (DTS-1)	Poor	24	380.32	157.07	30	Work upto Nov.25. 1 holiday
1971									
May	4532	4551	Blocky to closely jointed granite with thin kaolinized seams (DTS-I)	Poor	19	338.42	337.50	19	
June	4551	4566	-ditto-	Poor	15	342.67	417.25	15	
July	4566	4581	-ditto-	Poor	15	233.58	431.17	15	Excessive time for rib erection, form work and for mucking. Holidays not recorded in data.
Aug.	4581	4610	-ditto-	Poor	29	425.17	236.83	29	
Sept.	4610	4629	-ditto-	Poor	19	322.42	384.58	19	
Oct.	4629	4642	-ditto-	Poor	13	531.75	199.25	13	
Nov.	4642	4662	-ditto-	Poor	20	443.50	248.25	20	
1972									
Jan.	4696	4712	Schists (DTS-I)	Poor	16	403.42	292.33	16	
Feb.	4712	4737	Blocky to closely jointed granite with very minor schist lenses and schist seams	Fair	25	605.33	96.92	25	
March	4737	4774	-ditto-	Fair	37	658.00	46.00	37	2 holidays
April	4774	4787	-ditto-	Fair	13	288.00	87.50	23	1 holiday.
	4787	4810	-ditto-	Good	23	228.33	86.17	52	Good advance rate.
May	4810	4877	Moderately jointed coarse grained granite	Good	67	650.42	94.25	67	
June	4877	4916	-ditto-	Good	39	553.33	65.67	83	
	4917	4948	-ditto-	Good	31				
	4916	4917	Loose fall in above rock	Poor	1	104.00	14.50	-	Not considered for analysis.

1	2	3	4	5	6	7	8	9	10
July	4948	5030	Moderately jointed coarse grained granite	Good	82	642.83	106.17	82	
Sept.	5088	5105	-ditto-	Fair	17	281.00	24.75	38	Low APR
	5105	5149	Moderately jointed coarse grained granite	Good	44	352.08	58.17	79	
Dec.	5299								
Dec.	5299	5333	Sheared to crushed gneiss and schistose gneiss	Fair	34	688.83	55.17	34	
1973									
Jan.	5333	5366	Sheared to crushed gneiss and schistose gneiss	Fair	33	696.83	23.42	33	1 holiday
Feb.	5366	5410	Moderately jointed to blocky granite gneiss with minor kaolinized sheared schist seams.	Fair	44	542.50	99.83	44	1 holiday
March	5410	5449	-ditto	Fair	39	663.75	53.00	39	2 holidays
April	5449	5505	-ditto	Fair	56	603.08	102.17	56	
May	5505	5544	-ditto-	Fair	39	426.17	40.08	60	Work upto May,20.
Sept.	5584	5621	-ditto- (DTS-II)	Poor	37	620.50	100.00	37	
Oct.	5621	5645	-ditto-	Poor	24	506.75	132.25	24	3 holidays
Nov.	5645	5665	-ditto-	Poor	20	341.75	387.25	20	
Dec.	5665	5690	-ditto-	Poor	25	347.00	406.00	25	
1974									
Feb.	5704	5722	-ditto-	Poor	18	354.00	311.75	18	
March	5722	5739	-ditto-	Poor	17	334.42	359.83	17	2 holidays Cavity at chainage 5732.

APPENDIX IV

CHAINAGE WISE GEOLOGICAL AND MONTHLY PROGRESS DATA FOR BAGGI HEADING OF PANDOH-BAGGI TUNNEL (BEAS-SUTLEJ LINK PROJECT)

Year and month	Chainage		Geology	Job condition data					Remarks
	From (m)	To (m)		Job classification	Progress (m)	Actual working time (Hrs.)	Breakdown time (Hrs.)	Equivalent monthly progress (EMP) (m)	
1	2	3	4	5	6	7	8	9	10
1966									
Aug.	297	320	Phylitic quartzites	Fair	23	596.50	140.42	64	Low advance (per round (APR)
	320	361	Phylites	Fair	41				
Sept.	361	426	Phylites	Fair	65	528.83	154.33	65	Low APR
Oct.	426	454	Phylites	Fair	28	450.75	203.08	51	Low APR. Work from Oct.4 onwards only
	454	472	Phylitic quartzites	Fair	18				
1967									
Jan.	646	680	Phylitic quartzites	Fair	34	518.50	179.42	73	Low APR. 2 holidays
	680	719	Contact zone to blocky to highly jointed granite	Fair	39				
Feb.	719	787	Blocky to highly jointed granite	Fair	68	498.50	150.08	68	1 holiday. Low APR
March	787	888	Blocky to highly jointed granite	Fair	101	631.08	114.92	101	Some APR are good
April	888	930	Blocky to highly jointed granite	Good	42	645.58	79.17	118	
	930	1006	Jointed to massive granite	Good	76				

