# Assessment of site investigation and tunnel contract cost

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Clark, C. R. (1981) *Assessment of site investigation and tunnel contract cost*, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/7544/

# ASSESSMENT OF SITE INVESTIGATION AND TUNNEL CONTRACT COST

by

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Being a thesis presented to the University of Durham in fulfilment of the requirements for the degree of M.Sc. by research in the Department of Geological Sciences.

March 1981

# ABSTRACT

The thesis concerns the research into the development and application of empirical guidelines regarding the capability of site investigation to define uncertainty in ground conditions and hence to minimise contract cost. The data has been abstracted from the documents of contracts on the Northumbrian Water Authority's Tyneside Sewerage Scheme and, to allow cost comparisons to be made, a system of index-linking costs has been used, which removes their time-dependency.

A simplified theoretical approach, based on probability theory and decision analysis, has been included to model the situation of decision under uncertainty and comparisons are subsequently made between this approach and the empirical results. Conclusions are reached regarding the possible reduction in risk, financial uncertainty, with increasing site investigation.

# ACKNOWLEDGEMENTS

This thesis would not have been possible without the assistance of members of the staff of the Northumbrian Water Authority, particularly Central Site Office staff, who aided me in obtaining records and accounts for the various contracts. I would also like to give special thanks to my supervisor, Professor P.B.Attewell whose direction and drive played a crucial part in the production of this thesis.

To Hilary: who makes all things possible,

# CONTENTS

## SYMBOLS LIST

$a$ - action

$a_o$ - action under no investigation

$a_\theta$ - action which maximises the value
of terminal utility

$a'$ - action which maximises the
decision under prior knowledge

$c_s$ - cost of sampling

$E$ - Expected Value

$e$ - investigations (type)

$e_o$ - no investigations

$f(\underset{\sim}{\theta})$ - known function of $\theta$

$H(\theta)$ - correlated random field

$h(\theta)$ - unknown property

$K$ - unit cost of error

$k_o$ - unit cost of overestimation

$k_u$ - unit cost of underestimation

$k_s$ - unit cost of investigation

$k_t$ - unit terminal loss constant

$L_x$ - Universal Loss function

$l_t$ - Terminal loss function

$m$ - mean of additional tests

$m'$ - mean of original tests

$m''$ - resultant mean

$m(\theta)$ - mean value of $\theta$

$n$ - number of tests
$n'$ - prior number of tests
$n''$ - posterior number of tests
$n^*$ - optimum number of tests

$P(\theta)$ - Probability distribution of $\theta$
$P'(\theta)$ - Prior probability distribution of $\theta$
$P(x|\theta)$ - likelihood of probability distribution of $\theta$
$P''(\theta)$ - Posterior probability distribution of $\theta$

$R_i$ - Regression coefficients

$S$ - sample variance

$U$ - Universal utility function
$U_o$ - Universal utility without action
$u_t(\ )$ - terminal utility
$u_s(\ )$ - utility of sampling
$U(\ )$ - Universal utility with respect to included item(s)

$V(\ )$ - Conditional value of included items
$V_t$ - conditional value of terminal utility

$x$ - investigation results
$x'$ - results of prior investigations

$\beta(\ )$ - auto correlation function
$\theta$ - Variable defining ground conditions
$\theta i$ - Association of variables relating to ground conditions
$\theta o$ - Estimate of variable based on no information
$\theta B$ - Variable at value where choice of action immaterial
$\sigma$ - Population standard deviation
$\sigma^2$ - population variance
$\mu$ - population mean
$\gamma$ - independent residuals random field
$\prod$ - product of the probabilities

# CHAPTER 1

# INTRODUCTION

# CHAPTER 1

# INTRODUCTION

Many advances have been made in the tunnelling industry in the technical areas of constructing more efficient machinery and support methods. However,these improvements have not brought with them a commensurate improvement in the prediction of costs and it is still common practice to design for a 'worst-case' rather than an optimum design. Why is it that the prevailing attitude is that tunnelling is an 'art' rather than a science, sometimes with a greater faith in intuition than in information?

The main obstruction to a change in attitude is the relatively large area of uncertainty,in financial terms,'risk', that is inherent in tunnel contracts. The major element of uncertainty is the variability of ground conditions, even though information about it is provided by site investigations. The need for improvement in site investigation is appreciated by all sides of the civil engineering industry, as demonstrated by a recent seminar in London (QUARRELL,1979). To see how and where site investigation could be improved, a basic understanding is required of how it affects contract cost. The production of data for developing empirical relations is one of the prime aims of this research.

The original approach of this research into the cost effectiveness of site investigation in tunnels was theoretical, using probabilistic theory, especially Bayesian inference, to set up a framework whereby information can be updated, thus modelling the cumulative effect of site investigation. A detailed study can be found in (ATTEWELL, CRIPPS and WOODMAN, 1978), but a straightforward version has been included in the following chapter. In a desire for brevity, several simplifying assumptions have been taken. The reasoning behind these assumptions, as well as their validity, has also been included, with an extension of the discussion in a later chapter.

With the theoretical framework developed, the research could turn to the problem of abstracting and isolating cost data prior to the development of empirical relations between site investigation and contract cost escalation. All the information used in this report has been abstracted from the records of several contracts on the Northumbrian Water Authority's Tyneside Sewerage Scheme, which includes 75 km of interceptor sewer and involves a total cost of the order of £100,000,000. Further information is provided by NORGROVE and STAPLES (1976).

As no standardised form of abstracting information existed, the early studies were carried out with special thoroughness so that any approximations made in the analysis of later studies (and in the interests of speed) could actually be quantified by extrapolation from error bands based on the early studies.

With the production of empirical cost data, the twin lines of research could be brought together for comparison. It was apparent that although a single, important risk factor, site investigation, had been selected and isolated, the affects of all risk factors needed to be considered, if only subjectively, for an overall view.

The introduction of these additional factors bring a concomitant requirement for a contractual model. The contractual set-up has been well documented, and thus only a brief summary of the salient points has been included in the thesis. The creation of a contractual model generates a number of problems which, although financially motivated, are rooted in the philosophy of the input of both the Contractor and

Client and affect the ultimate outcome. Such problem detail must be considered outside the boundary of the present research. However, to illustrate the contractor's estimation of risk at tendering and to compare it with the contract cost escalation, an empirical estimation has been introduced. The problems of risk analysis in construction work are complex and, as with any statistical data, the larger the sample, the more accurate will be any inferences. The research upon which this thesis is based hopes to show that quantitive statements can be made about the cost effectiveness of site investigation, provided that sufficient cost data related to comparable engineering (contractual) situations is available.

# CHAPTER 2

# THEORY

# CHAPTER 2

## THEORY

The theory behind the problem of optimising site (sample) information in the prevailing conditions of uncertainty can broadly be split into four phases.

The first phase consists of defining the problems, the limits of the investigation, and the alternative courses of action with their relative outcomes. These outcomes will depend jointly on the decisions taken and the uncertainty of the variables. Also included within this phase is the comparison of the different outcomes, which is usually derived on a cost/time basis. The alternative courses of action are design decisions based on previous engineering experience, which allows reasonable cost estimates. However, the uncertainty in the ground variables, such as soil behaviour, requires some assumptions to be made.

Soils have a heterogeneous character, which arises from the random nature of the natural processes involved in their deposition. Certain of these processes of formation have been stochastically modelled (ALONSO and KRIZEK, 1975); for example, sea waves influencing the formation of beaches, and hydrological variables.

The strength of probabilistic models is not that they provide a firm optimum strategy, but that they give a range of possible answers with associated probability levels. These multiple solutions can allow the Engineer to use his critical judgement to reach an optimum decision.

Previously two types of model have had widespread use to reflect uncertainty in soil behaviour; 1) regression equations with independent residuals (BAECHER,1972); 2) a correlated random field ( VENEZIANO and FACCIOLI,1975). The regression equation is usually presented in the form,

$$h(\underset{\sim}{\theta}) = \sum_{i=1}^{n} R_i f(\underset{\sim}{\theta}) + Y(\underset{\sim}{\theta})$$

where $h(\underset{\sim}{\theta})$ is the unknown property ,

$f(\underset{\sim}{\theta})$ is a known function ,

$R_i$ are regression coefficients estimated from available data ,

and $Y(\underset{\sim}{\theta})$ is an independent residual random field measuring the local dispersion about an expected value. This residual error is assumed to be uncorrelated with any other residual error at a different location.

The second alternative of the correlated random field $H(\underset{\sim}{\theta})$ leads to a first order analysis, which has the advantage of being distribution-free and utilises only the first two moments (mean and variance) and correlation coefficients of the random variables as measures of uncertainty and joint behaviour. The covariance gives an indication of the spatial distances within which some degree of correlation might be expected. (The usual distances between points of soil reconnaisance are larger than the distances indicated by the covariance.)

Two advantages exist for considering the soil uncertainty using this second method. The first is that the spatial correlation function is continuous at zero, a property not shared by regression models with independent residuals. Second, a complete knowledge *a priori* (before sample) or *a posteriori* (after sampling) is an unnecessary assumption with a sufficient description being given by the first two moments. Sufficiency is defined as containing all of the information within the data to describe the field.

It is now desirable to make the assumption that the soil under consideration behaves homogeneously, even though heterogeneity is the expected condition, as the representation of a non-homogeneous field is beyond the scope of everyday use of the Engineer. This assumption is, however, in line with common site investigation practice; for example, in the analysis of borehole data, the major part of available S.I. information, boundaries are defined around regions of similar conditions, with single figures, ascertained from field and laboratory tests, being ascribed to soil properties. If the region is not homogeneous, then references are made to items, such as inclusions or lenses, and subjective assessments are made regarding their behaviour and the effect of their presence on the region as a whole. From a mathematical viewpoint, a field is homogeneous if it has a constant mean and an autocorrelation function dependent solely on the spatial argument, that is

$$m(\theta) = \mu = constant$$

$$\beta(\underset{\sim}{\theta}_1, \underset{\sim}{\theta}_2) = \beta(\underset{\sim}{\theta}_1 - \underset{\sim}{\theta}_2)$$

Thus far, the field has been considered as a random variable. However, decision parameters are not usually affected by a single variable, but by a series of independent variables forming a function. All these variables ($\theta_i$) may be associated into a common set $\{\theta_i\}$ or $\underset{\sim}{\theta}$ if vectorial notation is used.

In order to proceed, it is necessary to assign a form to the continuous random variable ($\theta$), which is used to define ground conditions in a sampling situation.

Although sampling in site investigation provides a series of discrete results, it is more convenient to consider it as a 'quasi continuous' method and hence to assume that the random function is continuous. Since information will be required concerning the posterior probability density, the form of the prior probability density should be such that it minimises the computational problems.

One such form is to assume that ground conditions can be represented by a normal distribution:

$$P(\theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(\theta-\mu)^2}{2\sigma^2}\right]$$

where $\mu$ and $\sigma^2$ are the population mean and variance, respectively.

This assumption leads directly on to the probabilistic phase, where the Engineer requires a method of revising his current decision based on information provided by additional sample information. A ready-made tool, Bayesian Inference, is available, which allows the combining of sample information with other information for subsequent inference. This method has been used in business studies for some time and fits neatly into the Engineer's desire to express, in objective terms, a degree of belief.

In a verbal form, Bayes'Theorem states:

$$\text{Posterior probability} = \frac{\text{(Prior probability)(Likelihood)}}{\sum\text{(Prior probability)(Likelihood)}}$$

where Prior probability P'(Θ) is the probability that a state of the world (Θ) exists,

and Likelihood P(x|Θ) is the probability that particular results (x) would be obtained from experiments ($e_x$) given the true state of conditions was (Θ)

and (Prior probability)(Likelihood) is a normalising factor

Therefore, using prime and double prime to signify prior and posterior probabilities, respectively, Bayes' Theorem can be re-written in notational form as,

$$P''(\theta|x) = P'(\theta)\, P(x|\theta) \Big/ \sum P'(\theta)\, P(x|\theta)$$

Returning momentarily to the use of a normal distribution to specify ground conditions, there are several advantages to the approach. It has mathematical tractability; that is, it is relatively easy to specify the posterior distribution, and the likelihood function is also uniquely specified. The posterior distribution is also a member of the same conjugate family, that is normal distribution, as the prior distribution, so that successive applications of Bayes' Theorem are not difficult. It is, therefore, feasible to calculate expectation from the prior distribution.

So far, nothing has been dictated about the prior distribution. If a large amount of sample information is to be collated then the posterior distribution will be weighted heavily towards it and will be relatively insensitive to the prior distribution. In this case the prior distribution can be said to represent an 'informationless' state. As the amount of sample information decreases, the choice of prior distribution plays an ever-increasing role. However, it is likely that any prior distribution will be based on available data whether they comprise subjective old records or objective preliminary tests. In order to indicate this reliance it is necessary to re-define the parameters of the normal distribution

$$P(\theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(\theta-\mu)^2}{2\sigma^2}\right]$$

Assuming that n' tests have already been carried out with results (x') and a sample variance of $S^2$, then the population variance ( $\sigma^2$ ) would be,

$$\sigma^2 = \frac{S^2}{n'} \quad \text{and mean } (m')$$

or the prior probability of ($\theta$), expressed as $P'(\theta|x')$, shows the conditional nature of its density function through the identity,

$$P'(\theta \mid x') = \prod \frac{\sqrt{n}}{\sqrt{2\pi S^2}} \exp\left[\frac{-(\theta - m')^2 n'}{2S^2}\right]$$

The likelihood of a distribution of a further (n) tests, given results (x) is,

$$P(x \mid \theta) = \prod \frac{\sqrt{n}}{\sqrt{2\pi S^2}} \exp\left[\frac{-(m - \theta)^2}{2S^2}\right]$$

where m is the mean of (n) tests.

The posterior distribution $P''(\theta|x',x)$ is proportional to $P'(\theta|x')$

and is therefore proportional to,

$$\exp\left[\frac{-1}{2S^2}\left((nm)^2 + (n'm')^2 + (n+n')\theta^2 - 2\theta(nm + n'm')\right)\right]$$

or,

$$\exp\left[\frac{-1}{2S^2}\left((nm)^2 + (n'm')^2 + n''(\theta - m'')^2 - (n''m'')^2\right)\right]$$

where $n'' = n + n'$, or the sum of the results,

and $m'' = \frac{n'm' + n\,m}{n''}$, or the posterior mean.

The posterior distribution (probability) is,

$$P''(\theta \mid x'') = \prod \frac{\sqrt{n''}}{\sqrt{2\pi S^2}} \exp\left[\frac{-n''(\theta - m'')^2}{2S^2}\right]$$

This analysis indicates that it is possible for the Engineer to make some probabilistic statements about the results of any additional testing. Eventually, he must make terminal decisions based on his current state of information. However, initially he must decide whether the additional sample/investigation is expected to be useful enough to justify its cost. In order to take this decision he must have estimated a utility or loss function for any possible outcome.

The universal utility (U) of an action should be dependent on the investigation (e), the results of the investigation (x), the results of the action (a) and the state of the world ($\theta$). If set notation is used, then $U = U\left\{e, x, a, \theta\right\}$ Although it will be shown later that there is a direct relation between utility and loss functions, it is usual, when optimising sample size, to deal with the loss function, of which three main forms are favoured. The simplest is the linear loss function which is linear between the result of action (a) and the state of the world ($\theta$). That is, if $a < \theta$ then the loss is $k_u$ $(\theta - a)$ where $k_u$ is the unit cost of underestimation, while if $a > \theta$ then the loss is $k_o$ $(a - \theta)$ where $k_o$ is the unit cost of overestimation. These constants ($k_u$) and ($k_o$) can be adjusted to show the relative importance of underestimating or overestimating a decision.

An alternative is to assume that the costs of underestimation and overestimation are equal ($k_u = k_o = K$) and that the loss is proportional to the square of the error, that is proportional to $(a-\theta)^2$. The resultant loss function is called a quadratic loss function where the optimum action is the expected value of ($\theta$), that is, its mean. Using the mean as a certainty-equivalent obviates the need for a complete determination of the prior distribution.

A third form of loss function is to assume that the loss is proportional to the exponential of the error, that is, proportional to exp $\left[\theta - a\right]$ which would imply that only a small saving would accrue from overestimating, whereas there would be a large potential loss from underestimating.

The expected utility of any action (a) given information (x) from experiment or investigation (e) depends on how accurately the conditions have been predicted,

$$E\;U(e,x,a) \equiv E''_{\theta|x}\cdot U(e,x,a,\theta)$$

where E is defined as the expected value $E''_{\theta|x}\cdot U = \int U\;P''(\theta|x)\;d\theta$, that is, the expected value of $U(e,x,a)$ is dependent on the posterior probability $P''(\theta|x)$.

Since the decision-maker has the choice of maximising his expected utility, given experiment (e) and outcome (x), the expected utility of this information $E\;U(e,x)$ is equivalent to the expected utility of any action (a) maximised for the action (a).

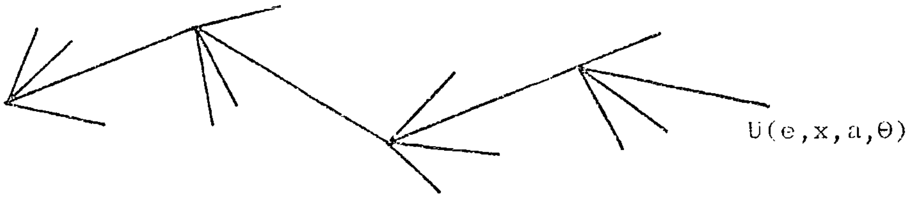
or, $$E\;U(e,x) \equiv \max_a E\;U(e,x,a)$$

However, the expected value of the experiments must be equivalent to the probability of the outcomes (x) given experiments (e) multiplied by the expected utility of the outcomes:

$$\begin{aligned} E\;U(e) &= E_{x|e}\cdot E\;U(e,x) \\ &= E_{x|e}\cdot \max_a E\;U(e,x,a) \\ &= E_{x|e}\cdot \max_a E''_{\theta|x}\cdot U(e,x,a,\theta) \end{aligned}$$

The objective is thus to maximise the expected utility of the experiment. This reasoning can equally well be expressed as a branch of a decision tree:

| | | | | | |
|---|---|---|---|---|---|
| Move No:- | 1 | 2 | 3 | 4 | 5 |
| Move By:- | Decision Maker | Chance | Decision Maker | Chance | |



| | | | | |
|---|---|---|---|---|
| Choice | e | x | a | θ |
| Dependency | - | $P(x\|e)$ | | $P''(\theta\|x)$ |

If the utility $U(e,x,a,\theta)$ can be expressed in monetary terms, then it can be represented as the sum of two parts: 1) the utility related to the cost of performing the experiment: $u_s(e,x)$, and 2) the utility related to cost of undertaking the action (a) given the true state of the world ($\theta$), which is known as the terminal utility: $u_t(a,\theta)$.

