THE ARUP JOURNAL

SUMMER 1988

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Contents

EDITOR'S NOTE:
This issue of The Arup Journal, *which departs from the usual format, describes some of the work being carried out by Arup Geotechnics worldwide. In many cases, this comprises the geotechnical component of projects for which structural, civil, building services and other types of engineering are being handled by different sections of Ove Arup Partnership.*

Front cover: Excavations at the British Library site, London (Photo: Harry Sowden)
Back cover: Hand-dug caisson at Embankment Place, London (Photo: Courtesy of *New Civil Engineer*)

Arup Geotechnics

Martyn Stroud

Introduction

Arups is about people and Arup Geotechnics is no exception. We are the bunch of people distributed throughout the Arup partnerships worldwide who specialize in worrying about the ground in all its engineering manifestations. Our enthusiasm for what lies beneath our feet and more particularly its interaction with the civil and building engineering structures around us is undaunted by mud, dust or extremes of climate. We revel in the challenge of trying to stop the march of sand dunes threatening to engulf the trans-Saudi Arabian Highway, or thawing permafrost triggering landslips in glaciated valleys in Alaska. Our concern is as much awakened by domestic houses in London slowly cracking due to the desiccation of clay subsoil by trees, as by the likely effect of earthquake activity on a new development in New Zealand built on lava flows and volcanic ash only 60,000 years old. We are just as excited about assisting contractors to tender for industrial plant situated on soluble gypsum rock in the Urals where the landscape is graded according to how many swallow holes emerge at the surface per annum, as designing landfalls for offshore pipelines through cliffs eroding at rates of 2m per year. We have sane and experienced people eagerly queueing for the privilege of standing on offshore rigs to supervise site investigations in anything the North Sea can throw at them. There are others who take wild delight in the contents of medieval cesspits, and modernists who are expert in weighing the risks of earthmoving Victorian refuse spiced by yet more recent industrial effluent.

Looking and seeing is arguably our most important facility. We have people who can see like eagles and are skilled in the interpretation of the ground from aerial photographs and satellite images. We have others with worm's eye views, burrowing deep into flooded strata, who, with the help of sonic beams, can see and record the shape of underground caverns made by man or the passage of water.

Seeing is nothing without an ability to communicate our understanding. We have many who at the drop of a geological hammer will willingly type geotechnical reports into the early hours of the morning to meet impossible deadlines. Yet more will transform our thoughts into clear graphic images which illustrate these reports.

Over the years the number of people exercising these strange subterranean passions has increased markedly. Arup Geotechnics now totals some 210 individuals in all. Of these about 90 are based in London, a further 60 or so in the UK Regions and Scotland, and a further 60 located in the offices of the firm's worldwide practices. Each local group over the years has built up considerable experience of the geology and ground conditions of their particular region and of the means by which geotechnical problems can readily be solved there. Each contributes its part to the total design service provided by Arups from these centres. Each also undertakes specific geotechnical commissions for an increasingly wide range of clients, including contractors, international petrochemical and industrial organizations, developers, financial houses, solicitors, loss adjusters, research bodies and local authorities.

A particular characteristic of the people who are Arup Geotechnics is their ability to talk to each other, across barriers of business structure, geography and time. Thus the current and past experience of the whole group is constantly being tapped and built on by individuals wherever they are, around the world. This corporate experience and the facility to mobilize it is a real strength. So is the enthusiasm of all our people. We hope that some of that enthusiasm and fascination with the mysteries of the underworld emerges in the following pages, where individuals talk in their own way of the interests and problems that currently concern them, from each corner of the world.