1	2	3	4	5	6	7	8	9	10
1968									
Jan.	1469	1553	Massive coarse grained porphyritic granite (MCGPG)	Good	84	589,32	112.43	84	2 holidays
Feb.	1553	1646	MCGPG	Good	93	615.25	51.42	93	
March	1646	1744	MCGPG	Good	98	647.83	68.08	98	
April	1744	1814	Blocky granite	Good	70	598.67	94.67	115	1 holiday
	1814	1859	MCGPG	Good	45				
May	1859	1890	MCGPG	Good	31	665.33	73.67	107	
	1890	1966	Blocky granite with schist bands	Good	76				
June	1966	2003	Blocky granite with schist bands tending to very poor	Fair	37	397.97	30.45	58	Cavity formed on June, 19.
Nov.	2143	2165	Blocky granite with schist bands	Good	22	536.00	39.50	93	1 holiday
	2174	2228	MCGPG	Good	54				
	2165	2174	Blocky granite with schist bands	Fair	9	117.50	1.00	50	Low APR
Dec.	2228	2243	MCGPG	Good	15	185.83	178.67	78	
	2275	2287	MCGPG	Good	12				
	2243	2275	MCGPG	Fair	32	351.08	25.83	49	Low APR
1969									
Jan.	2287	2298	MCGPG	Good	125	694.42	53.91	125	*No visible effect on tunnelling. Hence considered under good job condition
	2298	2332	Very coarse grained massive granite	Good					
	2332	2378	MCGPG	Good					
	2378	2379	Thinly foliated and sheared schist*	Good					
	2379	2393	Blocky CGPG	Good					
	2393	2412	MCGPG	Good					

1	2	3	4	5	6	7	8	9	10
Feb.	2412	2519	MCGPG	Good	107	601.50	32.50	107	1 holiday
March	2519	2551	MCGPG	Good	32	205.00	11.25	110	Cavity formed on March 10.
June	2576	2603	Highly broken granite	Fair	27	274.42	38.50	60	
	2603	2654	Blocky and MCGPG (moderately broken and jointed)	Good	51	337.75	54.17	93	
July	2654	2748	MCGPG (Moderately broken and jointed)	Good	94	621.50	105.00	94	
Aug.	2748	2787	-ditto-	Good	39	615.92	104.08	92	1 holiday
	2787	2840	CGPG	Good	53				
Sept.	2840	2896	CGPG	Good	56	573.08	116.17	88	1 holiday
	2896	2928	Massive to blocky CGPG	Good	32				
Oct.	2928	2974	-ditto-	Good	46	283.58	82.08	85	3 holidays
	2974	3005	Transition zone through a granite band	Fair	31	240.25	73.50	68	
Nov.	3005	3038	Talcase schist	Poor	33	467.83	69.17	38	3 holidays. 4 days spent in exploratory drilling.
Dec.	3038	3058	Talcase schist	Poor	20	336.83	102.67	35	13 days spent in exploratory drilling
1970									
Jan.	3058	3076	Talcase schist	Poor	18	368.67	57.58	27	2 holidays. 3 days lost in concreting
	3076	3094	Blocky to jointed CGPG	Good	18	131.75	51.33	76	
March	3172	3226	-ditto-	Good	54	381.00	131.00	80	Final concreting started
	3226	3239	Very poor schistose granite	Fair	13	184.58	36.92	40	