Therefore, $U \equiv u_t(a,\theta) + u_s(e,x)$.

This simplification ignores non-monetary consequences, such as disturbance.

It follows then that the expected utility of an experiment E U(e) can be represented as the sum of part utilities:

$$\begin{aligned} E\ U(e) &\equiv E_{x|e} \cdot \max_a E''_{\theta|x} \cdot U \\ &\equiv E_{x|e} \cdot \max_a E''_{\theta|x} \cdot \left[u_s(e,x) + u_t(a,\theta)\right] \end{aligned}$$

Since, by definition, $u_s(e,x)$ is independent of (a) and ($\theta$), this equation can be rewritten as,

$$E\ U(e) = E_{x|e} \cdot \left[u_s(e,x) + \max_a E''_{\theta|x} \cdot u_t(a,\theta)\right]$$

which could also be written as,

$$E\ U(e) = E\ u_s(e) + E\ u_t(e)$$

where $u_s(e) \equiv E_{x|e} \cdot u_s(e,x)$,

and $u_t(e) \equiv E_{x|e} \cdot \max_a E''_{\theta|x} \cdot u_t(a,\theta)$

Estimation of the expected sampling utility, $E\ u_s(e)$, is fairly simple, since $u_s(e,x)$ is usually either independent of the results (x) or simply-related to them.

Computation of the expected terminal utility, $E\ u_t(e)$ is also facilitated if it is a function solely of the action (a) and the state of the world ($\theta$), because, for a given (e,x), it will depend on (e,x) only through the measure $P''(\theta|x)$ and not through the utility function itself.

Before showing how this simplification can be used with reference to specific utility functions, the concept of loss function and value of information will be discussed.

If it is assumed that the state of the world ($\theta_o$) were known and the terminal action ($a_o$) could be chosen, then the utility may be defined in these conditions as ($U_o$). Consider, then, that there is the choice of experiment (e) with results (x) and subsequent choice of action (a). The definition of the loss of opportunity, or loss function ($L_x$), is given by

$$L_x = U_o - U_x$$

where $U_o \geqq U_x$ for all a.

If the sampling and terminal utilities are additive, then the loss function can be similarly split.

Defining the cost of sampling ($c_s$) $\equiv$ $-u_s$ then, $U_x = u_t + u_s = u_t - c_s$

The cost of no sampling is $c_s(e_o) = 0$

Therefore, $$U_o = u_t(a_o, \theta_o)$$

Define the terminal loss function $l_t(a,\theta)$ as

$$l_t(a,\theta) \equiv u_t(a_o, \theta_o) - u_t(a, \theta)$$

Therefore, $$L_x = l_t(a,\theta) + c_s(e,x).$$

In written form, this result means that the loss function is the sum of 1) the cost of investigating rather than choosing a terminal decision, 2) the cost of the opportunity of making the wrong decision after the investigation has been conducted.

Since the loss function can be expressed as the sum of the terminal loss function and the sampling cost, so also can the expected loss function, $E\left[L_x\right]$, or, $E\left[L_x\right] = E\left[l_t(a,\theta)\right] + E\left[c_s(e,x)\right]$.

Provided that it is accepted that the loss function can be separated into two parts, the analysis of the expected loss functions can sometimes facilitate the choosing of optimum sampling. If it is true that experiments in (e) space can be ordered, such that $E\left[u_t(e_n)\right]$ and $E\left[c_s(e_n)\right]$ are functions of increasing (n), then the objective becomes the maximisation of

$$E\left[U(e_n)\right] = E\left[u_t(e_n)\right] - E\left[c_s(e_n)\right]$$

or minimisation of $E\left[L(e_n)\right] = E\left[l_t(e_n)\right] + E\left[c_s(e_n)\right]$.

If the optimum value of n is n*, then in certain instances n* will be defined by an equation, which has an explicit solution or can be solved using iterative processes. Usually, however, $E\left[u_t(e_n)\right]$ and $E\left[c_s(e_n)\right]$ have to be evaluated at discrete points and plotted against (n).

Assume, then, that $E\left[L(e_{n'})\right] = E\left[l_t(e_{n'})\right] + E\left[c_s(e_{n'})\right]$ has been computed for some value n' of n. Then the increase in expected utility for n > n' is :

$$\begin{aligned} E\left[U(e_n)\right] - E\left[U(e'_n)\right] &= E\left[L(e'_n)\right] - E\left[L(e_n)\right] \\ &= \left[E\left[l_t(e'_n)\right] - E\left[l_t(e_n)\right]\right] - \left[E\left[c_s(e_n)\right] - E[c_s(e \end{aligned}$$

Therefore, since $E\left[l_t(e_n)\right]$ must be non-negative,

or $E\left[U(e_n)\right] - E\left[U(e'_n)\right] \leq E\left[l_t(e'_n)\right] - \left[E\left[c_s(e_n)\right] - E[c_s(e\right.$

, if the right-hand side of this equality is negative, then the left-hand side would also be negative.

Thus, (n) cannot be optimal unless,

$$E\left[c_s(e_n)\right] - E\left[c_s(e')\right] \leqq E\left[l_t(e_n')\right].$$

Given the prior situation of (n') with associated investigation cost and terminal loss function, the highest value of (n) which satisfies the equality is an upper-bound on the sample size.

Assume that $u_t(a_\theta, \theta) \geqq u_t(a,\theta)$, for all a where $a_\theta$ is the decision that maximises the terminal utility.

Assume also that $E\left[u_t(a',\theta)\right] \geqq E\left[u_t(a, \theta)\right]$, for all a, where a' maximises the decision measuring prior probability.

Then, if $(e_\infty)$ is an experiment capable of giving perfect information, its cost would be $c_s(e_\infty)$.

The net utility would be,

$$U_\infty = (a_\theta, \theta) - E\left[c_s(e_\infty)\right]$$

and the net utility of action without information $(U_o)$ would be,

$$U_o = u_t(a',\theta) - 0.$$

Therefore, $(U_\infty - U_o)$ will be positive if,

$$E\ c_s(e_\infty) < u_t(a_\theta,\theta) - u_t(a',\theta).$$

Defining the conditional value of perfect information, $V_t(e_\infty, \theta)$, as,

$$V_t(e_\infty,\theta) \equiv u_t(a_\theta,\theta) - u_t(a',\theta)$$

its value prior to the action would be its expected value or the expected value of perfect information (EVPI):

$$EVPI = E_\theta'.\left[V_t(e,\theta)\right] \equiv E_\theta'.\left[u_t(a_\theta,\theta) - u_t(a',\theta)\right].$$

However the expected terminal utilities of action without information and with perfect information are, respectively,

$$E\left[u_t(e_o)\right] = E_\theta'.u_t(a',\theta)$$

and $$E\left[u_t(e_\infty)\right] = E_\theta'.u_t(a_\theta,\theta).$$

Therefore, $EVPI = E_\theta'\left[V_t(e_\infty,\theta)\right] = E\left[V_t(e_\infty)\right] = E\left[u_t(e_\infty)\right] - E\left[u_t(e_o)\right].$

The value of sample information can be approached in a similar manner. If (a') is defined as the optimum action under prior distribution, that is,

$$E'_{\theta} \cdot u_t(a',\theta) = \max_a E'_{\theta} \cdot u_t(a,\theta),$$

if ($a_x$) is the optimum action under the posterior distribution given results (x) from investigation (e),

$$E''_{\theta|x} \cdot u_t(a_x,\theta) = \max_a E''_{\theta|x} \cdot u_t(a,\theta).$$

By choosing action ($a_x$), the terminal utility is increased by,

$$E''_{\theta|x} \cdot u_t(a_x,\theta) - E'_{\theta|x} \cdot u_t(a',\theta) \equiv V_t(e,x)$$

where $V_t(e,x)$ is the conditional value of sample information, which is conditional on (x), or after (x) has been ascertained. However the expected value of sample information (EVSI) can be ascertained from,

$$E_{x|e} \cdot V_t(e,x) \equiv E\left[V_t(e_x)\right].$$

The expected utility of any investigation is the expected utility of an action without information $E\left[u_t(e_o)\right]$ plus the expected value of that information $E\left[V_t(e_x)\right]$,

or, $$E\left[U_t(e_x)\right] = E\left[u_t(e_o)\right] + E\left[V_t(e_x)\right].$$

Similarly, the expected net gain of sample information (ENGS) can be defined as,

$$E\left[V(e_x)\right] \equiv E\left[V_t(e_x)\right] - E\left[c_s(e_x)\right].$$

As stated previously, the terminal utility function can be formulated in different ways, dependent, in a civil engineering context, on the Engineer's concept of the problem. Assuming that the primary objective is to maximise the expected information value, the results can be shown graphically with $E\left[V(e_n)\right]$ plotted against (n), where,

$$E\left[V(e_n)\right] = E\left[V_t(e_n)\right] - E\left[c_s(e_n)\right].$$

In the simple case, where two actions are possible, a, = $(a_1, a_2)$, the terminal utility is linear and the cost of sampling is linearly-related to sample size, then it is feasible to assess the optimum sample size.

Using the previously-utilised normal distribution, the prior probability, $P'(\theta|x)$, is proportional to $\exp\left[\frac{-(\theta - m')^2 n'}{2S^2}\right]$ and the likelihood, $P(x|\theta)$, is proportional to $\exp\left[\frac{-(m - \theta)^2 n}{2S^2}\right]$.

The action set $a = \{a_1, a_2\}$

and $u_t(a_i, \theta) = k_i + k_i\theta$. (i = 1,2)

Defining the breakdown action as $\theta_B \equiv \frac{k_1 - k_2}{K_2 - K_1}$,

with the terminal loss constant $k_t \equiv k_2 - k_1$

and $E\left[c_s(e_n)\right] = k_s n$

then the expected net gain $E\left[V(e_n)\right]$ is,

$$E\left[V(e_n)\right] = E\,V_t(e_n) - E\,c_s(e_n)$$
$$= k_t (n^*)^{-1/2} L_n(D^*) - k_s n$$

where $\frac{1}{n^*} = \frac{1}{n'} - \frac{1}{n'+n}$,

$$D^* = \left|\theta_b - m'\right| n^{*\,1/2}$$

and $$L_N(D^*) = \int_{D^*}^{\infty} (\theta - D^*) f(\theta)\, d\theta$$

with $L_N(D^*)$ being the standard density function which is computed in statistical tables as the Unit Normal Linear Loss Integral.

# CHAPTER 3

# METHODOLOGY

# CHAPTER 3

## METHODOLOGY

The ultimate aim of this research is to assess whether any empirical relations can be drawn between investigation results, actual conditions encountered and the engineering choices made. If any relations are apparent, then it should be feasible to use them to link practice with the detailed tunnelling cost models produced from probabilistic or set theory.

The assessment of any empirical relations needs to be formulated from detailed cost data and it was the acquisition of this data that forms the basis of the present work. Data acquisition has comprised the assimilation of the financial details of contracts let by the NWA as part of the Tyneside Sewerage Scheme. This scheme, with an estimated cost of £100 million, consists of replacing 180 major sewers flowing into the River Tyne with a rationalised system of 75 km of interceptor sewer flowing on both banks to a centrally-situated treatment works.* See Figure 1 for location of scheme and separate contracts.

The contracts were, usually, 3-5 km in length and their costs could be split into two categories. The first category dealt with costs associated with the construction work, known as Contract Costs, and the second dealt with the costs associated with the site investigation. Within either of these categories costs could be further subdivided into fairly discrete headings. For instance, under Site Investigation Costs the main subheadings are Preliminary Site Investigation, Main Site Investigation, Site Investigation Supervisory Costs and Costs

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* With preliminary treatment of west-east (from Gateshead) and east-west (from S.Shields) flow at Jarrow for transfer in system to Howdon treatment works and treatment of south bank east flow at either Dunston or Derwent Haugh (not yet decided which) for direct transfer at Scotswood into the north bank interceptor sewer.

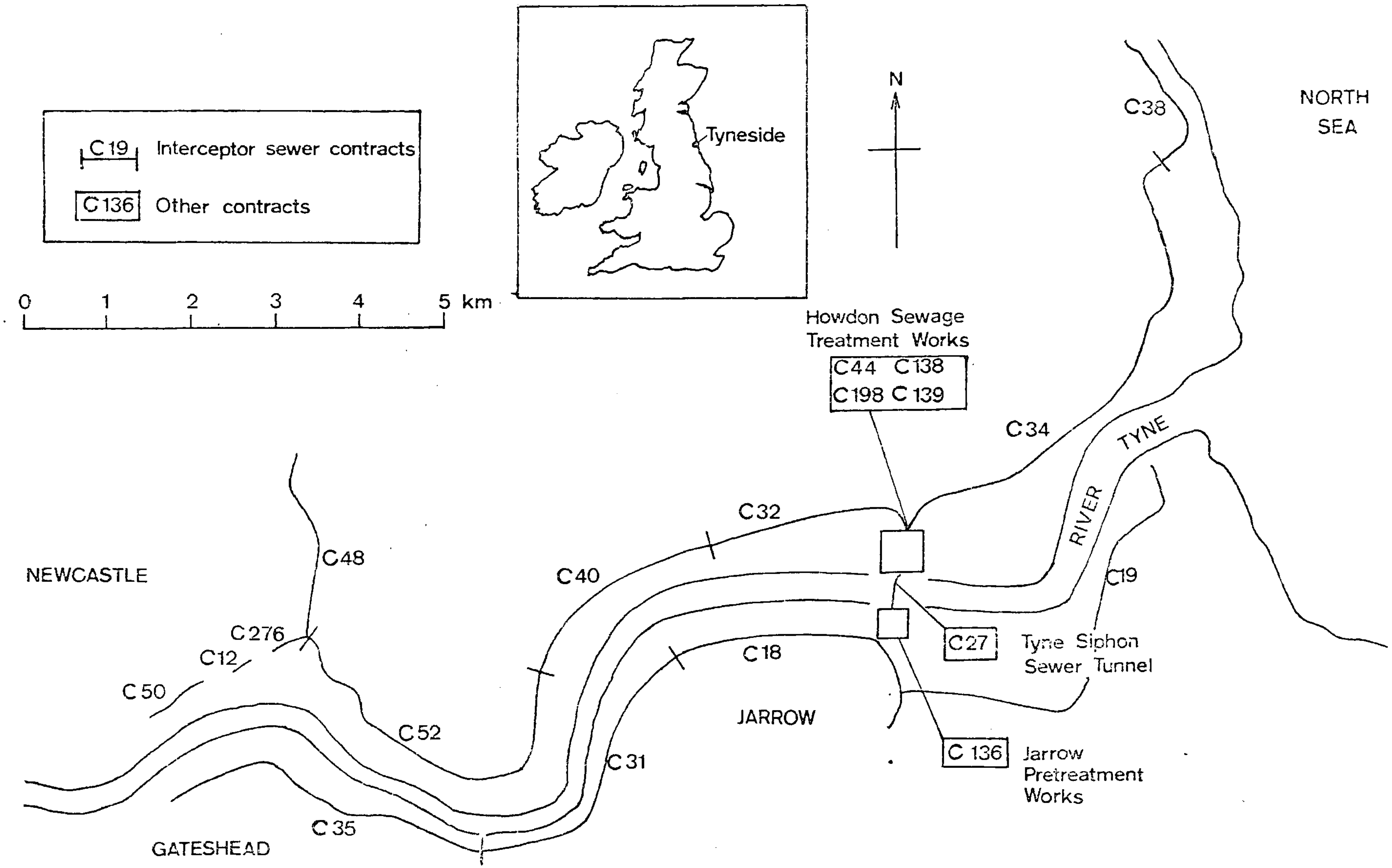

Fig.1 TYNESIDE SEWERAGE SCHEME — LOCATION PLAN

of Materials Testing and Geotechnical Investigation during Construction.

Although most of the costs were accurately known, in certain cases cost estimates needed to be derived. The usual method has been to try to use two or three different approaches to arrive at a figure and then compare these figures to assess an average cost.

At the completion of the detailed study for the fourth contract the method of data collection was reappraised to assess whether any short cuts could reasonably be applied to circumvent the time-consuming method used previously.

Comparison of the elements that constituted the contract cost has indicated that the summation of the certificated work and the site supervision costs (usually both more accurately known) amounted to better than 94% of the total cost and on the higher-value contracts to within 2% of the total cost. It therefore appeared reasonable to concentrate on these two elements, plus an allowance of 2% of the tender price as design costs. It should then be possible to give the total contract cost ± 5%.

Comparison of the constituent parts of the site investigation cost was not so clear-cut. Where probing ahead of the tunnel face occurred, the amalgamated cost of probing and payments to the main site investigation contractor was within 85-95% of the total site investigation cost. However, the lack of probing on Contract 40 gave particular prominence to additional items. For example, the Materials and Geotechnics cost on Contract 40 was 21% of the site investigation cost, whereas on Contract 52 it was only 4% based on monetary values of £1740 and £3200, respectively.

With respect to the Materials and Geotechnics cost during a contract, the method employed has been to ascribe a part directly to site investigation, with a percentage of the Materials cost assumed relevant to soils testing. Although this method could only be applied to two of the four contracts studied at the time of writing, it did seem to give a realistic answer. The cost of site investigation supervision, the other major item, was very dependent on the vagaries of personal memory, but apart from Contract 31 appeared to lie within 10-15% of the site investigation contractor's cost and on balance it was better to eliminate it from consideration by specifying it as 12.5% ± 2.5% of the main site investigation cost.

Thus it appeared that the same order of accuracy, as with the contract cost, could be achieved by assessing the total of the payment to the main site investigation contractor (+12.5%), probing and the Materials and Geotechnics cost, worked out as previously. Care still needed to be exercised to ensure that no large-scale site investigation programme, instigated during the construction phase, was overlooked.