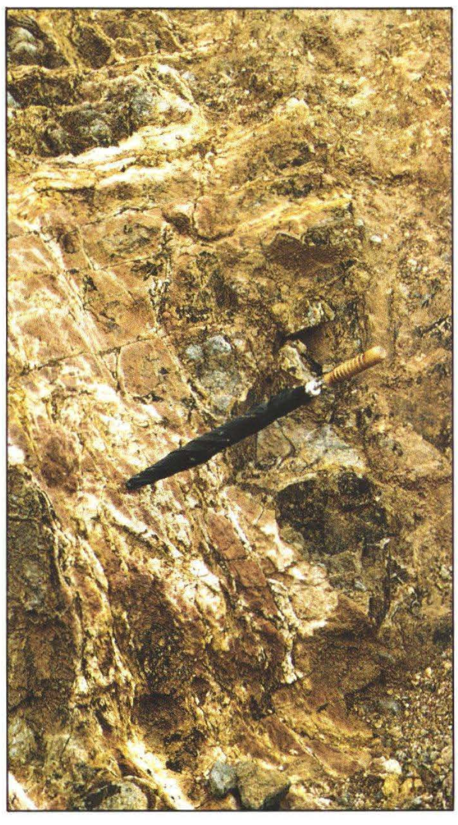


Photo: Martyn Stroud

Risk, responsibility and getting it right

Many could be forgiven for believing that the essence of geotechnical engineering is site investigation or the design and construction of foundations, retaining walls, embankment dams or cutting slopes. It is, of course, all of these. But it is more, just as architecture is more than the design of buildings. The architectural process begins with people, their needs, aspirations and diversity. Spaces are defined and enclosed, using both methods tried and tested over centuries and methods innovative and more daring. The risks are great. People resist precise definition and encapsulation; their needs and aspirations vary from individual to individual and from one group to another. There is no perfect solution, only some more right than others.

The risk of failure is highest when the human condition is not well understood or when the methods and materials of implementation are insensitively or thoughtlessly applied. The architectural creative process requires insight based on experience, energy and commitment to the created object throughout the whole process.

Geotechnical engineering too is a creative process. Soil, rock and water are almost as difficult to be precise about as people. Sampling and testing can be quite as misleading and we rely on our experience of previous encounters to guide judgement. But even for the most experienced and even with the best site investigation the process is beset with uncertainty. The essence of geotechnical engineering is the ability to engineer that uncertainty. This involves not only understanding the ground conditions thoroughly and coming to a view on the most probable conditions existing prior to or during construction, but also identifying the worst credible conditions that might exist and facing up to how these might be dealt with in the unlikely event that they materialize.

Some might give rise to minor complications which can be accommodated easily in the existing programme for the works. Others might imply long delays or substantially increased costs. For these it is vital that the design team and the client face the decision as to whether these consequences are acceptable, as early as possible. If they are not acceptable, an alternative basis for the design needs to be found to avoid the risk altogether. In short, an important part of getting it right is worrying about how it could go wrong.

Geotechnical engineering is above all about assessing the risks and developing a strategy for action. We have to do our best to anticipate the unexpected. This implies a questioning, critical approach at all times, with no room for complacency or arrogance. In formulating our designs we have continually to ask ourselves 'What if . . . ?' Plan B has to be evaluated before Plan A is embarked upon. Not only is this very important at the early stages of a project but in fact should be a continuous process throughout design and construction until the work is satisfactorily completed.

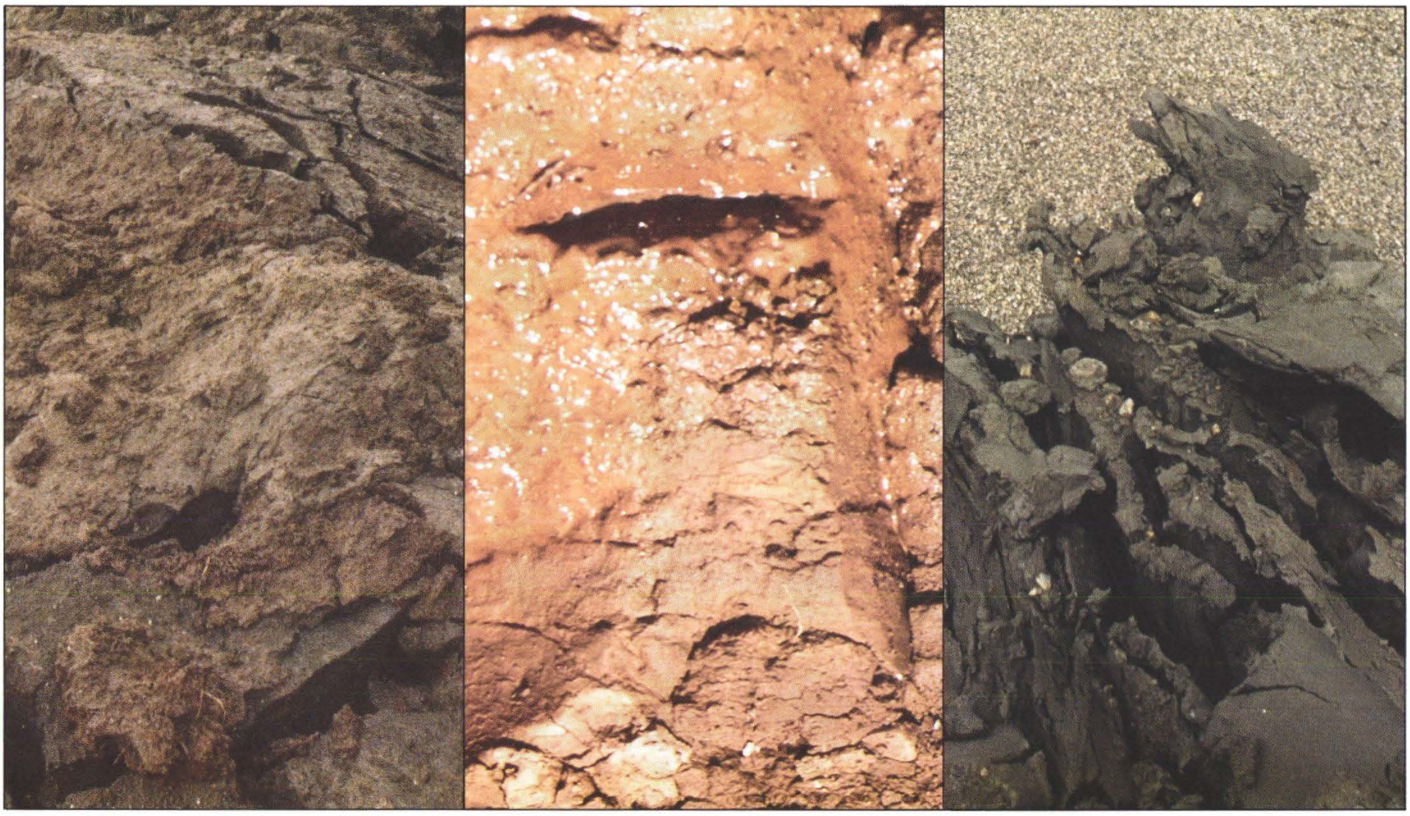
Two examples illustrate how easily things can go wrong.