1	2	3	4	5	6	7	8	9	10
April	3239 3253	3253 3271	Very poor MCGPG Kaolinized schistose granite	Fair Fair	14 18	414.75	307.42	40	Work upto April,24; concreting thereafter. Good advance.
May	3271	3295	Very poor kaolinized schistose granite	Poor	24	242.25	242.83	35	Work started on May,2 and continued upto May,22.
July	3299	3319	-ditto-	Poor	20	554.67	210.25	20	
Aug.	3319 3330	3330 3380	Transition zone MCGPG	Fair Good	11 50	125.58 436.67	30.25 121.75	49 64	Low APR. 1 holiday.
1971									
Jan.	3621	3697	MCGPG	Good	76	568.67	101.75	76	3 holidays
Feb.	3697	3765	MCGPG	Good	68	518.83	120.42	68	1 holiday
March	3765	3838	MCGPG	Good	73	535.58	131.42	73	2 holidays
April	3838	3902	MCGPG	Good	64	550.75	145.42	64	1 holiday
May	3902	3969	MCGPG	Good	67	627.58	100.17	67	
June	3969	4001	Very poor MCGPG	Fair	32	605.75	115.58	32	
July	4001	4058	MCGPG	Good	57	539.33	134.67	59	1 holiday. Work started on July,2.
Dec.	4308	4372	MCGPG	Good	64	536.92	184.50	64	1 holiday
1972									
Jan.	4372	4437	MCGPG and jointed granite with shear zones.	Good	65	567.92	112.75	65	2 holidays
Feb.	4437	4515	MCGPG	Good	78	584.08	103.25	78	
March	4515	4592	MCGPG	Good	77	619.75	94.17	77	1 holiday
April	4592	4674	MCGPG	Good	82	585.50	118.92	82	1 holiday
May	4674	4766	MCGPG	Good	92	680.25	62.75	92	

1	2	3	4	5	6	7	8	9	10
July	4785	4823	Moderately jointed granite with thin bands of schist and kaolinized seams.	Fair	38	588.17	50.25	44	4 days lost in cavity
Aug.	4823	4851	-ditto-	Fair	28	640.00	45.92	28	2 holidays
Sept.	4851	4915	-ditto-	Fair	64	676.67	50.92	64	
Oct.	4915	4933	-ditto-	Fair	18	233.50	14.00	46	2 holidays. Work upto Oct., 27.
	4933	4964	Moderately jointed good granite.	Good	31	287.17	45.33	65	
Dec.	5075	5117	Talc schist	Poor	42	702.92	27.92	42	
1973									
Jan.	5117	5171	Jointed granite	Fair	54	651.67	51.50	54	1 holiday. Low APR
Feb.	5171	5222	Jointed granite	Fair	51	574.17	72.17	51	1 holiday. Low APR
March	5222	5273	Blocky to jointed granite with schistose gneiss	Fair	51	689.17	35.17	51	Low APR
April	5273	5312	Moderately jointed good granite	Fair	39	640.92	52.25	39	1 holiday. Low APR
May	5312	5365	-ditto-	Fair	53	664.08	84.92	53	Low APR
June	5365	5426	-ditto-	Good	61	625.67	87.42	61	1 holiday. Good advance.
Aug.	5469	5495	Very poor coarse grained granite	Fair	26	602.17	101.83	26	2 holidays.
Sept.	5495	5520	-ditto-	Fair	25	311.75	134.83	42	
	5520	5544	Coarse grained granite	Good	24	213.25	70.84	59	
Oct.	5544	5593	Coarse grained granite and schistose gneiss.	Good	49	507.58	152.67	49	2 holidays.
1974									
Feb.	5729	5763	Very poor coarse grained granite	Fair	34	494.83	178.42	34	

APPENDIX V

ACTUAL WORKING TIME(AWT) FREQUENCY DISTRIBUTION UNDER FAIR JOB CONDITION

Class interval (Hrs.)	Management condition								
	Good			Fair			Poor		
	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
≤ 4	1	0.003	0.14	0	0.000	0.00	0	0.000	0.00
4-6	13	0.038	3.90	1	0.001	0.08	0	0.000	0.00
6-8	59	0.170	20.95	9	0.014	1.44	0	0.000	0.00
8-10	69	0.199	40.90	22	0.033	4.77	2	0.023	1.74
10-12	65	0.188	59.68	38	0.058	10.53	0	0.000	1.74
12-14	43	0.124	72.11	65	0.098	20.38	8	0.093	11.05
14-16	50	0.145	86.56	144	0.218	42.20	12	0.140	25.00
16-18	24	0.069	93.50	96	0.145	56.74	8	0.093	34.30
18-20	7	0.020	95.52	79	0.120	68.71	4	0.047	38.95
20-22	6	0.017	97.25	79	0.120	80.68	12	0.140	52.91
22-24	2	0.006	97.83	45	0.068	87.50	6	0.069	59.88
24-26	2	0.006	98.41	26	0.039	91.44	7	0.081	68.02
26-28	0	0.000	98.41	13	0.020	93.40	3	0.035	71.51
28-30	0	0.000	98.41	9	0.014	94.77	2	0.023	73.84
30-32	1	0.003	98.70	8	0.012	95.98	4	0.047	78.49
32-34	0	0.000	98.70	6	0.009	96.89	5	0.058	84.30
34-36	0	0.000	98.70	3	0.004	97.35	5	0.058	90.12
> 36	4	0.012	99.85	17	0.026	99.92	8	0.093	99.42