A list could then be built up of the cost information required from a contract:

A. <u>Contract Cost</u>

1) Certificated Value
2) Site Supervision Cost
3) Tender Price (2% as Design Cost)
4) List of Claims and Variation Orders detailing value and cause

B. <u>Site Investigation Cost</u>

1) Payment to main Site Investigation contractor(s)
2) Cost of any probing or similar work
3) Materials and Geotechnics Costs during the construction phase

In Tables (1 and 2) the contract costs and site investigation

TABLE 1

## COMPARISON ON CONTRACT COST

| NWA CONTRACT NO. | | 27 | 31 | 40 | 52 |
|---|---|---|---|---|---|
| $\frac{\text{Certificated Cost}}{\text{Total Cost}}$ | % | 95.1 | 86.9 | 95.3 | 94.7 |
| $\frac{\text{Site Supervision Cost}}{\text{Total Cost}}$ | % | 3.2 | 7.1 | 2.8 | 3.5 |
| $\frac{\text{Site Supervision Cost}}{\text{Certificated Cost}}$ | % | 3.5 | 8.1 | 2.9 | 3.7 |
| $\frac{\text{Other Costs}}{\text{Certificated Cost}}$ | % | 1.9 | 7.0 | 2.0 | 1.9 |
| $\frac{\text{Other Costs}}{\text{Total Cost}}$ | % | 1.8 | 6.1 | 1.9 | 1.8 |

| NWA CONTRACT NO. | 27 | | 31 | | 40 | | 52 | |
|---|---|---|---|---|---|---|---|---|
| | Actual | Adjusted* | Actual | Adjusted* | Actual | Adjusted* | Actual | Adjusted* |
| Site Investigation (Contractor) / Total Site Investigation % | 29.6 | 32.2 | 70.9 | 75.0 | 57.7 | 61.6 | 33.9 | 46.0 |
| Site Investigation (Contractor) and Probing Cost / Site Investigation (Contractor) % | 96.7 | 96.0 | 91.3 | 91.0 | 57.7 | 61.6 | 84.6 | 86.7 |
| Site Investigation Supervisory Cost(NWA Staff) / Site Investigation (Contractor) % | 11.2 | 10.5 | 6.8 | 6.9 | 13.6 | 14.8 | 12.0 | 12.7 |
| Site Investigation Supervisory Cost(NWA Staff) / Total Site Investigation % | 3.3 | 4.0 | 4.8 | 5.2 | 7.8 | 9.1 | 4.1 | 5.9 |

* All cost adjusted to January 1979 value.

TABLE 2 COMPARISON OF SITE INVESTIGATION COST costs of the four detailed studies are compared, while in Table 3 the actual monetary values of these contracts are compared with the estimates, as based on the foregoing arguments.

It will be seen in Table 2 that for each contract there is a column designated "adjusted" costs, which costs differ slightly from the actual costs. This term "adjusted" means the January 1979 value of the costs and the reason for the need for this adjustment will now be explained.

In order for comparisons to be made both within contracts and between contracts, it is necessary to eliminate any variable factors which influence the costs.

Because of the period of time elapsed between the inception of the original Tyneside Sewerage Scheme and the final completion of the individual contracts, in some cases in excess of ten years, it would be unrealistic to make any cost comparisions, without making adjustments for inflation. Over the ten-year period (January 1969 to January 1979) the value of the pound has dropped (at a variable rate) fr 106p to 35p, using average 1970 value = 100 as per Contruction Indices, so accounting for this time-dependency had to be achieved in a manner which took account of the variation.

No absolute method of performing these adjustments was known, so the choice of method depended on the required degree of weighting towards certain constitutive factors and on the amount of complication. Several methods were tried, with, where possible, direct comparisons being made between them. Three of the methods were based on the 'Economic Trends' issued by the Central Statistics Office and published by HMSO.

a) Purchasing Power of the Pound

This method of index-linking is the most rudimentary in that it

| NWA CONTRACT NO. | TOTAL CONTRACT COST | | | SITE INVESTIGATION COST | | |
|---|---|---|---|---|---|---|
| | ACTUAL £ | ESTIMATED £ | PERCENTAGE DIFFERENCE % | ACTUAL £ | ESTIMATED £ | PERCENTAGE DIFFERENCE % |
| 27 | 3,402,248 | 3,275,915 | - 3.7 | 83,379 | 83,765 | + 0.5 |
| 31 | 849,304 | 814,671 | - 4.1 | 5,095 | 5,104 | 0 |
| 40 | 3,809,473 | 3,795,311 | - 0.4 | 9,528 | 8,941 | - 6.2 |
| 52 | 6,654,548 | 6,570,973 | - 1.3 | 72,864 | 66,720 | - 8.4 |

TABLE 3 COMPARISON OF ACTUAL AND ESTIMATED COST

assumes that all costs are subject to the same fall in value, with no reference being made to the underlying factors which affect the purchasing power of the pound. If the value of the pound at the rate of payment was 42p, say, and at the chosen base date was 35p, say, then the value of the cost (x) should be increased by a factor $(\frac{42}{35})$ to give the relative value of the cost of the chosen base date.

b) Wholesale Retail Price Index (WRPI) and General Retail Price Index (GRPI)

These two further indices, published by the Central Statistics Office, have the attractiveness of being the most generally-quoted and best understood. They differ from each other in that the WRPI refers to all manufactured products sold in Britain, whereas the GRPI includes services.

It would be expected that there should be an inverse relationship between either of these price indices and the purchasing power of the pound. For example, if January 1977 and January 1979 are considered, the GRPI values, assuming an average 1970 value = 100, are 235.9 and 283.4 respectively, while comparative figures for the purchasing power of the pound are 42p and 35p. Therefore the correction factor previously stated of $(\frac{42}{35}) = 1.20$ would be for the GRPI the inverse of the indices, i.e. $(\frac{283.4}{235.9}) = 1.20$ (to two decimal places), effectively the same.

Using either WRPI or GRPI the adjustment ratio is direct. For example, if the payment date was January 1974 with a GRPI of 136.8 and the chosen base date December 1976 (229.8), then the ratio to update the cost would be $(\frac{229.8}{136.8})$. This case of manipulation can be extended to payment dates after the chosen base date, for example January 1977 where the adjustment would be $(\frac{229.8}{235.9})$, or a reduction in cost.

c) Construction (Baxter) Indices

As mentioned previously, the civil engineering industry realised the necessity for introducing an in-built inflation adjustment into contracts programmed to last more than one year. Since February 1974 price fluctuations in labour, plant and a range of construction materials have been accounted for by indices published monthly by HMSO in the Construction Indices.

The method allows the Engineer and Contractor prior to the commencement of the contract, to agree the breakdown of a (0.85) stable coefficient split into the various categories, e.g. (0.4.) labour, (0.2) plant, and so on. The remaining (0.15) is normally considered as fixed. The monthly interim certificates can thus be altered to allow for inflation.

It would appear, on first examination, that this method would be ideal for index-linking all contract costs, but there are some severe problems. First, and most important, a considerable number of the costs pre-date the inception of 'Baxter' Indices and there is no method of extrapolating the existing system. It would, also, be difficult to assign costs, outside the direct construction, to relevant categories, such as land and legal fees.

A further problem manifests itself with the Baxter Indices, as there appears to be two methods of updating costs to a chosen base date. When used to index link cost during a construction contract, all costs are referred back to a base month, usually 42 days - prior to the commencement of the contract. In order to update costs to your chosen base date one has the alternative of reversing the process and then using the Baxter Indices to link the original base date and the chosen base or one can link the date of payment to one's chosen base date via the Baxter Indices. The resulting answers show a fair degree of divergence.

d) Term Contract Rate Index

This trial method was used on the first of the contracts, C27, to link the annual percentage increase to costs to the annual change in the cost of an essential site investigation item. The chosen item was "Shell and Auger Drilling from 0'-30' ", an item integral to most site investigations. The scope of this item was found, however, to be very limited and its use was not repeated in any of the further contract studies.

The annual percentage cost increases related to the various methods have been compared in Figure 2. It will be seen that there is reasonable agreement between the hybrid Baxter Indices and GRPI, with a correlation coefficient of 0.95.GRPI was therefore chosen as the main method of price adjustment, as it had the benefits of spanning the complete period under investigation, that is, from 1968 onwards, as well as good tractability, which allows simple revisions to new base dates. This last benefit was an important factor since the originally suggested base date of December 1976 already looks inappropriate and even the revised base date, January 1979, is currently over a year out of date.

Inflation is not the only factor that distorts cost comparisons. Another obvious factor is the physical dimensions of the tunnel. It is evident that costs are likely to be more closely-related to excavated volume than the linear metre, the quantity usually specified in Bills of Quantities.

Initially, only construction length was considered, but as the comparative figures for Contracts 31 and 40 indicate, the adjusted

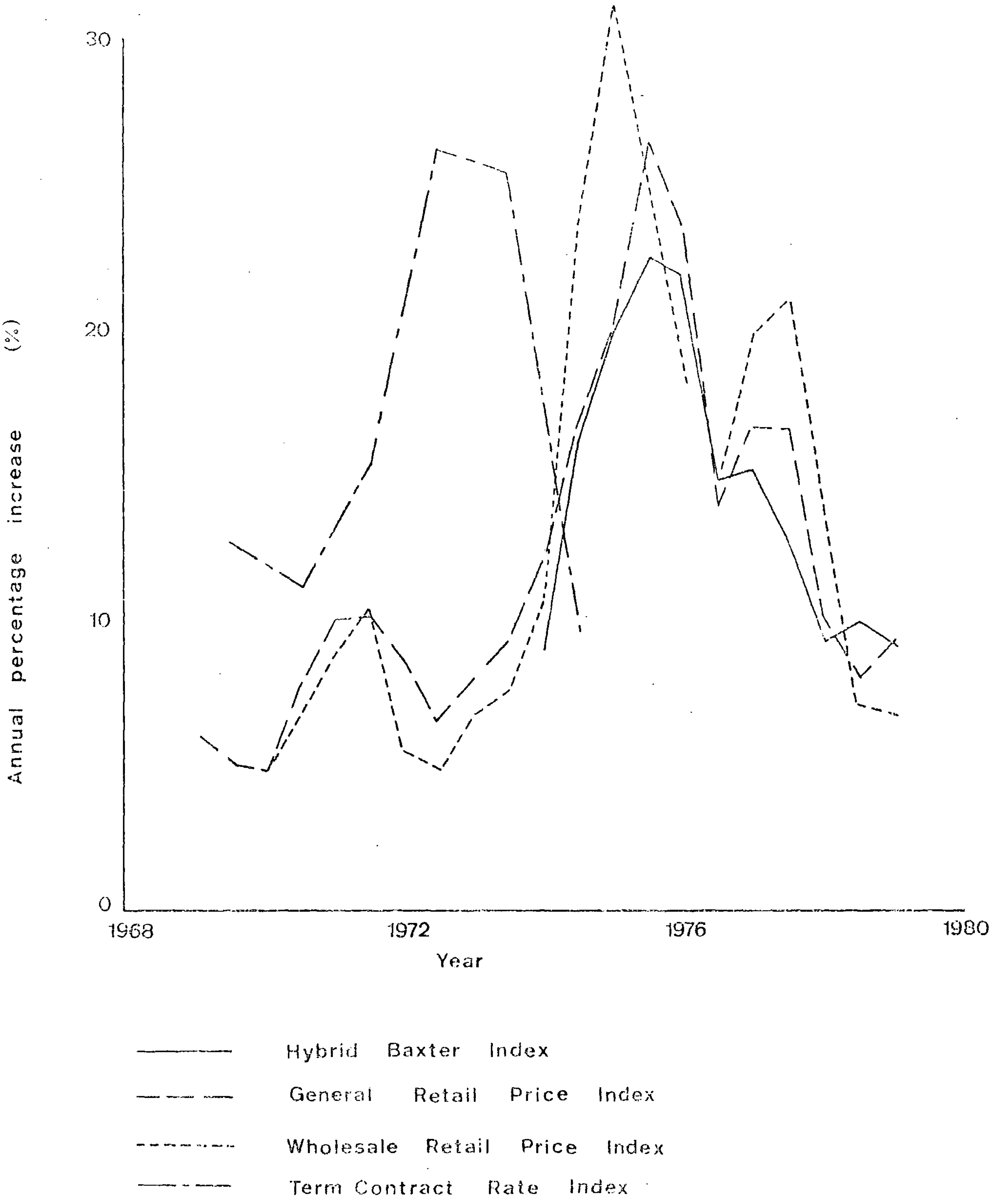

Fig.2 COMPARISON OF METHODS OF INFLATION ADJUSTMENT

costs per linear metre bear little relationship, being £482/lin.m. and £1565/lin.m., respectively. It is not until the adjusted cost per excavated volume is examined (£194/$m^3$ for C31 and £178/$m^3$ for C40) that a closer agreement is found, that is, within approximately 8%.

The influence of geological conditions should also be included within this category of distortions to cost comparisons as they are the main integral factor governing the choice of how much of each tunnelling method is used on a contract. Categorisation of the ground into anything more specific than 'rock', 'soft ground' or 'fill' would be difficult owing to its high degree of variability. This last problem is discussed further in Section 6, which deals with the whole question of applying the practical results of the research to the theory.

# CHAPTER 4

# EMPIRICAL RESULTS

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# EMPIRICAL RESULTS

Having produced the data in a form whereby comparisons can be made it is interesting to see what, if any, trends are indicated. The basic form is created by reducing the contracts to sets of figures. These costs are set out in Tables 4-9 but an explanation is required detailing what is included and excluded in the various headings, so as to facilitate their interpretation.

The items included within the contract cost are the construction cost, interpreted as the certificated value of the work undertaken by the main contractor, and the additional costs. In aggregating the additional costs every attempt was made to ensure consistency of constituent elements. The two main elements were the design cost and the site supervision cost, which could be accurately abstracted from records. The design costs, however, were based on a percentage of the tender price, as no accurate figure was available for the complete Tyneside Sewerage Scheme ,which was how the project was originally envisage and designed. Other items included within the additional costs were the land and legal fees, incurred by the NWA, and sundry items paid for directly by the NWA, which avoid the contractor's profit mark-up. Although in the cases so far studied the legal fees have been small compared with the construction cost, the situation could arise where large compensation claims would be paid out, which could seriously affect the total contract cost.

Although most of the construction work on these contracts concerned excavating and lining of sewer in tunnel and the sinking of associated shafts and manholes, there was an additional amount of peripheral work, in the form of, for instance, finishing work. In all but one case, these costs have been allowed to remain within

TABLE 4

## Tunnelling Costs

## Contract 27

| | |
|---|---|
| Location | River Tyne Sewage Siphon Tunnel |
| Type of Contract | Admeasurement, 4th Edition, VOP |
| Contract Dates | May 1973 - June 1976 |
| Tunnel Length | 488m between shafts |
| Excavated Diameter | 3.40m |
| Finished Diameter | 3.20m |
| Tender Price | £2,299,932.37 |

| | | Actual Cost | Cost Adjusted to Dec.1976 value | Cost Adjusted to Jan.1979 value |
|---|---|---|---|---|
| Construction Cost | (£) | 3,120,948.08 | 4,278,311 | 5,347,889 |
| Additional Cost | (£) | 281,300.26 | 355,942 | 444,928 |
| Contract Cost | (£) | 3,402,248.34 | 4,634,253 | 5,792,817 |
| Cost/lin.m | ($^{£}/_{m}$) | 6,971.82 | 9,496.42 | 11,870.53 |
| Cost/$m^3$ | ($^{£}/_{m^3}$) | 659.06 | 897.71 | 1,122.14 |

| | |
|---|---|
| Site Investigation Contracts | C1, C2, C17, C22 |
| Site Investigation Dates | March 1969 - January 1974 |
| Number of Boreholes | 32 |

| | | Actual Cost | Cost Adjusted to Dec.1976 value | Cost Adjusted to Jan.1979 value |
|---|---|---|---|---|
| SI Costs (excluding probing) | (£) | 28,836.87 | 61,634.17 | 77,042.71 |
| Cost of Probing | (£) | 54,542.24 | 78,918.46 | 98,648,08 |
| Total Cost of SI | (£) | 83,379.11 | 140,552.63 | 175,690.79 |
| Av.S.I. cost/BH | ( $£/_{BH}$) | 649.06 | 1,387.29 | 1,734.11 |
| | | | | |
| Cost of Claims and VO's attributed to SI | (£) | 125,126.04 | 171,515 | 214,394 |

TABLE 5

Tunnelling Costs

Contract 27 (Primary)*

| | |
|---|---|
| Location | River Tyne Sewage Siphon Tunnel |
| Type of Contract | Admeasurement 4th Edition VOP |
| Contract Dates | May 1973 - May 1975 |
| Tunnel Length | 488 m (between shafts) |
| Excavated Diameter | 3.4m (3.67 m if shafts considered as part of tunnel length) |
| Finished Diameter | 3.2m |
| Tender Price | - |

| | Actual Cost | Cost adjusted to Dec.1976 value | Cost adjusted to Jan.1976 value |
|---|---|---|---|
| Construction Cost(£) | 1,031,882.16 | 1,620,535 | 2,025,669 |
| Additional Cost (£) | 195,687.13 | 247,612 | 309,515 |
| Contract Cost (£) | 1,227,569.29 | 1,868,147 | 2,335,184 |
| Cost/lin.m .(£/m) | 2,515.51 | 3,828.17 | 4,785.21 |
| Cost/$m^3$ (£/$m^3$) | 273.80 | 361.88 | 452.35 |

| | |
|---|---|
| Site Investigation Contracts | C1, C2, C17 |
| Site Investigation Dates | Apr.1969 - Aug.1972 |
| Number of Boreholes | 16 |

| | Actual Cost | Cost adjusted to Dec.1976 value | Cost adjusted to Jan.1979 value |
|---|---|---|---|
| S.I.Costs(excluding probing) (£) | 26,766.17 | 57,485.10 | 71,856.38 |
| Cost of probing(£) | 54,542.24 | 78,918.46 | 98,648.08 |
| Total Cost of S.I.(£) | 81,308.41 | 136,403.56 | 170,504.46 |
| Av.S.I.cost/BH(£/BH) | 1,116.32 | 2,397.50 | 2,996.88 |
| Cost of S.I./lin.m (excluding probing)(£/m) | 54.85 | 117.80 | 147.25 |
| Cost of Claims and VO's attributed to SI (£) | 125,126.04 | 171,515 | 214,394 |

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*Contract 27 (Primary) refers to the part of Contract 27 dealing with the excavation and primary lining of tunnel and shafts. It is represented in the figures as C27P.