A supermarket was to be constructed at a location approximately 80km from the centre of London on the edge of the London Clay basin. The site investigation correctly identified London Clay, but unusually, the borehole records showed that casing was necessary to considerable depths in every hole in an attempt to seal off water flows. In most holes it was not possible to do so. This information was not spotted by the engineer who, from experience in central London, specified large diameter underreamed piles. It subsequently proved impossible to construct the underreams because of water ingress and collapsing ground. At this point the engineer panicked. The piling contract was determined and a new contract was let to a different contractor for driven piles. After a substantial number of piles had been driven this contract was stopped by the local authority because of noise and vibration affecting neighbouring properties. Straight shafted bored piles fully cased to their base were then embarked upon. These were successfully installed. A substantial claim against the engineer was made by the client because of additional cost and programme delays.

From the site investigation data there was no certainty that water was going to be a problem, but had the possible risk been identified at the outset, checks and tests could have been devised, with alternative courses of action pre-planned and ready for implementation if the worst fears were realized.

Even where the geology is correctly identified and the design established, it is vital to be vigilant throughout construction because conditions may change in quite a subtle way. In one such case the unexpected absence of water became a major problem. An office block in Leeds required piled foundations and rock socket piles were designed to be founded in the Coal Measures mudstones and siltstones. The design and construction methods were confirmed by means of a trial pile. The rock socket bore was noted to be wet during construction and the pile performed extremely well up to three times design load. In due course the contract piles were installed and in order to check their performance, two contract pile tests were carried out. Both piles failed. One failed to reach even half the design load. Subsequent investigation demonstrated that in these piles a skin of mudstone paste up to 50mm thick lined the shaft and base of the rock socket. The contractor's method for the construction of the contract piles was the same as for the trial pile, but under the greater part of the site the water seeping into the bore during augering was not as great as it had been at the trial pile position. The quantity of water was evidently sufficient to work the mudstone spoil into a paste but insufficient to wash it from the walls. Thus when the cleaning bucket was applied, the paste became smoothly plastered around the bore and was not easily detected by inspection from the surface. In this case the solution was to re-pile, taking care to add water to the shaft to ensure adequate washing and cleaning action as the bucket was applied. The cost implications of re-piling were clearly substantial.

Thus, even where the design has been established and checked by trials, etc., it is important that vigilance be maintained. Monitoring and careful observation during construction are essential features of the geotechnical process to confirm that the assumptions inherent in the design remain appropriate to the conditions actually met in practice. For maximum effectiveness the process of understanding the ground, developing a design, observing the implemen-



tation of that design and demonstrating on the basis of reasonable engineering evidence that the work has been satisfactorily completed, is all one continuous process, requiring one coherent strategy. We subdivide this process at our peril.