APPENDIX VI

ACTUAL WORKING TIME (AWT) FREQUENCY DISTRIBUTION UNDER POOR JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
(Hrs.)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
≤ 8	3	0.026	2.19	5	0.032	2.88	2	0.013	1.01
8-10	11	0.096	11.84	14	0.090	11.86	2	0.013	2.36
10-12	8	0.070	18.86	11	0.070	18.91	4	0.027	5.07
12-14	17	0.149	33.77	12	0.077	26.60	8	0.054	10.47
14-16	21	0.184	52.19	19	0.122	38.78	4	0.027	13.18
16-18	10	0.088	60.96	10	0.064	45.19	12	0.081	21.28
18-20	16	0.140	75.00	19	0.122	57.37	12	0.081	29.39
20-22	8	0.070	82.02	14	0.090	66.35	11	0.074	36.82
22-24	6	0.053	87.28	14	0.090	75.32	16	0.108	47.64
24-26	7	0.061	93.42	8	0.051	80.45	18	0.122	59.80
26-28	1	0.009	94.30	5	0.032	83.65	9	0.061	65.88
28-30	0	0.000	94.30	6	0.038	87.50	8	0.054	71.28
30-32	1	0.009	95.17	3	0.019	89.42	9	0.061	77.36
32-34	3	0.026	97.80	4	0.026	91.99	4	0.027	80.07
34-36	0	0.000	97.80	2	0.013	93.27	7	0.047	84.80
> 36	2	0.018	99.56	10	0.064	99.68	22	0.149	99.66

APPENDIX VII

BREAKDOWN TIME (BDT) FREQUENCY DISTRIBUTION UNDER FAIR JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
(Hrs.)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
0-1	195	0.563	56.21	341	0.517	51.59	35	0.407	40.12
1-2	47	0.136	69.80	94	0.142	65.83	13	0.151	55.23
2-3	24	0.069	76.73	74	0.112	77.04	12	0.139	69.19
3-4	20	0.058	82.51	36	0.054	82.50	3	0.035	72.67
4-5	14	0.040	86.56	30	0.045	87.04	3	0.035	76.16
5-6	7	0.020	88.58	23	0.035	90.53	4	0.047	80.81
6-7	5	0.014	90.03	7	0.011	91.59	2	0.023	83.14
7-8	2	0.006	90.61	12	0.018	93.41	4	0.047	87.79
8-9	3	0.009	91.47	3	0.004	93.86	1	0.012	88.95
9-10	4	0.012	92.63	3	0.004	94.32	1	0.012	90.12
10-11	4	0.012	93.79	5	0.007	95.07	3	0.035	93.60
11-12	3	0.009	94.65	6	0.009	95.98	0	0.000	93.60
> 12	18	0.052	99.85	26	0.039	99.92	5	0.058	99.42

APPENDIX VIII

BREAKDOWN TIME (BDT) FREQUENCY DISTRIBUTION UNDER POOR JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
(Hrs.)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
0-1	60	0.526	52.19	32	0.205	20.19	4	0.027	2.36
1-2	19	0.167	68.86	17	0.109	31.09	5	0.034	5.74
2-3	11	0.096	78.51	20	0.128	43.91	15	0.101	15.88
3-4	9	0.079	86.40	12	0.077	51.60	9	0.061	21.96
4-5	3	0.026	89.03	4	0.026	54.17	6	0.040	26.01
5-6	2	0.017	90.79	9	0.058	59.93	8	0.054	31.42
6-7	1	0.009	91.67	10	0.064	66.35	8	0.054	36.82
7-8	1	0.009	92.54	6	0.038	70.19	4	0.027	39.53
8-9	1	0.009	93.42	7	0.045	74.68	5	0.034	42.91
9-10	2	0.017	95.17	5	0.032	77.88	6	0.040	46.96
10-11	1	0.009	96.05	5	0.032	81.09	5	0.034	50.34
11-12	0	0.000	96.05	4	0.026	83.65	10	0.068	57.09
> 12	4	0.035	99.56	25	0.160	99.68	63	0.426	99.66