TABLE 6

Tunnelling Costs

Contract 31

| | |
|---|---|
| Location | South Bank Interceptor sewer (Reyrolle's to Stoneygate Lane) |
| Type of Contract: | Admeasurement 4th Edition Fixed Price |
| Contract Dates: | May 1973 - May 1975 |
| Tunnel Length: | 2793 m |
| Excavated Diameter: | 1.78m |
| Finished Diameter: | 1.20m |
| Tender Price: | £853,437.45 |

| | Actual Cost | Cost adjusted to Dec. 1976 value | Cost adjusted to Jan 1979 value |
|---|---|---|---|
| Construction Cost (£) | 737,635.79 | 972,578 | 1,215,723 |
| Additional Costs (£) | 111,668.58 | 173,762 | 217,203 |
| Contract Cost (£) | 849,304.37 | 1,146,340 | 1,432,926 |
| Cost/lin.m.(£/m) | 285.67 | 385.58 | 481.98 |
| Cost/$m^3$ (£/$m^3$) | 114.80 | 154.95 | 193.69 |

| | |
|---|---|
| Site Investigation Contracts | C3, C14, C17 |
| Site Investigation Dates | Sept.1969 - Mar.1972 |
| Number of Boreholes | 35 |

| | Actual Cost | Cost adjusted to Dec.1976 value | Cost adjusted to Jan.1979 value |
|---|---|---|---|
| S.I.Costs (excluding probing) (£) | 4,057.36 | 9.063.85 | 11,329.81 |
| Cost of probing (£) | 1,037.74 | 1,719.21 | 2,149.01 |
| Total Cost of S.I. (£) | 5,095.10 | 10,783.06 | 13,478.82 |
| Av.S.I.cost/BH (£/BH) | 103.26 | 231.11 | 288.96 |
| Cost of S.I./lin.m. (exluding probing)(£/m) | 1.36 | 3.05 | 3.81 |
| Cost of Claims and VO's attributed to S.I. (£) | 16,380 | 28,000 | 35,000 |

## TABLE 7

## Tunnelling Costs

## Contract 32

| | |
|---|---|
| Location: | North Bank Interceptor Sewer<br>(Howdon Sewage Treatment Works to Willington) |
| Type of Contract: | Admeasurement VOP Clause 4th Edition |
| Contract Dates: | April 1974 - May 1977 |
| Tunnel Length: | 2808 m |
| Excavated Diamter: | 3.20m and 3.97m |
| Finished Diameter: | 2.93m |
| Tender Price: | £2,386,524.91 |

| | Actual Cost | Cost adjusted to Jan. 1979 value |
|---|---|---|
| Construction Cost(£) | 3,861,662.07 | 5,426,167 |
| Additional Cost (£) | 280,322.98 | 404,710 |
| Contract Cost (£) | 4,141,985.05 | 5,830,877 |
| Cost/lin.m.(£/m) | 1,475.07 | 2,076.52 |
| Cost/$m^3$ (£/$m^3$) | 173.28 | 243.94 |

| | |
|---|---|
| Site Investigation Contracts | C 1,C 3,C14,C17,C22,C37,C51,C74 |
| Site Investigation Dates | Nov. 1969 - Sept. 1975 |
| Number of Boreholes | 77 |

| | Actual Cost | Cost adjusted to Jan. 1979 value |
|---|---|---|
| S.I.Costs(excluding probing) (£) | 18,635,02 | 41,275.05 |
| Cost of Probing (£) | 0 | 0 |
| Total Cost of S.I (£) | 18,635.06 | 41,275.05 |
| Av.S.I.cost/BH (£/BH) | 197.23 | 448.78 |
| Cost of S.I./lin m (excluding probing)(£/m) | 6.64 | 14.70 |
| Cost of Claims and VO's attributed to S.I.(£) | 725,498 | 819,367 |

TABLE 8

Tunnelling Costs — Contract 40

| | |
|---|---|
| Location: | North Bank Interceptor Sewer<br>(Willington to Low Walker) |
| Type of Contract: | Admeasurement 5th Edition CPF |
| Contract Dates: | May 1975 - May 1977 |
| Tunnel Length: | 3183 m |
| Excavated Diameter: | 3.35 m |
| Finished Diameter: | 2.83m |
| Tender Price: | £3,552,651.23 |

| | Actual Cost | Cost adjusted to Dec.1976 value | Cost adjusted to Jan. 1979 value |
|---|---|---|---|
| Construction Cost (£) | 3,631,029.14 | 3,671,543 | 4,725,679 |
| Additional Cost (£) | 178,444.24 | 222,509 | 274,408 |
| Contract Cost (£) | 3,809,473.38 | 4,003,052 | 5,000,087 |
| Cost/lin.m (£/m) | 1,196.82 | 1,257.63 | 1,570.87 |
| Cost/$m^3$ (£/$m^3$) | 135.78 | 142.68 | 178.22 |

| | |
|---|---|
| Site Investigation Contracts | C1, C14,C17,C37,C51 |
| Site Investigation Dates | Dec.1968 - Mar.1975 |
| Number of Boreholes | 49 |

| | Actual Cost | Cost adjusted to Dec.1976 value | Cost adjusted to Jan.1979 value |
|---|---|---|---|
| S.I.Costs(excluding probing) (£) | 9,528.11 | 18,586.99 | 23,233.74 |
| Cost of probing (£) | - | - | - |
| Total Cost of S.I.(£) | 9,528.11 | 18,586.99 | 23,233.74 |
| Av.S.I.cost/BH (£/BH) | 112.12 | 233.66 | 292.07 |
| Cost of S.I./lin.m (excluding probing) (£/m) | 2.99 | 5.84 | 7.30 |
| Cost of Claims and VO's attributed to S.I.(£) | 28,560 | 27,500 | 34,375 |

TABLE 9

## Tunnelling Costs

## Contract 52

| | |
|---|---|
| Location: | North Bank Interceptor Sewer<br>(Low Walker to Trafalgar Street) |
| Type of Contract: | Admeasurement 5th Edition CPF |
| Contract Dates: | Feb.1976 - April 1979 |
| Tunnel Length: | 4562 m |
| Excavated Diameter: | Soft Ground - 3.35 m<br>Rock (Arch Construction) 3.35 m |
| Finished Diameter: | 2.75 m |
| Tender Price: | £5,548,626 |

| | | Actual Cost | Cost adjusted to Jan. 1979 value |
|---|---|---|---|
| Construction Cost | (£) | 6,304,683 | 7,106,500 |
| Additional Cost | (£) | 349,884.75 | 490,754 |
| Contract Cost | (£) | 6,654,567.75 | 7,597,254 |
| Cost/lin.m. | (£/m) | 1,458.70 | 1,667.53 |
| Cost/$m^3$ | (£/$m^3$) | 155.66 | 177.94 |

| | |
|---|---|
| Site Investigation Contracts | C4, C22, C37, C74 |
| Site Investigation Dates | Jan. 1970 - Feb. 1976 |
| Number of Boreholes | 85 |

| | | Actual Cost | Cost adjusted to Jan. 1979 value |
|---|---|---|---|
| S.I. Costs (excluding probing) | (£) | 36,956.34 | 69,755.83 |
| Cost of probing | (£) | 36,907.44 | 44,147.00 |
| Total Cost of S.I. | (£) | 73,863.78 | 113,902.83 |
| Av.S.I.cost/BH | (£/BH) | 290.78 | 615.88 |
| Cost of S.I./lin.m | (£/m) | 7.89 | 15,30 |
| (excluding probing) | | | |
| Cost of Claims and V.O's attributed to S.I. | (£) | 498,000 | 538,768 |

the construction cost as they did not provide any substantial influence on the overall cost. However, in Contract 27, where a large amount of surface works at Jarrow Pretreatment Works was included, the cost of constructing the tunnel and North and South access shafts was assessed separately and is included in Table 5., under Contract 27 Primary.

Even on the construction of a sewer, different site conditions will lead to different constructional methods, usually into open-cut excavation, soft ground tunnelling and rock tunnelling. Not only is the method of excavation dependent on tunnelling category, but also the choice of primary lining. For instance, in an open-cut situation precast reinforced concrete culvert section may be used, whereas if excavation had been by tunnelling, precast segmental rings would have been the usual choice.

To illustrate the relative importance of these different working methods, with respect to cost appraisal, the investigated contracts have been broken down into the percentages of tunnelling category based on both contract length and billed price. The results are shown in Table 10. The percentage costs in Table 10 exclude the site mobilisation cost of the tunnelling equipment, so, in order to show the complete cost of excavation and primary lining, Table 11 has been included giving the respective financial values.

Returning to the tunnelling costs in Tables 4-9, an important series of costs come under the heading "Value of Claims and Variation Orders attributable to Site Investigation". In terms of the theory these costs are the monetary results of actions. For instance, on Contract 27 the action was the use of a roadheader to excavate the tunnel under compressed air. The result of the action not being optimum was that, when the tunnel face conditions consisted of two thirds 'hard' sandstone, the machine was unable to proceed

| NWA Contract No. | Site Mobilisation Cost (Tunnelling Equipment) £ | Tender Price of Excavation and Primary Lining £ |
|---|---|---|
| 27 | 165,000 | 1,179,122 |
| 31 | (included in tender price) | 459,311 |
| 32 | 156,000 | 825,737 |
| 40 | 200,000 | 1,359,873 |
| 52 | 315,000 | 2,604,890 |

TABLE 11 : Overall cost of Tunnelling and Primary Lining

| NWA Contract No. | Tunnelling Category by length % | | | Excavation & Primary Lining as a Percentage by cost of tender price % | | |
|---|---|---|---|---|---|---|
| | Open Cut | Soft Ground | Rock | Open Cut | Soft Ground | Rock |
| 27 | 0 | 0 | 100 | 0 | 0 | 51.3 |
| 31 | 44.3 | 55.7 | 0 | 16.0 | 37.8 | 0 |
| 32 | 0 | 100 | 0 | 0 | 34.6 | 0 |
| 40 | 9.9 | 90.1 | 0 | 6.6 | 31.7 | 0 |
| 52 | 0 | 58.7 | 41.3 | 0 | 30.0 | 17.0 |

TABLE 10 Categorisation of Contracts into Tunnel Type

and had to be removed. The monetary result of the action was a Clause 12 claim from the Contractor which, including the four weeks delay, cost the client £114,525.24. In other cases, where the problem is not so severe, it is possible that it can be covered by the issue of a variation order. This practice is often used where the true extent of a problem is on a greater scale than the allowance made for the condition in the Bill of Quantities. For instance, in Contract 52 part of the additional cost for remedial work to the rock tunnel drives was paid as variation orders.

The costs under this heading are, therefore, the aggregate of Clause 12 claims, related compensation claims and variation orders, where inadequate information about ground conditions could be seen to be the cause. The relation of these costs to a geotechnical loss function is discussed in Chapter 6.

Taking comparisons one step further, certain ratios and percentages have been made of the costs and are shown in Table 12. The most commonly quoted of these figures, the percentage of site investigation cost to construction, lies within the expected range of $\frac{1}{2}$ - $1\frac{1}{2}$% for all the contracts, except Contract 27, where the special conditions necessitated continuous advance probing.

To facilitate the appreciation of the concepts behind the theory, certain of the ratios and percentages have been used to produce rudimentary graphs. The first of these graphs, Figure 3, compares the value of claims and variation orders attributed to site investigation, expressed as a fraction of site investigation costs, against the site investigation costs expressed as a percentage of the construction cost.

Intuitively it is to be expected that the lower the relative site

|  | NWA Contract Number | C27 | C27 Primary | C31 | C32 | C40 | C52 |
|---|---|---|---|---|---|---|---|
| Claims and V.O.'s Attributable to Site Investigation / Site Investigation (Ratio) | Actual | 1.50 | 1.54 | 3.21 | 39.2 | 3.00 | 6.83 |
|  | Adjusted* | 1.22 | 1.26 | 2.60 | 19.6 | 1.48 | 4.73 |
| Claims and V.O.'s Attributable to Site Investigation / Site Investigation (excluding probing) (Ratio) | Actual | 4.34 | 4.67 | 4.04 | 39.2 | 3.00 | 13.4 |
|  | Adjusted* | 2.78 | 2.98 | 3.09 | 19.6 | 1.48 | 7.72 |
| Claims and V.O.'s Attributable to Site Investigation / Site Investigation per Linear Metre of Tunnel ($x10^3M$) | Actual | 0.73 | 0.75 | 8.93 | 100 | 8.28 | 31.2 |
|  | Adjusted* | 0.60 | 0.61 | 7.73 | 55.7 | 4.71 | 21.6 |
| Claims and V.O.'s Attributable to Site Investigation / Site Investigation per $M^3$ of Excavated Volume ($x10^4M^3$) | Actual | 0.77 | 0.79 | 2.20 | 93.7 | 7.29 | 27.5 |
|  | Adjusted* | 0.63 | 0.65 | 1.92 | 47.4 | 4.15 | 19.0 |

* All costs adjusted to January 1979 values

TABLE 12 Cost Percentages and Ratios

|  | NWA Contract Number | C27 | C27 Primary | C31 | C32 | C40 | C52 |
|---|---|---|---|---|---|---|---|
| Claims and V.O.'s Attributable to Site Investigation / Tender Cost % | Actual | 5.44 | - | 1.92 | 30.3 | 0.80 | 8.98 |
|  | Adjusted* | 3.96 | - | 1.77 | 16.1 | 0.56 | 6.68 |
| Claims and V.O.'s and S.I. / Tender Cost % | Actual | 9.07 | - | 2.52 | 31.1 | 1.07 | 10.3 |
|  | Adjusted* | 7.30 | - | 2.45 | 17.0 | 0.94 | 8.09 |
| Site Investigation / Tender Cost % | Actual | 3.63 | - | 0.60 | 0.77 | 0.27 | 1.31 |
|  | Adjusted* | 3.24 | - | 0.68 | 0.82 | 0.38 | 1.41 |
| Claims and V.O.'s Attributable to Site Investigation / Total Contract Cost % | Actual | 3.68 | 10.2 | 1.93 | 17.5 | 0.75 | 7.48 |
|  | Adjusted* | 3.70 | 9.18 | 2.44 | 14.1 | 0.69 | 7.08 |
| Claims, V.O.'s and S.I. / Total Contract Cost % | Actual | 6.13 | 16.8 | 2.53 | 18.0 | 1.00 | 8.58 |
|  | Adjusted* | 6.73 | 16.5 | 3.38 | 14.8 | 1.15 | 8.58 |
| Site Investigation / Total Contract Cost % | Actual | 2.45 | 6.62 | 0.60 | 0.45 | 0.25 | 1.09 |
|  | Adjusted* | 3.03 | 7.30 | 0.94 | 0.72 | 0.46 | 1.50 |

* All costs adjusted to January 1979 values

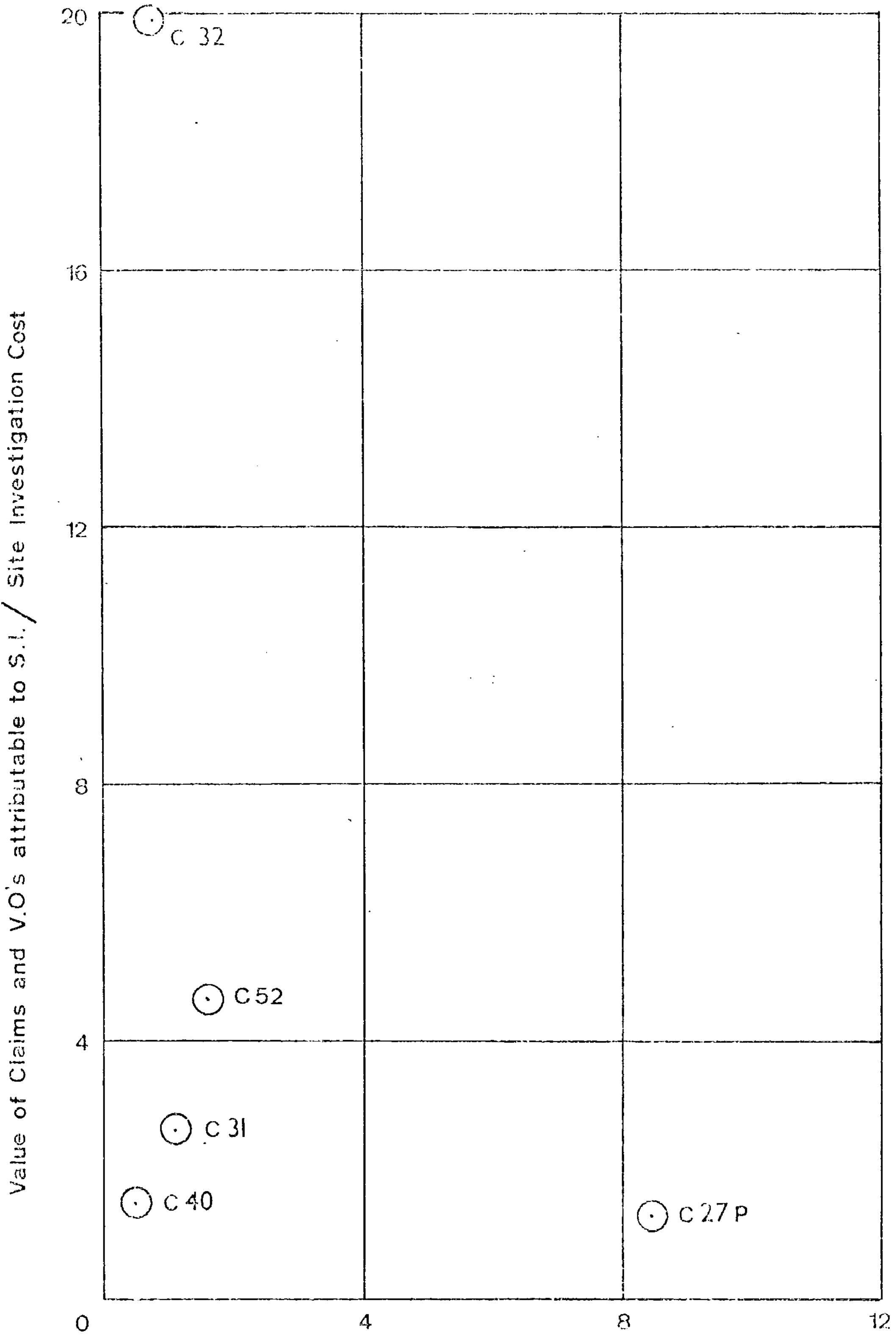
TABLE 12 Cost Percentages and Ratios

/cont'd...

|  | NWA Contract Number | C27 | C27 Primary | C31 | C32 | C40 | C52 |
|---|---|---|---|---|---|---|---|
| Claims and V.O.'s Attributable to Site Investigation / Construction Cost % | Actual | 4.00 | 12.1 | 2.22 | 18.8 | 0.79 | 7.90 |
|  | Adjusted* | 4.00 | 10.6 | 2.88 | 15.1 | 0.73 | 7.58 |
| Claims, V.O.'s and S.I. / Construction Cost % | Actual | 6.68 | 20.0 | 2.91 | 19.3 | 1.05 | 9.05 |
|  | Adjusted* | 7.29 | 19.0 | 3.99 | 15.9 | 1.22 | 9.18 |
| Site Investigation / Construction Cost % | Actual | 2.67 | 7.88 | 0.69 | 0.48 | 0.26 | 1.16 |
|  | Adjusted* | 3.29 | 8.42 | 1.11 | 0.77 | 0.49 | 1.60 |
| Site Investigation Excluding Probing / Construction Cost % | Actual | 0.92 | 2.59 | 0.55 | 0.48 | 0.26 | 0.57 |
|  | Adjusted* | 1.44 | 3.55 | 0.93 | 0.77 | 0.49 | 0.95 |

/cont'd.....