With increasing pressures of time, commercial competition during tendering and mounting concern over litigation, there is an unfortunate tendency in the industry these days to split the geotechnical process into discrete packages. One party for example may be responsible for the site investigation, including its interpretation. The structural engineer or architect will be responsible for the choice of foundation type and its performance specification. A third party again may be held responsible for the design and construction of the geotechnical elements, for example the CFA piles or the vibro replacement, usually a specialist contractor. Yet another may be responsible for supervision and quality control.

Such an arrangement can be disastrous unless one party takes responsibility for the overall geotechnical design strategy and worries it through from inception to successful conclusion.

The following example illustrates the point:

An industrial estate was to be constructed on an area of derelict railway land in the south of England. The site investigation correctly identified the ground conditions as being loosely tipped chalk fill placed at the time of original railway construction. The site investigation report concluded that it would be dangerous to build on the chalk fill as it stood, and recommended vibro replacement as a possible means of densifying it. The engineer had used vibro before in other circumstances and felt that it was a cheap and attractive option. The vibro replacement contractor designed a layout of stone columns which were subsequently installed with a guarantee that they would perform.

Heavy rain fell in the autumn months following installation of the stone columns at a time when roughly half of the industrial units were nearing completion. Following the rainfall a number of the units settled by as much as 100mm over a period of only a few days. As a result, many of the units had to be demolished and rebuilt on piled foundations. The delay and additional costs were considerable and litigation ensued. Subsequent investigation demonstrated that the settlement was due to a number of factors, but amongst them was the fact that the vibro stone columns had caused very little densification of the chalk fill at all. Water penetration into the body of the loose chalk fill had caused collapse settlement with consequent removal of support to the stone columns which then also settled. It was significant that the site investigation specialist had recommended vibro but made no assessment of its appropriateness or its chances of success. The specialist foundation contractor offered vibro replacement and guaranteed it, although it transpired he had never attempted it before in chalk fill. The engineer relied on these specialists and did not question the feasibility of using vibro replacement in the chalk fill. No trials were carried out prior to installation and no tests were carried out after installation. It was assumed the technique would work and that it had worked.

Chalk fill appears at first sight to be a granular material for which vibro replacement is generally a very effective solution. But in fact the microscopic structure of chalk is such that when the calcareous skeleton is crushed, water is released which causes the broken structure to slurry into a paste. In this case the insertion of the vibro poker into the chalk fill caused local crushing and slurrying of the chalk in such a way that the poker was surrounded by a blanket of chalk paste. The vibrational energy of poker was then rapidly dissipated and could not be effective in densifying the body of the chalk fill mass.

In this case a desire to limit the responsibility taken on board by each of the three parties involved, led to a totally unchallenged design concept. Each had the ability to criticize it, but no one did. However we arrange our contractual inter-relationships we should not be so preoccupied with them that the real point is missed. It is more important to minimize the risks than to distribute them. It is more important to get the engineering right than to prescribe our responsibilities so severely that we fail to communicate.

Getting it right requires the skills, experience and commitment from all those involved: from client, the design team, site investigation contractor, and foundation specialist contractor. Effective interactive communication is therefore vital. Effective communication at best involves overlapping thinking and is the antidote of underlapping thinking where whole areas of risk can remain unidentified.

Getting it right requires a critical and questioning approach throughout. It requires careful observation and feedback to confirm that the process is on course. This takes time and of course some money. But a little more money spent during a project, particularly in the early stages, is likely to save much more later.

Ove once defined 'design' simply and concisely as 'constructive forethought'. Nowhere is this more true than in the ground. Constructive forethought implies creativity and the concept of thinking things through, of anticipating what can go wrong. We can do much to forewarn ourselves by worrying things out in this manner and we can do much to forearm ourselves by developing a corresponding strategy, reviewed regularly in the light of observation of the works as they proceed.

In this way we have a chance of getting it right, at least some of the time.

May constructive forethought go with us all!

Influence of geotechnics on design

Philip Dauncey

This article is based on a paper presented at the Arup Partnerships' Seminar on Design, held at Ashford Castle, County Mayo, Ireland in March 1988.

Introduction

The designer aims to create a building or structure that is attractive, functions effectively and exists comfortably within its environment. In the development of a design there is often a great deal of thought and debate as to how the structure relates to the above-ground environment. However it is sometimes forgotten that the environment extends below ground level where every site is different with a unique combination of ground and groundwater conditions. It is equally important that the design is in sympathy with the below-ground environment.

Clearly the ground and groundwater conditions always directly influence the design of those parts of the structure below ground — influencing the form of foundations, basements, retaining walls, tunnels and earthworks. However, there are occasions when the ground and groundwater conditions influence the design of the structure above ground, affecting the location, layout or structural form.