APPENDIX IX

ADVANCE PER ROUND (APR) FREQUENCY DISTRIBUTION UNDER FAIR JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position	Frequency	Relative frequency	Plotting position
(m)	(F)	(RF)	(PP)	(F)	(RF)	(PP)	(F)	(RF)	(PP)
≤ 0.61	6	0.017	1.59	31	0.047	4.62	6	0.070	6.39
0.61-0.91	55	0.159	17.48	101	0.153	19.92	40	0.465	52.90
0.91-1.22	56	0.162	33.67	266	0.403	60.23	22	0.256	78.49
1.22-1.52	70	0.202	53.90	137	0.207	80.98	15	0.174	95.93
1.52-1.83	137	0.396	93.50	71	0.108	91.74	3	0.035	99.42
1.83-2.13	3	0.009	94.36	25	0.038	95.53	0	-	-
2.13-2.44	8	0.023	96.68	23	0.035	99.01	0	-	-
>2.44	11	0.032	99.85	6	0.009	99.92	0	-	-

APPENDIX X

ADVANCE PER ROUND (APR) FREQUENCY DISTRIBUTION UNDER POOR JOB CONDITION

Class interval	Management condition								
	Good			Fair			Poor		
(m)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)	Frequency (F)	Relative frequency (RF)	Plotting position (PP)
⩽ 0.61	7	0.061	5.70	8	0.051	4.81	7	0.047	4.39
0.61-0.91	52	0.456	51.32	60	0.385	43.27	29	0.196	23.99
0.91-1.22	40	0.351	86.40	43	0.276	70.83	57	0.385	62.50
1.22-1.52	7	0.061	92.54	6	0.038	74.68	41	0.277	90.20
1.52-1.83	8	0.070	99.56	21	0.135	88.14	7	0.047	94.93
1.83-2.13	0	-	-	7	0.045	92.63	1	0.007	95.61
2.13-2.44	0	-	-	8	0.051	97.76	4	0.027	98.31
>2.44	0	-	-	3	0.019	99.68	2	0.013	99.66

APPENDIX XI

COMPUTER PROGRAM FOR COMPUTATION OF WEIBULL DISTRIBUTION PARAMETERS

```
C       COMPUTATION OF WEIBULL DISTRIBUTION PARAMETERS
        OPEN(UNIT=1,FILE='RES1.DAT')
        PRINT 61
 61     FORMAT(8X,'EX',8X,'VX',9X,'B',9X,'C')
 60     READ(1,1) EX,VX
 1      FORMAT(2F10.5)
        PRINT 1,EX,VX
        NCONT=0.0
        C=0.5
        ADC=0.5
        CALL RESDUE(EX,VX,C,RES1)
        IF(ABS(RES1)-0.001)3,3,102
 102    IF(RES1)2,3,4
 2      C=C+ADC
        CALL RESDUE(EX,VX,C,RES1)
        IF(ABS(RES1)-0.001)3,3,90
 90     IF(RES1)2,3,5
 5      C1=C
        C2=C1-ADC
 6      C=(C1+C2)/2.
        CALL RESDUE(EX,VX,C,RES1)
        IF(ABS(RES1)-0.001)3,3,9
 9      IF(RES1)7,3,8
 7      C2=C
        GO TO 6
 8      C1=C
        GO TO 6
 4      CONTINUE
 22     C=C+ADC
        CALL RESDUE(EX,VX,C,RES1)
        IF(ABS(RES1)-0.001)3,3,101
 101    IF(RES1)55,3,22
 55     C1=C
        C2=C-ADC
  66    C=(C1+C2)/2.
        CALL RESDUE(EX,VX,C,RES1)
```

```
      IF(ABS(RES1)-0.001)3,3,99
 99   IF(RES1)77,3,86
 77   C1=C
      GO TO 66
 86   C2=C
      GO TO 66
 3    CONTINUE
 1000 FORMAT(5X,'NCONT='I5,'RES1=',E14.6)
      Z=1./C
      CALL GAMA(Z,RES)
      A1=RES
      B=(C*EX)/A1
      PRINT 100,EX,VX,B,C
      TYPE 100,EX,VX,B,C
      GO TO 60
 100  FORMAT(4F10.5)
      CLOSE(UNIT=1)
      STOP
      END
      SUBROUTINE RESDUE(EX,VX,C,RES1)
      Z=1./C
      CALL GAMA(Z,RES)
      A1=RES
      Z=2./C
      CALL GAMA(Z,RES)
      A2=RES
      RES1=1.+VX/EX**2-2.*C*A2/(A1*A1)
      PRINT1,RES1,C
 1    FORMAT(2F10.5)
      RETURN
      END
      SUBROUTINE GAMA(Z,RES)
      IF(Z.LE.1.0E-02)Z=1.0E-02
 2    FORMAT(5X,'Z=',E13.7/)
C     PRINT 2,Z
      DIMENSION CZ(16)
```

```
      CZ(1)=1.0
      CZ(2)=0.57721566
      CZ(3)=-0.65587807
      CZ(4)=-0.04200263
      CZ(5)=0.16653861
      CZ(6)=-0.04219773
      CZ(7)=-0.00962197
      CZ(8)=0.00721894
      CZ(9)=-0.00116516
      CZ(10)=-0.00021524
      CZ(11)=0.00012805
      CZ(12)=-0.00002013
      CZ(13)=-0.000000125
      CZ(14)=0.00000113
      CZ(15)=-0.00000020
      CZ(16)=0.00000001
      PI=3.1415926
9     IF(Z-1.)10,10,11
10    SUM=0.0
      DO 8 I=1,16
8     SUM=SUM+CZ(I)*Z**I
      RES=1./SUM
      GO TO 13
11    GB=Z**Z*EXP(-Z)*SQRT(2.*PI/Z)
      GT1=1./(12.*Z)+1./(288.*Z*Z)
      GT2=139./(51840.*Z*Z*Z)+571./(2488320.*Z*Z*Z*Z)
      GT=1.+GT1-GT2
      RES=GB*GT
13    CONTINUE
      RETURN
      END
```