Table 12 Cost Percentages and Ratios



Site Investigation / Construction Cost (%)

All costs adjusted to January 1979 value

Fig. 3 COMPARISON OF THE RATIO OF COST ESCALATION TO EXPENDITURE ON GROUND UNCERTAINTY WITH PERCENTAGE INFORMATION COST investigation cost the higher the risk of large claims, and, conversely, the higher the site investigation cost the lower the risk of claims. Of the cases studied so far four fell into the category of low site investigation cost and one in the high site investigation cost bracket. If sufficient data were available to produce a scattergram,it is expected that it would take the general form of Figure 4, where the area of maximum shading would indicate the maximum number of contracts.

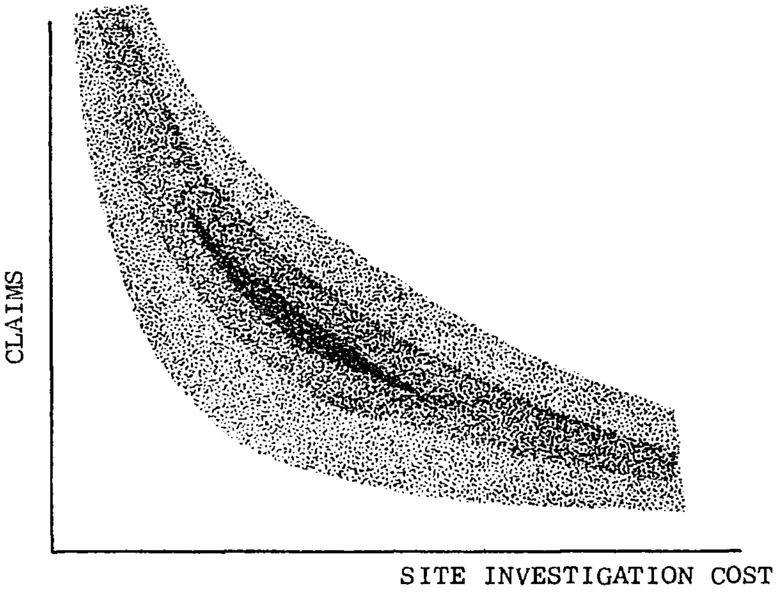
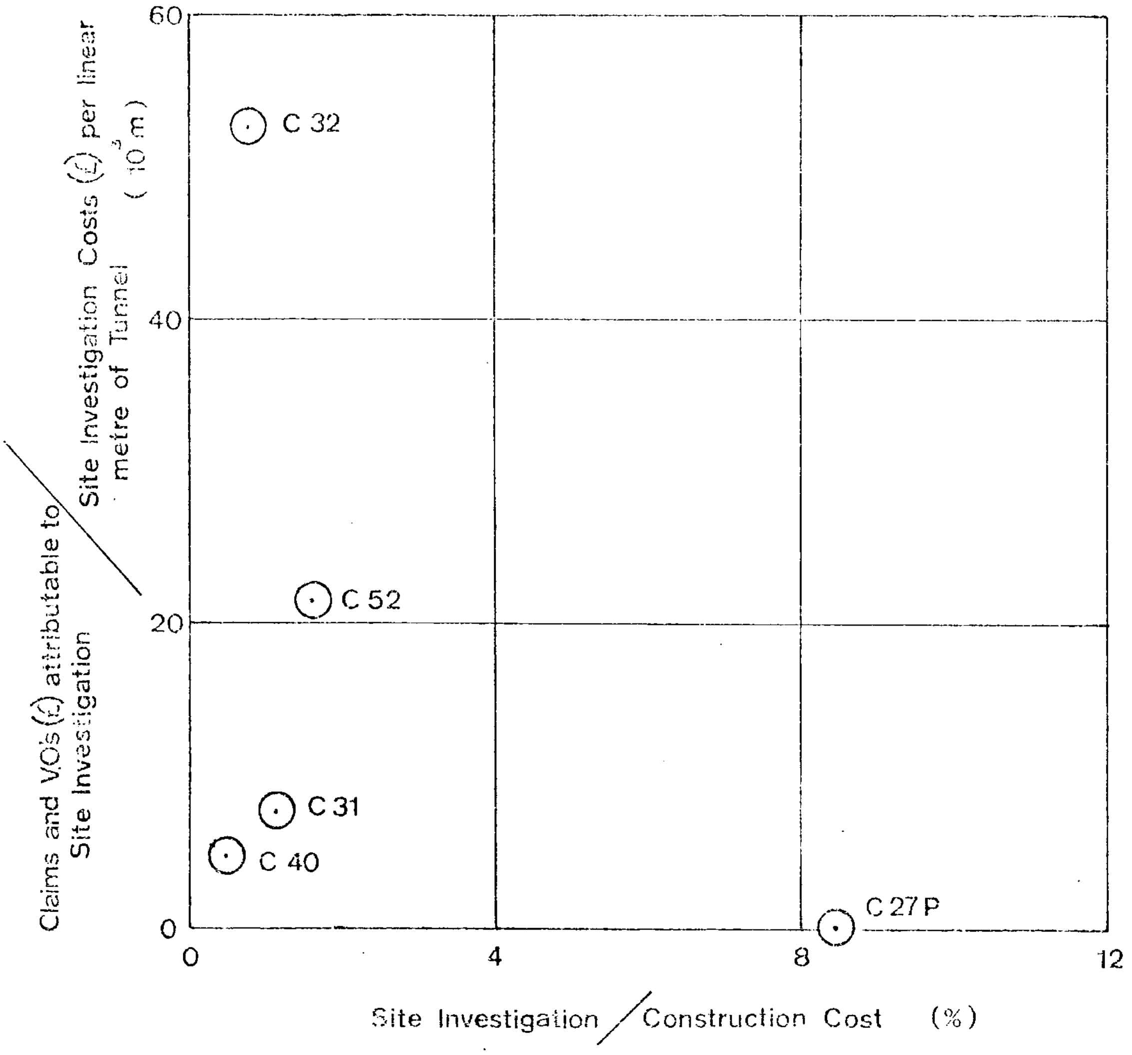


FIGURE 4

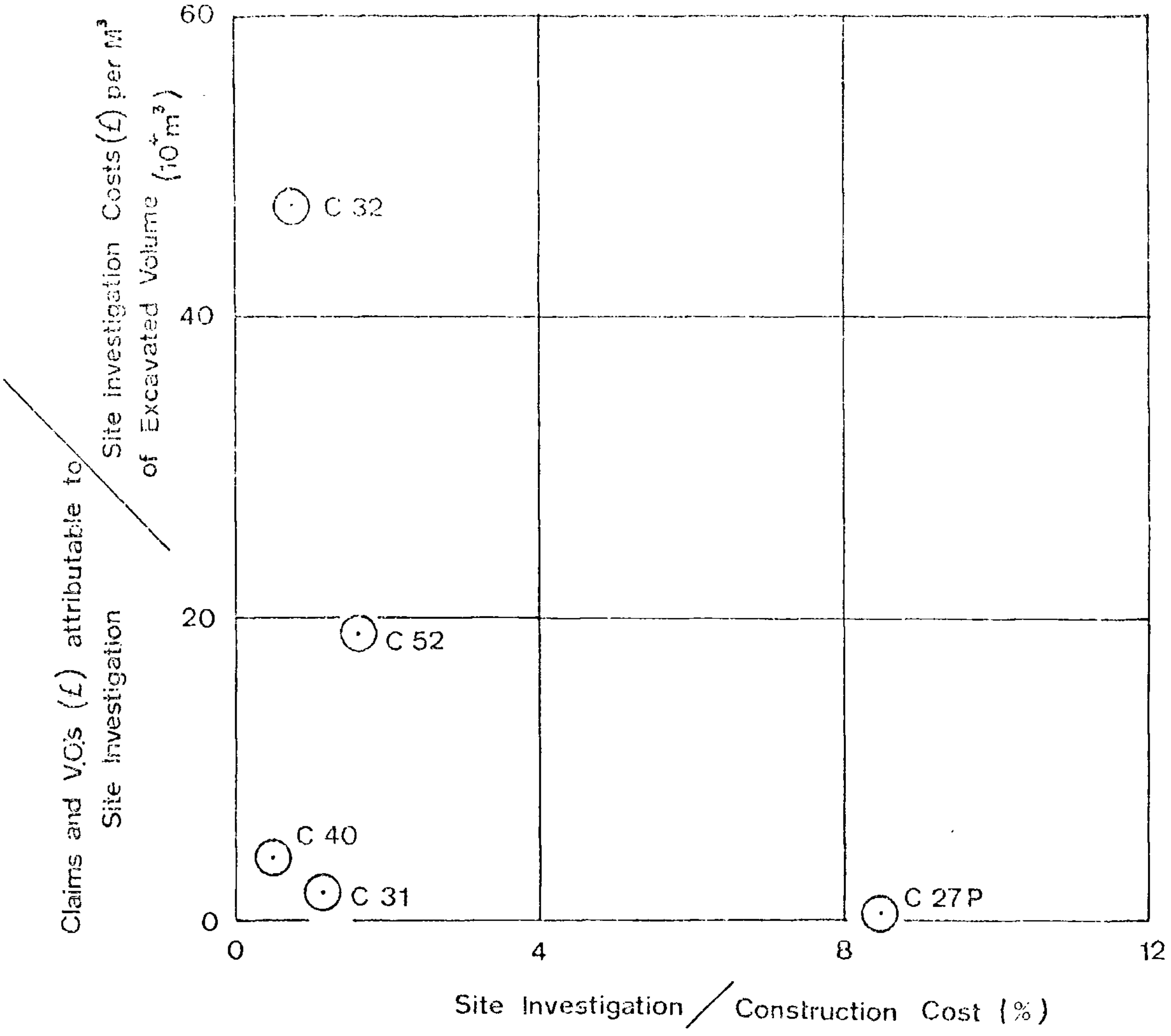
Although little can be assessed from Figure 2 there are indications of a wide dispersion in the range of $\frac{1}{2}$-$1\frac{1}{2}$%, as expected from the higher risk.

In formulating Figure 3 only the absolute values of site investigation cost are considered, taking no account of site investigation density, which would be expected to be directly related to information density. In order to create a measure of information density two further graphs (see Figures 5 and 6) have been drawn,



All costs adjusted to January 1979 value

Fig. 5 COMPARISON OF THE RATIO OF COST ESCALATION TO EXPENDITURE ON GROUND UNCERTAINTY PER UNIT LENGTH WITH PERCENTAGE INFORMATION COST



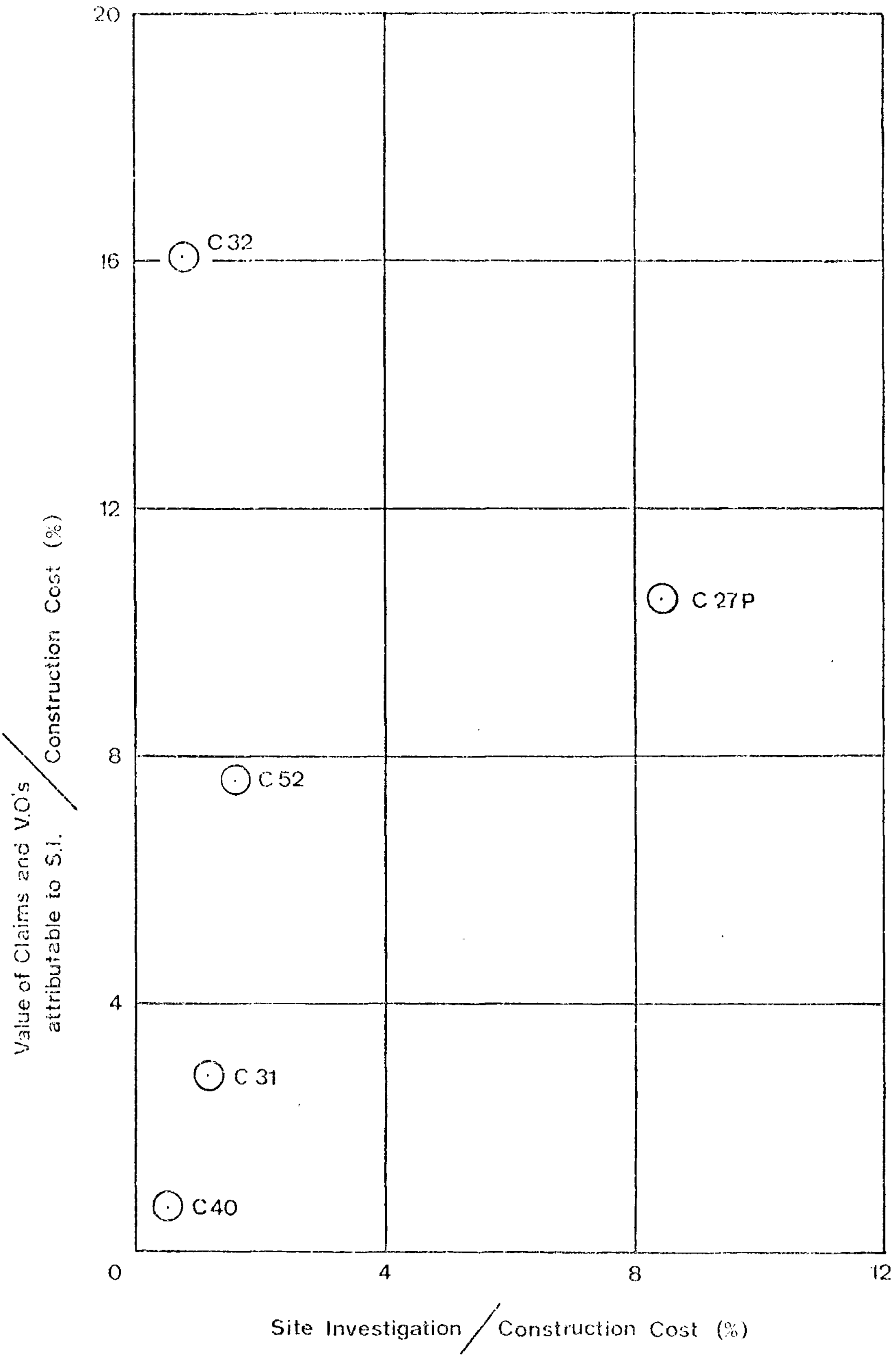
All costs adjusted to January 1979 value

Fig. 6 COMPARISON OF THE RATIO OF COST ESCALATION TO EXPENDITURE ON GROUND UNCERTAINTY PER UNIT EXCAVATED VOLUME WITH PERCENTAGE INFORMATION COST which use site investigation costs per unit sewer length and per unit excavated volume, respectively. It can be seen that the original shape of Figure 2 has been substantially unaffected, which would indicate a fairly uniform site investigation density over the different contracts.

Expressing "Claims and V.O's attributable to Site Investigation" as a fraction of the Site Investigation Cost serves to illustrate the potentially large discrepancy between the money expended on reducing uncertainty about ground conditions and the cost escalation of a contract caused by this risk. It does not, however, allow direct comparison between the claims (results of non-optimum actions) and the site investigation. For this reason Figures 7 and 8 have been drawn, showing claims and claims plus site investigation costs expressed as a percentage of adjusted construction cost.

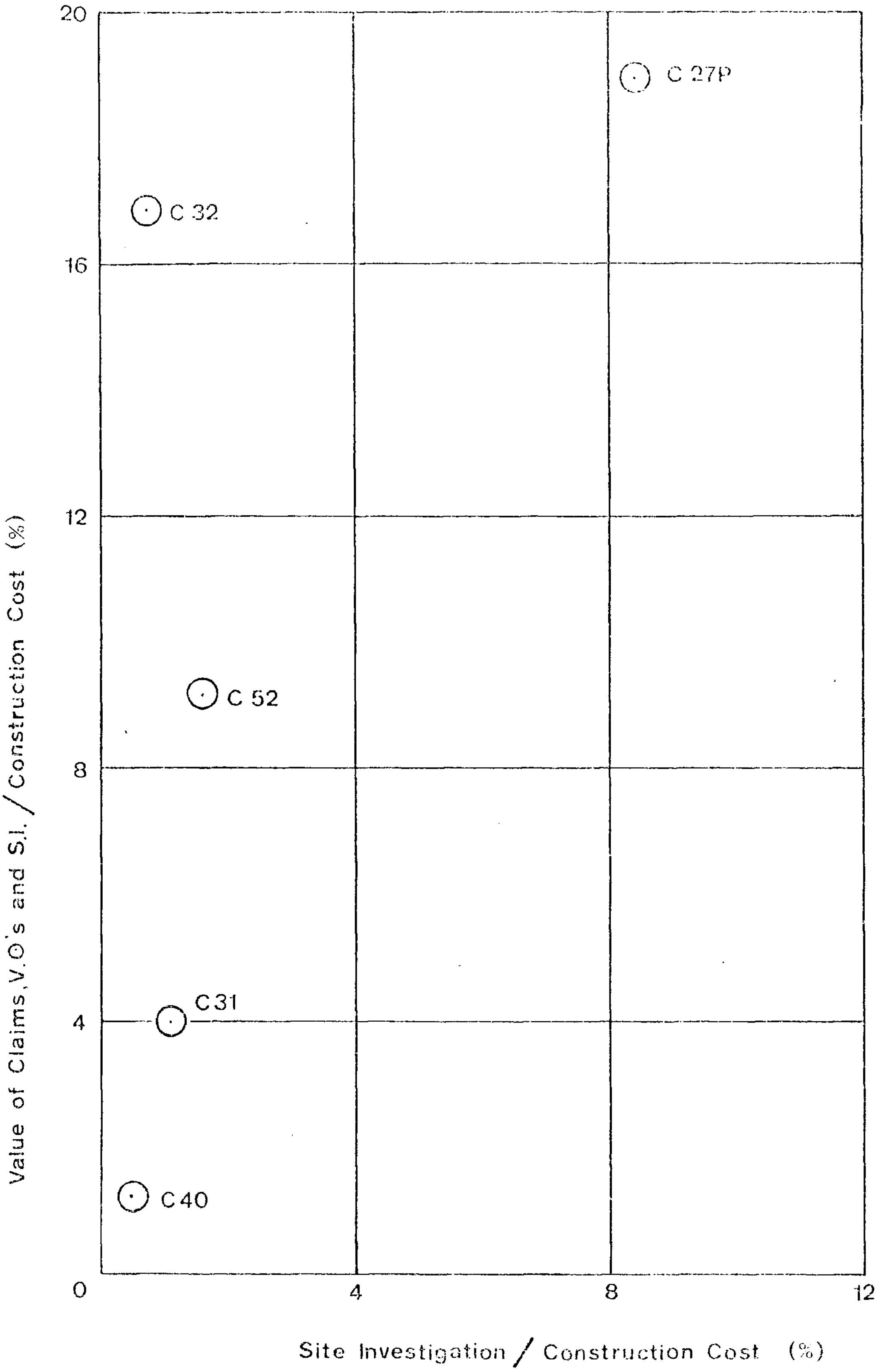
It is evident that neither of these graphs represent any marked deviation from Figures 3 and 4 , although they do, perhaps, emphasise the uniqueness of Contract 27 (the sub-aqueous tunnel less than half a kilometre in length).