APPENDIX XII

COMPUTER PROGRAM FOR SIMULATION OF TUNNEL EXCAVATION

```
C     SIMULATION OF TUNNEL EXCAVATION
      DIMENSION BAWT(4,4),CAWT(4,4),EXB(4,4),APO(4,4),PL(4),EY(4,4),
     1K(4,4),STDX(4,4),BBDT(4,4),CBDT(4,4),AMTLP(4,4),STDY(4,4)
      OPEN(UNIT=1,DEVICE='DSK',FILE='SIM.DAT')
C     IF NSW=0 SUBROUTINE WEIBUL IS USED FOR AWT
C     IF NSW=1 SUBROUTINE LNOR IS USED FOR AWT
C     IF NSB=0 SUBROUTINE EXPNT IS USED FOR BDT
C     IF NSB=1 SUBROUTINE WEBUL IS USED FOR BDT
      READ(1,4)NSW,NSB
      PRINT 4,NSW,NSB
      TYPE4,NSW,NSB
4     FORMAT(2I2)
      KK=4
      D=1.
      DIST=0.0
      DISTZ=0.0
      AVAWT=0.0
      AVBDT=0.0
      AK=0.0
      TIME=0.0
C     JC=NUMBER OF JOB CONDITIONS
C     MC=NUMBER OF MANAGEMENT CONDITIONS
      DSTM=0.0
      TTZ=0.0
      READ(1,4)JC,MC
      PRINT 111,JC,MC
      TYPE4,JC,MC
      READ(1,2)((EY(I,J),I=1,MC),J=1,JC)
      TYPE112,((EY(I,J),I=1,MC),J=1,JC)
      READ(1,2)((STDY(I,J),I=1,MC),J=1,JC)
      TYPE113,((STDY(I,J),I=1,MC),J=1,JC)
1     FORMAT(2I5)
      READ(1,2)((BAWT(I,J),I=1,MC),J=1,JC)
      TYPE 114,((BAWT(I,J),I=1,MC),J=1,JC)
      READ(1,2)((CAWT(I,J),I=1,MC),J=1,JC)
      TYPE 115,((CAWT(I,J),I=1,MC),J=1,JC)
```

```
      READ(1,2)((EXB(I,J),I=1,MC),J=1,JC)
      TYPE 116,((EXB(I,J),I=1,MC),J=1,JC)
      READ(1,2)((BBDT(I,J),I=1,MC),J=1,JC)
      TYPE 118,((BBDT(I,J),J=1,JC),I=1,MC)
      READ(1,2)((CBDT(I,J),I=1,MC),J=1,JC)
      TYPE 119,((CBDT(I,J),J=1,JC),I=1,MC)
      READ(1,2)((APO(I,J),I=1,MC),J=1,JC)
      TYPE117,((APO(I,J),I=1,MC),J=1,JC)
      READ(1,2)((AWTLP(I,J),I=1,MC),J=1,JC)
      TYPE 120,((AWTLP(I,J),I=1,MC),J=1,JC)
2     FORMAT(9F8.5)

111   FORMAT(5X,'JC=',I5,'MC=',I5/)
112   FORMAT(5X,'EY=',9F10.3/)
113   FORMAT(5X,'STDY=',9F10.3/)
114   FORMAT(5X,'BAWT=',9F10.5/)
115   FORMAT(5X,'CAWT=',9F10.5/)
116   FORMAT(5X,'EXB=',9F10.3/)
117   FORMAT(5X,'APO=',9F10.3/)
118   FORMAT(5X,'BBDT=',9F10.5/)
119   FORMAT(5X,'CBDT=',9F10.5/)
120   FORMAT(5X,'AWTLP=',9F8.4/)
      PRINT 311
      DO 310J=1,JC
310   PRINT6,(EY(I,J),I=1,MC),(STDY(I,J),I=1,MC),(BAWT(I,J),I=1,MC),(CAWT
     1T(I,J),I=1,MC)
 6    FORMAT(4(3F9.5,5X)//)
311   FORMAT(12X,'EY',30X,'STDY',30X,'BAWT',30X,'CAWT'/)
      PRINT 411
      DO 410J=1,JC
410   PRINT 16,(BBDT(I,J),I=1,MC),(CBDT(I,J),I=1,MC),(EXB(I,J),I=1,MC
     1),(APO(I,J),I=1,MC)
16    FORMAT(4(3F9.5,5X)//)
411   FORMAT(12X,'BBDT',30X,'CBDT',30X,'EXB',30X,'APO'/)
      PRINT2,((AWTLP(I,J),I=1,MC),J=1,JC)
21    M=1
```

```
      READ(1,3)ET,NZ,(PL(I),I=1,3),II
      TYPE5,ET,NZ,(PL(I),I=1,3),II
      PRINT5,ET,NZ,(PL(I),I=1,3)
 3    FORMAT(F10.4,I5,3F10.4,I5)
 5    FORMAT(5X,F10.4,I5,3F10.4,I5)
 31   IF(NSW.EQ.0)CALL WEIBUL(BAWT(N,NZ),CAWT(N,NZ),AWTLP(N,NZ),AWT,KK)
      IF(NSW.EQ.1)CALL LNOR(EY(N,NZ) ,STDY(N,NZ),AWT,KK)
      IF(NSB.EQ.0)CALL EXPNT(EXB(N,NZ) ,BDT,KK)
      IF(NSB.EQ.1) CALL WEBUL(BBDT(N,NZ),CBDT(N,NZ),BDT,KK)
      AVAWT=AVAWT+AWT
      AVBDT=AVBDT+BDT
      AK=AK+1.
      TCT=AWT+BDT
      TIME=TIME+TCT
      DIST=DIST+APO(N,NZ)
      GO TO 100
C     GO TO(10,20,30),K
      PRINT 13
 13   FORMAT(10X,'APO',11X,'NG',11X,'MF',11X,'FP',6X,'ZONE NO',4X,'ZONE
     1TIME',6X,'REMARKS')
 10   PRINT 40,APO(N,NZ),AWT,BDT,TCT,NZ
      TYPE 40,APO(N,NZ),AWT,BDT,TCT,NZ
 40   FORMAT(2F13.2,'+',F6.2,'=',F6.2,17X,I13)
      GO TO 100
 20   PRINT 50,APO(N,NZ),AWT,BDT,TCT,NZ
      TYPE 50,APO(N,NZ),AWT,BDT,TCT,NZ
 50   FORMAT(F13.2,13X,F13.2,'+',F6.2,'=',F6.2.5X,I12)
      GO TO 100
 30   PRINT 60,APO(N,NZ),AWT,BDT,TCT,NZ
      TYPE 60,APO(N,NZ),AWT,BDT,TCT,NZ
 60   FORMAT(F13.2,26X,F13.2,'+',F6.2,'=',F6.2,I4)
 100  DD=D*720.
      IF(TIME-DD)22,130,130
 130  DSTM=DIST-DSTM
      TIM=TIME-TIM
      AVTM=TIM/AK
```

```
      AVAWT=AVAWT/AK
      AVBDT=AVBDT/AK
      AK=0.0
      D=D+1.
C     PRINT 131,DSTM,AVTM,AVAWT,AVBDT
      TYPE 131 ,DSTM,AVTM,AVAWT,AVBDT
      AVAWT=0.0
      AVBDT=0.0
      DSTM=DIST
      TIM=TIME
 131  FORMAT(/28X,'PROGRESS FOR MONTH=',F7.2//28X,'AV.CYCLE TIME FOR MON
     1TH=',F7.2//28X,'AV.MONTHLY AWT=',F15.2//28X,'AV. DAILY BDT=',F1
     15.2//1X,120('-')/)
 22   IF(DIST-ET)211,110,110
 110  TTZ=TIME-TTZ
      DISTZ=DIST-DISTZ
      PRINT 210,DISTZ,TTZ,TIME
      TYPE 210,DISTZ,TTZ,TIME
      TTZ=TIME
      DISTZ=DIST
 210  FORMAT(35X,'ZONE DIST=',F7.1/35X,'ZONE TIME=',F7.1/35X,'TOTAL TIM
     1=',F8.1)
      IF(IJ.EQ.0) GO TO 21
      CLOSE(UNIT=1)
      STOP
 211  XX=(DIST-DISTZ)/(ET-DISTZ)
      IF(XX-PL(N))31,32,32
 32   PRINT 140,PL(N),DISTZ,TTZ
      TYPE 140,PL(N),DISTZ,TTZ
 140  FORMAT(20X,'PL(N)=',F5.4,5X,'DISTZ=',F7.1,5X,'TTZ=',F7.1)
      N=N+1
      GO TO 31
      END
      SUBROUTINE WEIBUL (BAWT,CAWT,AWTLP,AWT,KK)
      R10=RAN(KK)
      KK=KK+1
```

```
      IF(KK.GE.55)KK=4
      AWT=BAWT *(-ALOG(R10))**(1./CAWT )+AWTLP
      RETURN
      END
      SUBROUTINE EXPNT(EXB ,BDT,KK)
      R4=RAN(5)
      KK=KK+1
      IF(KK.GE.55)KK=4
      BDT=-EXB*ALOG(R4)
      RETURN
      END
      SUBROUTINE LNOR(EY,STDY,AWT,KK)
      SUM=0.0
      DO 5I=1,12
      R=RAN(KK)
5     SUM=SUM+R
      KK=KK+1
      IF(KK.GE.55)KK=4
      AWT=EXP(EY+STDY*(SUM-6.0))
      RETURN
      END
      SUBROUTINE WEBUL(BBDT,CBDT,BDT,KK)
      R=RAN(KK)
      KK=KK+1
      IF(KK.GE.55)KK=4
      BDT=BBDT*(-ALOG(R))**(1./CBDT)
      RETURN
      END
```