It would be premature at this stage to attempt to establish any empirical equation for the graphs in Figures 7 and 8 . Non-linear regression analysis was attempted on the data, but the results were inconclusive.



All costs adjusted to January 1979 value

Fig. 7 COMPARISON BETWEEN PERCENTAGE COST ESCALATION DUE TO GROUND UNCERTAINTY AND PERCENTAGE INFORMATION COST



All costs adjusted to January 1979 value

Fig. 8 COMPARISON BETWEEN PERCENTAGE COST OF GROUND UNCERTAINTY AND PERCENTAGE INFORMATION COST

# CHAPTER 5

# CONTRACTUAL PROCEDURE

# CHAPTER 5

# CONTRACTUAL PROCEDURE

In order to better understand the problems of relating theory to the actual results, there is a preliminary need for an appreciation of current tunnelling contract procedure. For an in-depth analysis reference should be made to (ABRAHAMSON, 1973), (LEENEY, 1979) and (ABRAHAMSON, 19 79 ).

With the increased specialisation of tunnelling contractors and a diminishing number of contracts leading to increased competitiveness and lower profit margins, there is a clear incentive, particularly on the part of the Client, to reduce disputes and apportion risk equitably.

It is in the interests of both the Client and the Contractor to minimise uncertainty. Without evidence of the very low probability of high cost risks contractors are liable to make allowances for them, which, in turn, will have to be paid for by the Client through a higher tender price. Equally the costing of high risk is liable to penalise the careful contractor and aid the foolhardy or inexperienced contractor in winning a contract, as the latter is less likely to make realistic allowances for unknown variables.

In the contracting situation, risk is compounded from the unquantifiable costs related to uncertainties and there is a wide variety of risks involved in planning work over a future period. Uncertainties, which influence contracts, fall into three main categories.

Government influence, both direct and indirect, manifests itself through the control of such factors as inflation, interest rates and also in the implementation of laws relating to labour, safety and so on. Although not really applicable to this country, the stability of the society can play a major part in forecasting contractor costs abroad.

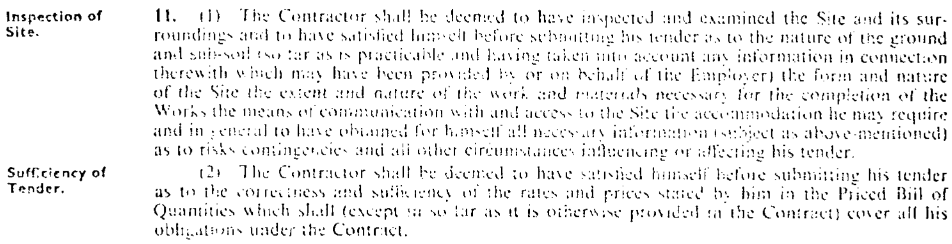
In the cases studied so far the Client has also been the Engineer, so factors influenced by both of these have been lumped together. In the private sector they would be separated under the two headings. The Client/Engineer influences the contract through the formation of the Bill of Quantities and Specification and also in the control of the contract where disputes can arise over workmanship or personnel relations.

The third category relates to uncertainties in the physical conditions, which can lead to unforeseeable circumstances and compensation claims. It is with attempts to examine this third category that the present research is concerned, with tunnelling contracts being used since they are probably the most sensitive of civil engineering works to variations in subsurface information.

The present research has looked into admeasurement contracts, a system of contract most widely used throughout the civil engineering industry. It bases its achievement of a fair price for the work on the use of competitive tendering, usually from a list of selected tenderers, assuming that competition will induce the contractor to assess realistically the risk assigned to him.

Contracts are usually let under the Conditions of Contract and Forms of Tender, Agreement and Bond for use in connection with Works of Civil Engineering Construction 5th Edition (June, 1973, revised January 1979), which are documents agreed by the Institution of Civil Engineers, Consultants and the Federation of Civil Engineering Contractors. The document is more commonly known as "The ICE Conditions of Contract". Within its framework there are clauses which relate specifically to provision for unforeseen conditions and the major ones will be explained in greater detail below.

However, before detailing the clauses to which a contractor has recourse for additional payment or time, it is desirable to explain what is expected of a contractor prior to the commencement of a contract, a requirement which is covered in Clause 11 of the ICE Conditions of Contract.



**Inspection of Site.**

11. (1) The Contractor shall be deemed to have inspected and examined the Site and its surroundings and to have satisfied himself before submitting his tender as to the nature of the ground and sub-soil (so far as is practicable and having taken into account any information in connection therewith which may have been provided by or on behalf of the Employer) the form and nature of the Site the extent and nature of the work and materials necessary for the completion of the Works the means of communication with and access to the Site the accommodation he may require and in general to have obtained for himself all necessary information (subject as above-mentioned) as to risks contingencies and all other circumstances influencing or affecting his tender.

**Sufficiency of Tender.**

(2) The Contractor shall be deemed to have satisfied himself before submitting his tender as to the correctness and sufficiency of the rates and prices stated by him in the Priced Bill of Quantities which shall (except in so far as it is otherwise provided in the Contract) cover all his obligations under the Contract.

As can be seen, it is not a precise definition. Although investigations are required for the site and its surroundings, they are not required for the subsoil, where the contractor is only deemed to have satisfied himself as to the nature of the subsoil. The Clause would suggest that he need not resort to opening up the subsoil provided he takes into consideration the available information.

Contractors would have the right to recompense if, the Client warranted the information he provided or asked the Contractor to use it in his estimate at the tender stage.

Similarly, the Engineer does not have the power to warrant any information and may be in breach of warranty of his authority should he do so. Any reckless (knowing not 'true', but not knowing 'untrue') or fraudulent (knowing 'untrue') statement made to the Contractor regarding conditions would allow him to have recourse to damages. Even if the misrepresentation is made in innocence, the

Contractor would still be entitled to end the contract. Care, therefore, needs to be exercised as to what was actually represented, with the usual format being that Company 'X' made boreholes with results "such and such". In this situation it would be difficult for a contractor to claim any misrepresentation.

The inclusion of the phrase 'taken into account' in the 5th Edition is an improvement over the 4th Edition, where it was only implied and clearly indicates that any information provided by the Client should only be one of a number of factors governing the tender. It follows that the more information that is provided, the higher will be the degree of significance that can be applied to it and the more difficult for the Contractor to check. It would seem only reasonable that Contractors should be acquainted with what facility they have for undertaking additional site investigation should they wish to do so.

In a case where the Contractor believes that he has a justifiable claim to additional payment, the Clause which he invokes depends on the nature of problems. If the cost is due to alteration in the billed quantities then it is likely that it will be covered by Clause 51 or Clause 56.

**Ordered Variations.**

51. (1) The Engineer shall order any variation to any part of the Works that may in his opinion be necessary for the completion of the Works and shall have power to order any variation that for any other reason shall in his opinion be desirable for the satisfactory completion and functioning of the Works. Such variations may include additions omissions substitutions alterations changes in quality form character kind position dimension level or line and changes in the specified sequence method or timing of construction (if any).

**Ordered Variations to be in Writing.**

(2) No such variation shall be made by the Contractor without an order by the Engineer. All such orders shall be given in writing provided that if for any reason the Engineer shall find it necessary to give any such order orally in the first instance the Contractor shall comply with such oral order. Such oral order shall be confirmed in writing by the Engineer as soon as is possible in the circumstances. If the Contractor shall confirm in writing to the Engineer any oral order by the Engineer and such confirmation shall not be contradicted in writing by the Engineer forthwith it shall be deemed to be an order in writing by the Engineer. No variation ordered or deemed to be ordered in writing in accordance with sub-clauses (1) and (2) of this Clause shall in any way vitiate or invalidate the Contract but the value (if any) of all such variations shall be taken into account in ascertaining the amount of the Contract Price.

**Changes in Quantities.**

(3) No order in writing shall be required for increase or decrease in the quantity of any work where such increase or decrease is not the result of an order given under this Clause but is the result of the quantities exceeding or being less than those stated in the Bill of Quantities.

General opinion holds that the extent of this clause limits the variation to any part of the work, but does not include an alteration to the whole works, for example, a change of location. To be validated by the clause, the variation must have been authorised prior to the undertaking by the Engineer who can only do so under special authority from the Client. (The Client cannot make the order as he would be in breach of contract.) This order, whether verbal, later to be confirmed in writing, or written, does not exclude drawings or sketches which indicate a definite method of working. A point worth noting is that the contractor may not, under his own authorisation, alter the work and would be liable to pay damages if he did so.

**Measurement and Valuation.**

56. (1) The Engineer shall except as otherwise stated ascertain and determine by admeasurement the value in accordance with the Contract of the work done in accordance with the Contract.

**Increase or Decrease of Rate.**

(2) Should the actual quantities executed in respect of any item be greater or less than those stated in the Bill of Quantities and if in the opinion of the Engineer such increase or decrease of itself shall so warrant the Engineer shall after consultation with the Contractor determine an appropriate increase or decrease of any rates or prices rendered unreasonable or inapplicable in consequence thereof and shall notify the Contractor accordingly.

**Attending for Measurement.**

(3) The Engineer shall when he requires any part or parts of the work to be measured give reasonable notice to the Contractor who shall attend or send a qualified agent to assist the Engineer or the Engineer's Representative in making such measurement and shall furnish all particulars required by either of them. Should the Contractor not attend or neglect or omit to send such agent then the measurement made by the Engineer or approved by him shall be taken to be the correct measurement of the work.

Where it can be proved that there is a difference between actual quantities and billed quantities, the Contractor has a right to an increase in the rate. Similarly, if a decrease in quantity makes a particular working method uneconomic, he would have a right to an increase in the rate. In effect, the Client is guaranteeing the quantities estimated from the site investigation. The estimation of a suitable revised rate should take into account whether the original rate was uneconomic for the specified quantity allowing for any inflexibility in his working method.

Where the additional cost due to unforeseen conditions cannot be included with the Bill of Quantities, or by using billed rates, the Contractor has recourse under Clause 12.

**Adverse Physical Conditions and Artificial Obstructions.**

12. (1) If during the execution of the Works the Contractor shall encounter physical conditions (other than weather conditions or conditions due to weather conditions) or artificial obstructions which conditions or obstructions he considers could not reasonably have been foreseen by an experienced contractor and the Contractor is of opinion that additional cost will be incurred which would not have been incurred if the physical conditions or artificial obstructions had not been encountered he shall if he intends to make any claim for additional payment give notice to the Engineer pursuant to Clause 52(4) and shall specify in such notice the physical conditions and/or artificial obstructions encountered and with the notice if practicable or as soon as possible thereafter give details of the anticipated effects thereof the measures he is taking or is proposing to take and the extent of the anticipated delay in or interference with the execution of the Works.

**Measures to be Taken.**

(2) Following receipt of a notice under sub-clause (1) of this Clause the Engineer may if he thinks fit *inter alia:—*

(a) require the Contractor to provide an estimate of the cost of the measures he is taking or is proposing to take;
(b) approve in writing such measures with or without modification;
(c) give written instructions as to how the physical conditions or artificial obstructions are to be dealt with;
(d) order a suspension under Clause 40 or a variation under Clause 51.

**Delay and Extra Cost.**

(3) To the extent that the Engineer shall decide that the whole or some part of the said physical conditions or artificial obstructions could not reasonably have been foreseen by an experienced contractor the Engineer shall take any delay suffered by the Contractor as a result of such conditions or obstructions into account in determining any extension of time to which the Contractor is entitled under Clause 44 and the Contractor shall subject to Clause 52(4) (notwithstanding that the Engineer may not have given any instructions or orders pursuant to sub-clause (2) of this Clause) be paid in accordance with Clause 60 such sum as represents the reasonable cost of carrying out any additional work done and additional Constructional Plant used which would not have been done or used had such conditions or obstructions or such part thereof as the case may be not been encountered together with a reasonable percentage addition thereto in respect of profit and the reasonable costs incurred by the Contractor by reason of any unavoidable delay or disruption of working suffered as a consequence of encountering the said conditions or obstructions or such part thereof.

**Conditions Reasonably Foreseeable.**

(4) If the Engineer shall decide that the physical conditions or artificial obstructions could in whole or in part have been reasonably foreseen by an experienced contractor he shall so inform the Contractor in writing as soon as he shall have reached that decision but the value of any variation previously ordered by him pursuant to sub-clause (2)(d) of this Clause shall be ascertained in accordance with Clause 52 and included in the Contract Price.

This clause is at the centre of the risk-sharing principle and hinges on the phrase "....which conditions or obstructions he (the Contractor)considers could not reasonably have been foreseen by an experienced contractor...". The ambiguity of these words is a major cause of disputes.

The fact that the condition might have been foreseen does not automatically discount the claim. The general consensus of opinion is that there is likely to be no claim if an "experienced" contractor could have foreseen a substantial risk in the condition.

It is often argued by contractors that a particular design showed that the Engineer did not expect particular physical conditions to eventuate. (A case in point was on NWA Contract 32 Tunnel Drive C4-C2 where the Contractor maintained that the tolerances specified in the Bill of Quantities indicated the Engineer did not expect to encounter the prevailing conditions of waterbearing sands, silts and gravels.) From a legal point of view, however, even if this situation was a failure on the part of the Engineer, (the author's opinion is that it was not a failure) it does exempt the Contractor from his full duties under Clause 11.

Often, enforced alterations to the working method disrupt the critical path (Clause 14) programme and the Contractor would be entitled under Clause 13 to claim for any costs due to the delay and disruption. In order that, in this situation, the Contractor is not placed in a position whereby he would have a claim against him for liquidated damages due to overrun of the contract period, Clause 44 can be invoked to enable him to receive an extension of time for the completion of work.

In addition to compensation for any alteration to contract work as specified under Clauses 12,13,51, the Contractor has the right to claim damages for breach of contract due to delay and disruption of his programme. Usually it is lost profits that the Contractor wishes to recoup; that is, the fact that his plant and labour are tied up in a contract for longer than originally envisaged reduces his ability to gain profit from alternative contracts during the overrun period. Although it is common practice for a Contractor to base his disruption claim on the difference between programmed and actual progress, it is necessary for him to prove what his actual progress would have been, had the cause of the delay not existed. Assessment of disruption is, therefore, very difficult, with the arbitrator left to judge the balance between fair recompense for the Contractor and losses due to his own inefficiencies.

So far, this section has dealt with the method whereby the Contractor may recover, under an admeasurement system, any additional costs caused by unforeseen conditions. However in the situation where there is insufficient information available about conditions to enable the Contractor realistically to price his risk, there are alternative types of contracts where the Client accepts a large share of the risk.

In the case of Target Cost contracts, an estimated value is assessed, which is altered to reflect any variations in work or escalation of costs. An accurate record of the Contractor's costs is kept and the difference between the actual and target cost is shared between the Contractor and Client in a pre-arranged manner. Often the overheads and profit are separated from the rest and paid on a fee basis.

If the Client is prepared to accept even more of the risk, he can have the work carried out under a Cost Reimbursible contract. The Contractor carries only minimal risk, as costs are paid out as the work is carried out, with the overheads and profits again paid out on a fee basis, usually calculated as a percentage of costs. It is essential in the case of Cost Reimbursible contracts that the Engineer and his staff keep tight control on site expenditure to ensure a satisfactory return on the Client's money.

# CHAPTER 6

# COMPARISON OF THEORY WITH EMPIRICAL RESULTS

# CHAPTER 6

## COMPARISON OF THEORY WITH EMPIRICAL RESULTS

The theory was developed along the lines of considering a contract as an amalgamation of four phases; exploration, determination, action and outcome. Of these phases the one that is of primary interest to the Engineer is the action phase, so initial consideration will be given to it.

The action phase can be considered analogous to the basic design decisions. Results from the research would indicate that the design choices for tunnelling can be split into three discrete categories:

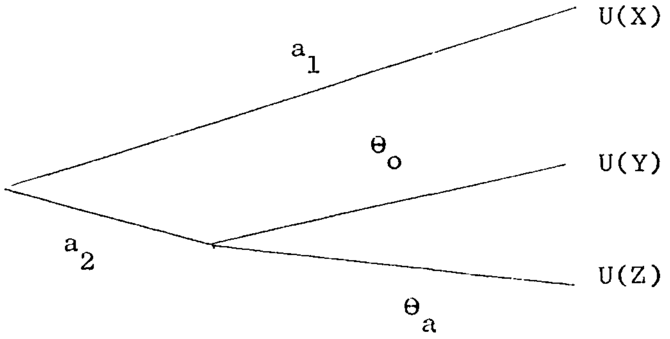
| | | |
|---|---|---|
| Excavation | A. | 1) Open-cut Excavation<br>2) Soft Ground tunnelling<br>3) Rock Tunnelling<br>4) Pipe Jacking |
| Primary Lining | B. | 1) Smooth Bore Tunnel<br>2) Bolted Segmental Rings<br>3) Colliery Arches<br>4) In-situ Construction/Pipes |
| Additional Measures | C. | 1) None<br>2) Compressed Air<br>3) Chemical/Cement Grouting<br>4) Others (eg. freezing) |

Thus a basic design choice for a contract could be listed as (A2, B3, C1). The choice in category A is usually enforced by physical parameters, length and/or depth, and its choice eliminates choice in categories B and C. Similarly, choice in category B restricts choice in category C.

Using Contract 32 (Section MHC4-MHC2), as an example, the ground conditions, length of contract and depth to (most) of the line made choice A2 the only alternative. In the case of primary lining, although (B1) would have been a possible alternative, the ground conditions over (most) of the contract made B2 the only viable solution. The only difficult decision came with whether or not to have additional measures.

The choice could further be reduced on economic grounds to whether or not to have compressed air. In this situation only two states of the world needed be considered (a) Compressed Air is needed ($\theta_a$), or (b) Compressed air is not needed ($\theta_o$).

This example could be illustrated by a part of a decision tree:



where U(X) is utility of the action ($a_1$) making provision for compressed air when it is not needed,
U(Y) is the utility of the action making no provision for compressed air when it is not needed,
and U(Z) is the utility of the action making no provision for compressed air when it is needed.

In order to proceed further, an understanding is required of utility and how the results can be used to create a physical representation. The theory indicated that if utility can be thought of in monetary terms, then the overall utility can be subdivided into the terminal utility and the utility of investigation.

Starting with basic assumptions concerning the site investigation, the theory has assumed the cost to be either independent or simply-related to the number of tests, which tests were in turn considered as discrete events with single outcomes. However, in practice there is a wide variety of tests ranging from seismic surveys to index tests and varying in complexity, cost and informational value.

In assessing the cost of site investigation, the method used in the research has been to formulate an average cost per borehole, which achieved the aim of creating a unit of information encompassing all tests. Comparison of the adjusted average cost per borehole to the average number of tests per borehole is shown in Figures 9 and 10 and would indicate that the simple relation holds reasonably well for four of the five contracts. The other contract, Contract 27, was a special case, with restrictions on the number and extent of boreholes.

Intuitively, it is to be expected that unless the high-cost of a particular borehole can be offset by a large amount of information from it, that is, an increased number of tests, then the value of undertaking that borehole should be questioned. This argument could be extended to the value of additional information on an individual borehole basis.

On the question of the representation of terminal utility, the problem is more complex. The first problem is whose terminal utility is being considered, or is there an absolute utility, which is a combination of both side's utility? The Engineer's, acting as an agent for the Client, is subject to professional obligations, regarding, for example, safety, as well as financial obligations, ensuring the quality of work at a reasonable price. A Contractor will be similarly motivated to maximise his profits without prejudicing his chances of future work. In order to assess his potential profits the Contractor must be able to estimate both the value of the work and the value of the work to him. These two valuations are not necessarily coincident, as the attractiveness of a contract is influenced by factors external to the work, such as utilisation of labour and plant, cash flow, and so on.

It would therefore appear reasonable to consider, for either side, the contract to be made up of a fixed cost plus a potential cost based on the inherent risk in the contract multiplied by the percentage of risk assumed by that side. This potential cost is realised in the form of claims.

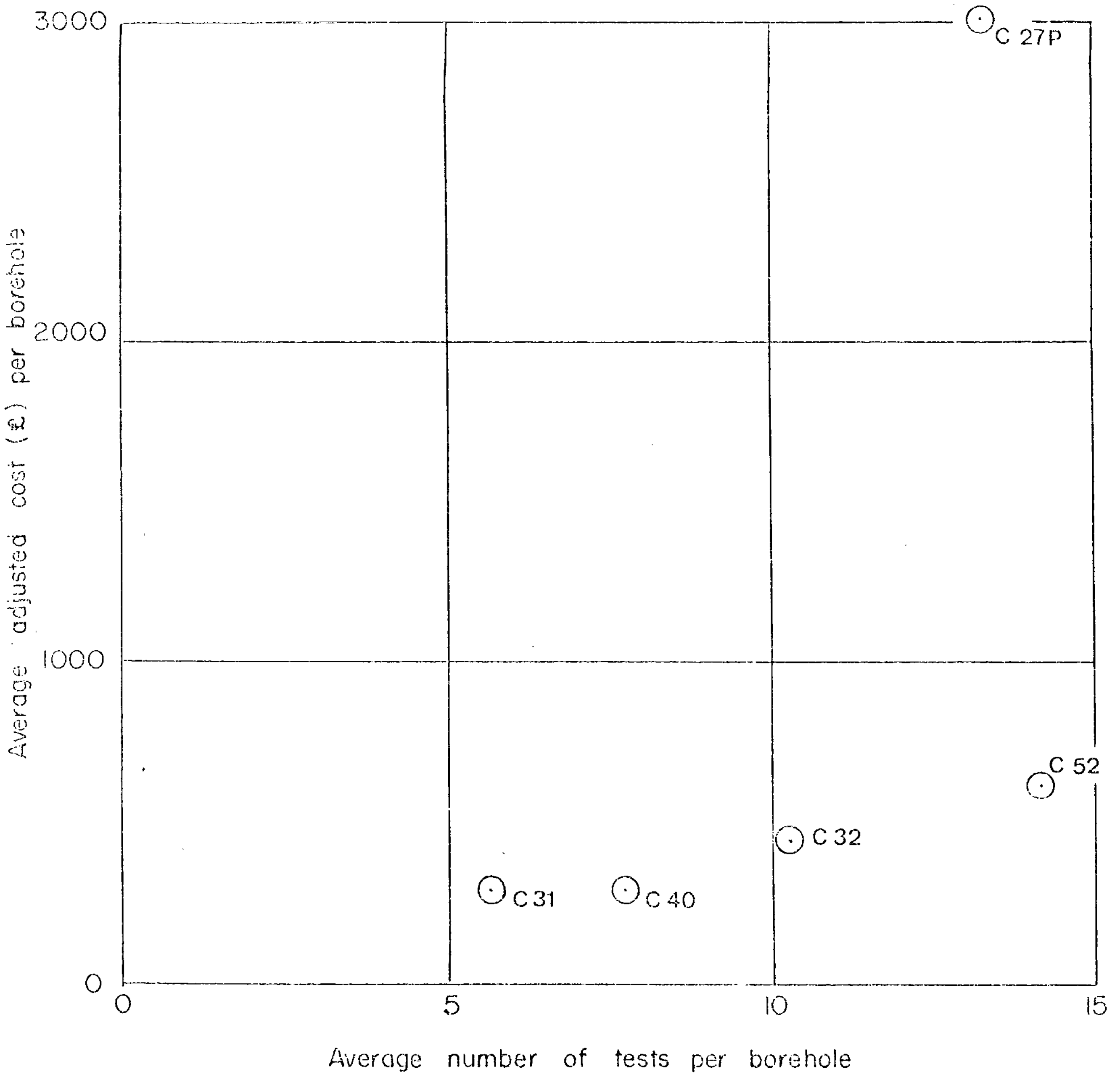


Fig. 9 EFFECT OF THE NUMBER OF TESTS ON BOREHOLE COSTS

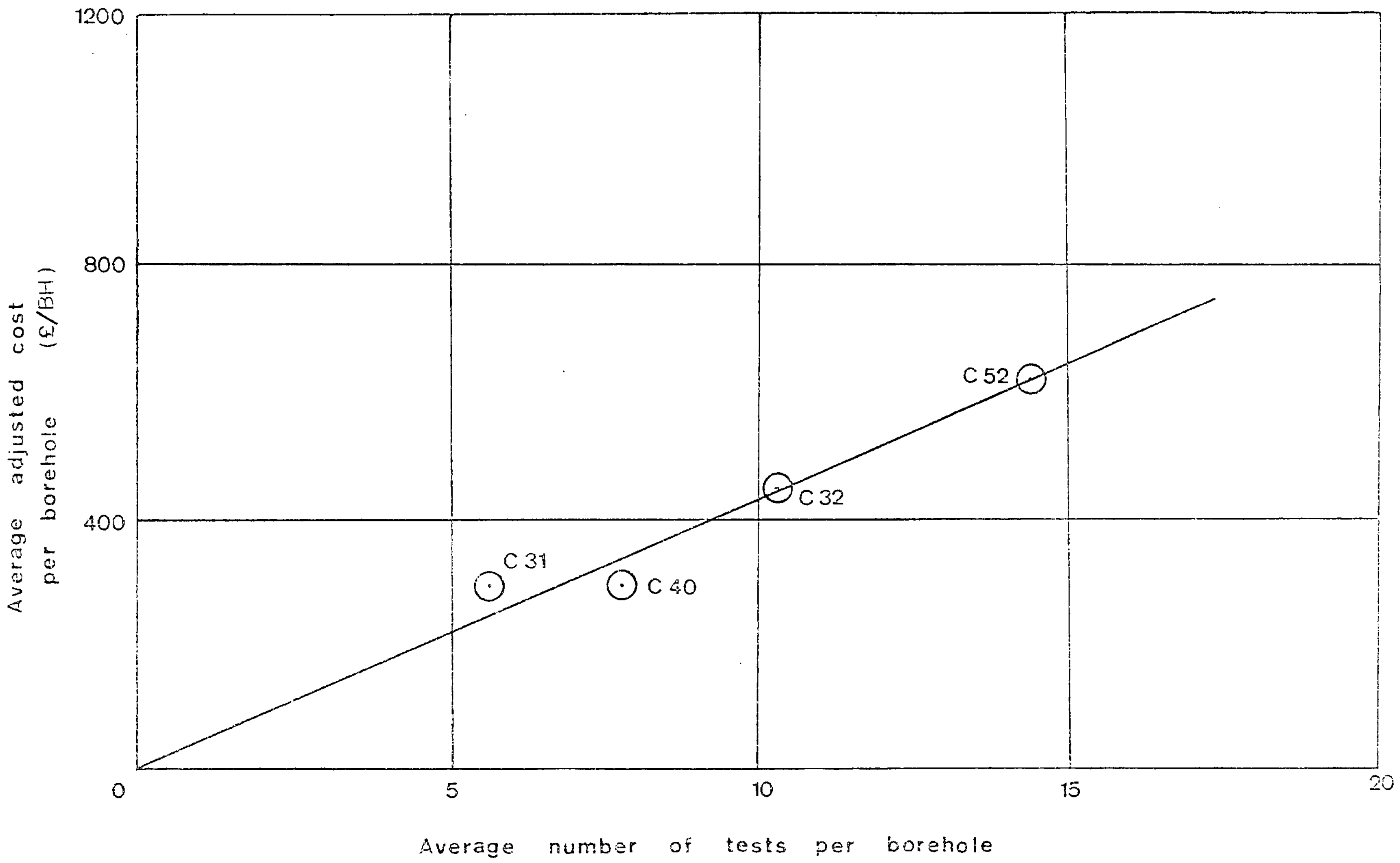


Fig. 10 EFFECT OF THE NUMBER OF TESTS ON BOREHOLE COSTS

It would be opportune at this point to show some supplementary evidence which supports the idea that Clause 12 claims can be used to derive a loss (negative of utility) function due to geotechnical uncertainty.

The initial reaction in this work was to assume that the 'low' winning tender could lead to high claims as the contractor tries to recoup lost "profit"; similarly a 'high' winning tender could lead to lower claims as the contractor might be willing to sacrifice some of his high profits for the 'goodwill' that a trouble-free contract generates.

In order to test these hypotheses an estimation of the variation in tendering was deduced by comparing the winning tender with the average of the second and third tenders (see Table 13). The second and third tenders were chosen since it was considered that they would be competitive, whereas higher tenders may not have been. A graph, Figure 11, has been drawn which directly compares the percentage by which the winning tender was below the average of the second and third tenders with the percentage that the final cost was greater than the tender price.

Two points arise from this graph. First there appears to be no correlation between a 'low' tender and the amount of overspending in claims, which reinforces the opinion that the client probably pays less than the true cost of a variation (THOMPSON and BARNES, 1977).

Given the assumption that a contractor's tender is made up of a fixed price plus an allowance for risk, it appears there may be a relation between the variation in risk pricing, expressed as the variation in tender price, and the maximum overrun of tender price that could be anticipated. Unfortunately there is little hard evidence to support this idea. However, if this form of graph were to be confirmed by

| NWA CONTRACT NUMBER | % WINNING TENDER BELOW AVERAGE OF SECOND AND THIRD TENDERS | % FINAL CONSTRUCTION COST (EXCLUDING PRICE VARIATION) ABOVE TENDER PRICE |
|---|---|---|
| 27 | 5.15 | +10.7 |
| 31 | 3.75 | -13.7 |
| 32 | 9.65 | +16.8 |
| 40 | 10.53 | -18.9 |
| 52 | 10.94 | - 5.3 |

TABLE 13 Variation of Tender Price and Construction Cost

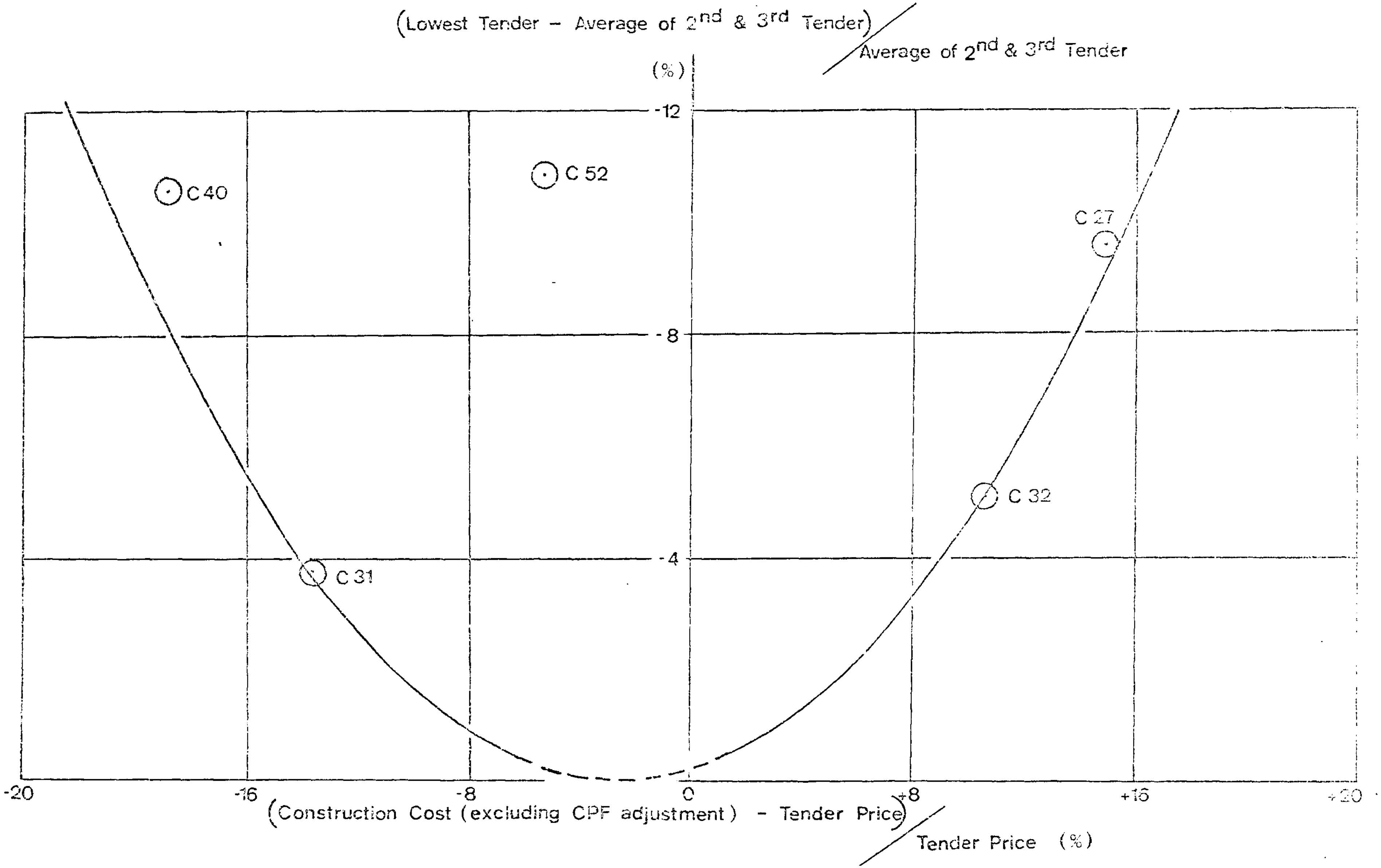


Fig.11 CONTRACTORS' ASSESSMENT OF RISK

other contracts in different branches of civil engineering, it would greatly ease the Client's problem of estimating the ultimate cost for loan sanction or cash flow analysis. Additional results are required prior to any firm conclusions regarding the use of a function to encompass the maximum tender overrun of construction cost. To demonstrate the idea of an all-embracing function a basic quadratic curve has been inserted to fit the existing results. An offset from the zero ordinate axis has been introduced to represent the idea of a natural conservatism on the part of the contractor to cover risks unpriced by the Client, for example, a shortfall in remuneration from the Contract Price Fluctuation Clause.

In all contracts studied in the research the final selection of contractor was arrived at by the competitive tendering of selected tenderers. To illustrate how the utility functions of Client/Engineer and Contractor interact, a cost-risk space could be created with Contractor and Client in opposite corners.

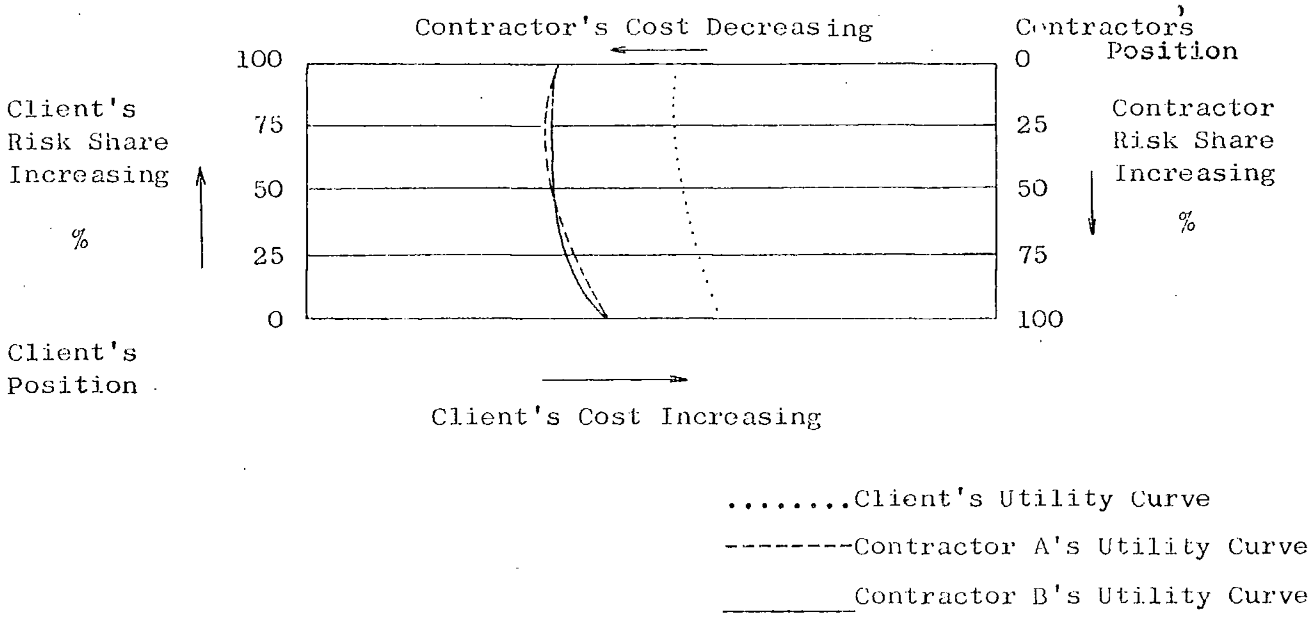


Figure 12 Cost Risk Space

Figure 12 shows the form that this cost-risk space could take. In a contractual sense the Client's risk could be thought of as extending from zero in a turnkey contract to 100% in a direct labour contract. The Client usually specifies (by implication) the level of risk he is prepared to accept by choosing the form of contract. The shape of the Contractor's utility curve shows his degree of risk aversion.