VITA

Roshan Lal Chauhan
Candidate for the Degree of
Doctor of Philosophy

Thesis: A SIMULATION STUDY OF TUNNEL EXCAVATION

Personal Data: Born May 5, 1945 in Himachal Pradesh (H.P.), India, son of Shrimati and Shri Kahna Singh Chauhan.

Education: Passed Matriculation Examination (1961) and Pre-University Examination (1962) of Panjab University; Bachelor of Engineering (1967) of University of Jodhpur; Post-Graduate Diploma (1972) and Master of Engineering (1973) of University of Roorkee, India.

Stood First in the School in Matriculation Examination; listed for merit in Pre-University Examination; awarded Gold Medals for Post-Graduate Diploma Examination and Master of Engineering Degree Examination.

Professional Experience: Worked in H.P. State Electricity Board on planning, design and construction of hydro-electric projects (1967-77).

Assigned to Water Resources Development Training Centre at University of Roorkee to teach courses on construction techniques and management (1978-82).

Responsible for developing technology for concrete lining of small diameter tunnels and for excavation of tunnels in squeezing rock conditions while posted on H.P. State's Giri Hydro-electric Project as construction engineer.

Thesis supervisor for Master of Engineering Degree at Water Resources Development Training Centre at University of Roorkee for nearly 20 candidates.

Author of technical papers in journals in India and abroad.

Institution Memberships: Member, Institution of Engineers (India),
Member, Indian Water Resources Society.

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