Two utility curves have been shown in Figure 12 for different contractors' tenders and it is clear that, if minimum tender price were the governing factor, at the 75% risk level to the Client, Contractor A's tender would be selected; similarly, at the 25% risk level to the Client, Contractor B's tender would be selected. If it were to be assumed that the Client was indifferent to his final location is cost-risk space, then his optimum position would be at a minimum distance from his graphical origin.

In the indicated case both the Contractor's utility curves are below the Client's utility curve, and hence represent an expected saving on what the Client is prepared to pay. It would be feasible to show a situation where none of the Contractor's tenders came up to the expectation of the Client in which case the terminal utility would have to be a compromise solution.

Having discussed the meaning and use of utility, it is now possible to proceed with the example shown in the decision tree where the example question was whether or not to provide for compressed air on section MH C4-C2 on Contract 32. The utility of the action making provision for compressed air when it is not needed would, in monetary terms, be the negative mobilisation cost for compressed air, since it is unlikely that compressed air would be used until ground conditions required it. This value can be termed (-C ). The utility of the action making no provision for compressed air when it is not needed would be nothing. The utility of the action making no provision for compressed air when it is needed would be slightly more complicated, but, as a simplication, consider it as the negative cost of undertaking the work with compressed air in the programme. In its turn this claim (CL) is likely to be proportional to the error in judgement ($\mathcal{E}$), $CL \propto \mathcal{E}$. The constant of proportionality ($f_c$) has been designated as the risk factor.

It is now possible to calculate the probability (P*) where the potential gain in not making for compressed air is equivalent to the risk of having to introduce it at a later stage and suffer a claim. From the decision tree,

$$U(X) = P^*U(Y) + (1-P^*)U(Z)$$

replacing with the monetary equivalents,

$$(-C) = P^*0 + (1-P^*)(-C-CL)$$

$$\text{or,} \quad P^* = \frac{CL}{C+CL}$$

$$= \frac{f_c\mathcal{E}}{C+f_c\mathcal{E}}$$

This expression would indicate that if the risk factor is high or, equally, if the error in judgement is large, the probability of conditions being better than those requiring compressed air would need to be 1, that is, a certainty.

The cost of mobilisation for compressed air can be assessed reasonably accurately, so in order to produce a numerical value for the probability, an estimation is required of the maximum error in judgement and the risk factor. One alternative for the risk factor would be to allow the Client to place a maximum value on the claims he was prepared to bear. For example, he might allow 10% of the total contract cost. An alternative would be to use the tentative information from Figure 11 to predict a value of maximum risk factor in terms of the construction cost. If the tenders are known, then the relative percentage of the claims can be read; for example, a tender divergence of 4% would give a maximum risk factor of 0.1.

Before discussing how to estimate the error in judgement it is necessary to understand what is meant by it. Error in judgement is the deviation of actual conditions from predicted conditions, where these conditions are linked to design decisions. Therefore, in order to create an estimation of error it is necessary to know which tests are used to influence decisions. Usually, tests are not considered in isolation, but are combined with different weightings to form a group. This group could be termed a design factor and there may be several design factors on a contract. Although this grouping is usually made subconsciously by the Engineer, the introduction of tunnelling cost programmes for computer (WHEBY, 1973) has seen the objective creation of design factors. In the case of soft ground tunnelling a stability number is used which combines the cohesion with the internal angle of friction.

The error in judgement can then be expressed as the deviation of the design factor, created from the actual conditions, from the design factor assessed from test results. If the assumption of the theory is accepted, that the probability distribution of conditions is normal, then it will be completely specified by the mean and variance of the test results, when combined as a design factor. Care would need to be taken to ensure that the variance from a small number of tests was not unrepresentative of the population variance. A way round this problem would be to place a minimum coefficient of variation on the results. This minimum value could be taken from a larger sample, for example from work detailed in HARR,1977, where several soil parameters are shown with their mean, variance and coefficient of variation (see Tables 14,15 and 16).

Without being specific, this section has tried to highlight conditions where empirical results gained from the research can be allied to theory in order to aid the Engineer in his decisions. The final sections will deal with areas of future possible developments and some of the assumptions made both in this section and the previous theory section.

| | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Material | Frictional angle, degrees | Tangent of frictional angle | Unconfined compression strength, ton/ft² | Number of samples | Mean | Standard deviation | Coefficient of variation, % | Source |
| Gravel | x | | | 38 | 36.22 | 2.16 | 6.0 | Private communication |
| Sand | x | | | 73 | 38.80 | 2.80 | 7.0 | from |
| Sand | x | | | 136 | 36.40 | 4.05 | 11.0 | Prof. R. D. Holtz |
| Sand | x | | | 30 | 40.52 | 4.56 | 11.0 | of Purdue University |
| Gravelly sand | x | | | 81 | 37.33 | 1.97 | 5.3 | Schultze (1972) |
| Sand | | x | | 81 | 0.762 | 0.056 | 7.3 | Schultze (1972) |
| Sand | | x | | 50 | 0.717 | 0.093 | 13.0 | Schultze (1975) |
| Sand, loose | x | | | | | | 14.0 | Singh (1972) |
| dense | x | | | | | | 12.6 | Singh (1972) |
| Silty sand | | x | | 82 | 0.692 | 0.096 | 13.8 | Lumb (1966) |
| Clay: depth, ft | | | | | | | | |
| 5 | | | x | 279 | 2.08 | 1.02 | 49.1 | Fredlund and Dahlman (1972) |
| 10 | | | x | 295 | 1.68 | 0.69 | 40.9 | Fredlund and Dahlman (1972) |
| 15 | | | x | 187 | 1.49 | 0.59 | 39.6 | Fredlund and Dahlman (1972) |
| 20 | | | x | 53 | 1.30 | 0.62 | 47.7 | Fredlund and Dahlman (1972) |
| Clay | | | x | 231 | 0.97 | 0.26 | 29.0 | Matsuo and Kuroda (1974) |
| Clay | | | x | 97 | | | 30.0-40.0 | Ladd, Moh, and Gifford (1972) |
| Clay shale† | | | x | | | | 37.0-51.0 | Lumb (1972) |
| till† | | | x | | | | 63.0-85.0 | Lumb (1972) |
| till | | | x | | 3.24 | 1.17 | 36.1 | Morse (1972) |

† Lumb notes these two materials are extremely variable and believes that these results are probably close to the upper possible limits of variability for any natural soils.

TABLE 14 : Strength Parameters (Harr, 1977)

| | Parameter | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | Void ratio | Porosity | Specific gravity of solids | Water content | Unit weight, lb/ft³ | Degree of saturation | Number of samples | Mean | Standard deviation | Coefficient of variation | Source |
| Gravelly sand | x | | | | | | 93 | 0.506 | 0.150 | 29.6 | Schultze (1972) |
| | | x | | | | | 93 | 0.330 | 0.062 | 18.6 | Schultze (1972) |
| Coarse sand | x | | | | | | 67 | 0.570 | 0.107 | 18.8 | Schultze (1972) |
| | | x | | | | | 67 | 0.399 | 0.039 | 9.8 | Schultze (1972) |
| Medium sand | x | | | | | | 38 | 0.686 | 0.128 | 17.5 | Schultze (1972) |
| | | x | | | | | 38 | 0.404 | 0.041 | 10.1 | Schultze (1972) |
| Fine sand | x | | | | | | 70 | 0.663 | 0.088 | 13.3 | Schultze (1972) |
| | | x | | | | | 70 | 0.390 | 0.032 | 8.0 | Schultze (1972) |
| Silt | x | | | | | | 327 | 0.631 | 0.136 | 21.6 | Schultze (1972) |
| | | x | | | | | 327 | 0.383 | 0.051 | 13.3 | Schultze (1972) |
| | | | x | | | | 329 | 2.563 | 0.029 | 1.1 | Schultze (1972) |
| | | | | x | | | 406 | 0.206 | 0.047 | 22.8 | Schultze (1972) |
| | | | | | | x | 334 | 0.845 | 0.162 | 19.2 | Schultze (1972) |
| Silty clay | x | | | | | | 57 | 2.33 | 0.46 | 20.0 | Padilla and Vanmarcke (1974) |
| | | | x | | | | 4 | 2.66 | 0.05 | 1.87 | Padilla and Vanmarcke (1974) |
| | | | | x | | | 790 | 0.84 | 0.19 | 22.0 | Padilla and Vanmarcke (1974) |
| Clay: depth, ft | | | | | | | | | | | |
| 5 | x | | | | | | 120 | 0.900 | 0.157 | 17.5 | Fredlund and Dahlman (1972) |
| 10 | x | | | | | | 96 | 0.911 | 0.138 | 15.1 | Fredlund and Dahlman (1972) |
| 15 | x | | | | | | 47 | 0.909 | 0.186 | 20.4 | Fredlund and Dahlman (1972) |
| 20 | x | | | | | | 21 | 0.749 | 0.236 | 31.6 | Fredlund and Dahlman (1972) |
| 4 | | | | x | | | 430 | 0.289 | 0.051 | 17.7 | Fredlund and Dahlman (1972) |
| 10 | | | | x | | | 415 | 0.328 | 0.039 | 11.9 | Fredlund and Dahlman (1972) |
| 16 | | | | x | | | 307 | 0.355 | 0.043 | 12.2 | Fredlund and Dahlman (1972) |
| 20 | | | | x | | | 177 | 0.348 | 0.046 | 13.2 | Fredlund and Dahlman (1972) |
| 5 | | | | | | x | 111 | 0.919 | 0.121 | 13.2 | Fredlund and Dahlman (1972) |
| 10 | | | | | | x | 90 | 0.956 | 0.086 | 9.0 | Fredlund and Dahlman (1972) |
| 15 | | | | | | x | 38 | 0.975 | 0.084 | 8.6 | Fredlund and Dahlman (1972) |
| 20 | | | | | | x | 18 | 0.933 | 0.080 | 8.5 | Fredlund and Dahlman (1972) |
| | | | | x | | | 29 | 0.217 | 0.028 | 12.9 | Schultze (1972) |
| High plasticity | | | x | | | | 65 | 2.63 | 0.115 | 4.4 | Hammitt (1966) |
| | | | | x | | | 98 | 0.206 | 0.027 | 13.1 | Hammitt (1966) |
| | | | | | x | | 97 | 113.3 | 2.8 | 2.5 | Hammitt (1966) |
| Medium plasticity | | | x | | | | 65 | 2.66 | 0.060 | 2.3 | Hammitt (1966) |
| | | | | x | | | 99 | 0.131 | 0.0082 | 6.3 | Hammitt (1966) |
| | | | | | x | | 99 | 115.8 | 14.2 | 12.3 | Hammitt (1966) |
| Low plasticity | | | x | | | | 65 | 2.69 | 0.054 | 2.0 | Hammitt (1966) |
| | | | | x | | | 97 | 0.138 | 0.0092 | 6.7 | Hammitt (1966) |
| | | | | | x | | 97 | 112.5 | 2.09 | 1.9 | Hammitt (1966) |

TABLE 15: Volumetric and Gravimetric Parameters (Harr, 1977)

| | Parameter | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Material | Compressibility factor† | Preconsolidation pressure, ton/ft$^2$ | Recompression ratio‡ | Compression index | Number of samples | Mean | Standard deviation | Coefficient of variation, % | Source |
| Silty clay | x | | | | 57 | 0.28 | 0.044 | 16.0 | Padilla and Vanmarcke (1974) |
| | | x | | | 28 | 0.35 | 0.066 | 19.0 | Padilla and Vanmarcke (1974) |
| | | | x | | 57 | 0.019 | 0.015 | 79.0 | Padilla and Vanmarcke (1974) |
| Sandy clay | | | | x | 66 | 0.139 | 0.0354 | 25.5 | Lumb (1966) |
| Clay: depth, ft | | | | | | | | | |
| 5.1 | | | | x | 108 | 0.184 | 0.047 | 25.7 | Fredlund and Dahlman (1972) |
| 10.0 | | | | x | 95 | 0.167 | 0.048 | 28.8 | Fredlund and Dahlman (1972) |
| 14.3 | | | | x | 40 | 0.159 | 0.048 | 30.1 | Fredlund and Dahlman (1972) |
| 22.1 | | | | x | 20 | 0.110 | 0.052 | 47.1 | Fredlund and Dahlman (1972) |
| 5.1 | | | x | | 108 | 0.0654 | 0.0167 | 25.8 | Fredlund and Dahlman (1972) |
| 10.0 | | | x | | 95 | 0.0648 | 0.0201 | 31.0 | Fredlund and Dahlman (1972) |
| 14.3 | | | x | | 40 | 0.0651 | 0.0341 | 52.4 | Fredlund and Dahlman (1972) |
| 22.1 | | | x | | 20 | 0.0321 | 0.0171 | 53.3 | Fredlund and Dahlman (1972) |
| Clay | | | | x | 241 | 0.33 | 0.17 | 52.0 | Corotis, Azzouz, and Krizek (1975) |
| | | | | x | 314 | 0.16 | 0.06 | 39.0 | Corotis, Azzouz, and Krizek (1975) |
| | | | | x | 165 | 0.09 | 0.04 | 47.0 | Corotis, Azzouz, and Krizek (1975) |

† Compressibility factor = $C_c/(1 + e_0)$, $C_c$ = compression index, $e_0$ = initial void ratio.

‡ Recompression ratio = $C_r/(1 + e_0)$, $C_r$ = slope of $e$ log $\sigma$ curve under recompression (Fig. 9-3*b*).

TABLE 16 : Compressibility Parameters (Harr, 1977)

# CHAPTER 7

# FUTURE DEVELOPMENTS

# CHAPTER 7

## FUTURE DEVELOPMENTS

At this stage it seems appropriate to discuss some of the areas of error, pointing out possible lines of research or alternative approaches to the problem.

Ideas have been introduced from a variety of theoretical approaches in an attempt to explain and, where possible, model in relatively simple terms the complex problems of tunnelling. In several cases there are attractive, if more complicated, alternatives to some of the assumptions previously made in the text. An example, which requires further discussion, is the assumption that ground conditions can be modelled using normal distribution functions. The inherent weaknesses of using the normal distribution function are that it is symmetric over its range and assumes that negative results are possible.

In site investigation, neither of these assumptions can be considered to be truly valid, so if a greater degree of accuracy is required an alternative function should be used, for example a beta function of the form,

$$f(x) = \frac{1}{C}(x-a)^{\alpha}(b-x)^{\beta}$$

where $$C = \frac{\alpha!\,\beta!\,(b-a)^{\alpha+\beta+1}}{\alpha+\beta+1}$$

and a and b are the end limits.

The beta function overcomes the problems of the normal distribution function in that it has a limited range between points (a) and (b) and also posseses skewness, which allows it to model results which are heavily biased to a specific region.

Several of the ideas, which lie outside the mainstream of the research, have only been briefly investigated and further research could bring fruitful results. An area, where this comment is particularly relevant, is in the introduction of the concept of a contractor - client cost/risk space.

A cost/risk space has been used in research (ASHLEY,1977) to model joint-venture civil engineering in the U.S.A. However, its applicability to competitive tendering has not, so far, been tested. Any attempt would require an in-depth knowledge of the contractor's approach to tendering as well as that of the client. Different contractor strategems would obviously lead to different contractor utilities.

The use of a cost/risk space allows visual representation of the relative positions of the client and contractor and how an alteration in either position affects the position of the other. As mentioned previously, if the client is indifferent to his position on the utility curve then it is probable that the ultimate contractual solution would be mutually beneficial. Unfortunately, in a body subject to public accountability the selection of a non-minimum tender would lead to heavy criticism, so a primary step would appear to be the education of all concerned, whether directly or indirectly, that the minimum tender does not necessarily lead to the minimum cost.

Assuming that acceptance of cost/risk space as a useful tool is forthcoming, the question remains as to how movements in cost/risk space can be translated into 'real' terms. Crude adjustment in cost/risk space could be achieved by altering the form of contract, for example, from admeasurement to target cost. However, a subtler form of adjustment is required if it is to have sufficient adaptability in an on-going negotiation. A rapid shift in cost/risk space could only be achieved by restructuring the contract to allow alterations to be included at both the pre-tender and post-tender stage.

# CHAPTER 8

# CONCLUSIONS

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The initial basis of the research was to investigate the cost effectiveness of site investigation in tunnels and the effect that this information had on overall cost. However, it was soon realised that the information could not be considered in isolation and the research was extended to include aspects of general civil engineering contract risk whether economic or political in origin.

The main achievement of the research has been to show that it is possible to visualise contracts as a series of decision and state variables. Appreciation of these various factors should facilitate better planning at the investigation stage. Further, in separating out the effects of the major state variable, ground conditions, as a series of cost percentages the research has illustrated quantitatively the sensitivity of contract cost to site investigation information.

There is a large potential for sensitivity analyses, not just in tunnelling, but in the whole civil engineering field, as an aid to increasing the Engineer's awareness. Any analyses should include all the key factors affecting cost. Work (ASHLEY, TSE and EINSTEIN, 1979) has already been started on this subject, where a ranking system was used to clarify further the main variables.

Concerning the cost-effectiveness of the site investigation of the tunnelling contracts, overall conclusions are difficult. The production of case histories allows specific problems to be highlighted, for example the need for slake-durability tests where tunnelling is expected to be in mudstones and shales. With the accumulation of data from a series of case studies it can be shown that the problems encountered on any tunnelling contract can be divided into two 'loose' categories. The first category of problems occur because the site investigation information is either insufficient or misleading, which increases the difficulty of choosing the optimum design decision at the tender/pre-construction stage. The second category concerns problems where there is sufficient information for the optimum choice but inadequate information to accurately predict the extent of the action. Thus slake-durability is an example of the first, whereas additional excavation would fall into the second category.

As errors in the second category are, by definition, unlikely to affect design-decisions, no large-scale alteration to working method would be expected. Where fundamental design-decisions are brought into question, the possibilities of cost escalation are increased dramatically as illustrated by the major claims on the tunnelling contracts studied.

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