Historically, the expected ground conditions have undoubtedly influenced the design of buildings and the sites that have been chosen for them. Peter Rice[1], for example, attributes the squatter and heavier style of the English Gothic cathedrals compared to those in France to the poorer ground on which the English cathedrals were often built. The alluvial soils underlying many of them required a more massive structure to distribute the stresses resulting from settlement, giving rise to the difference in style.

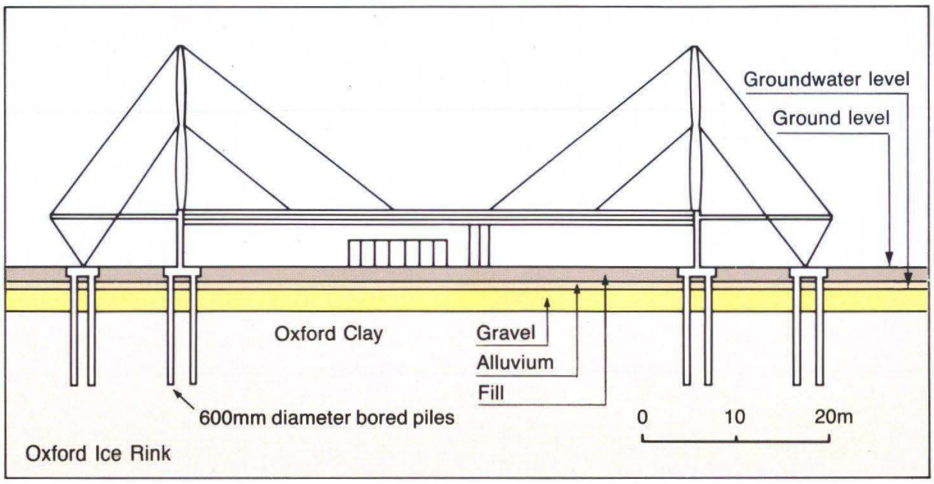
In this paper six Arup projects illustrate some of the many ways that ground conditions can influence design above ground.

Oxford Ice Rink

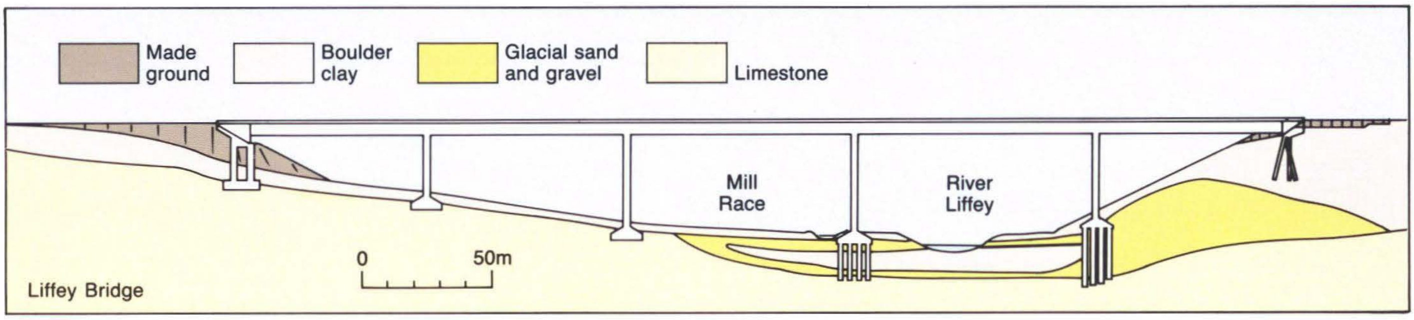
The ground conditions at this site were a contributory factor to the selection of a lightweight cable-stayed structure in preference to a more conventional building.

The site is underlain by about 2m of fill overlying 1m of soft alluvial clay. Beneath the alluvial clay is 2 to 3m of dense gravel and then stiff Oxford Clay. The groundwater level is about 2.3m below ground level and near to the top of the alluvium. The high groundwater level meant that construction of spread foundations on the gravel would necessitate dewatering, and the overlying deposits have a low bearing capacity.

With these ground conditions it was apparent that there would be advantages in concentrating the major loads onto relatively few piled foundations. This was one of the factors in choosing a cable-stayed structure with just two masts, each supported on four compression piles, and two main anchorages, each restrained by four tension piles.



Oxford Ice Rink



Liffey Bridge, Ireland

This bridge crosses the steep-sided valley of the River Liffey to the west of Dublin in an area of outstanding natural beauty.

At the location of the crossing, limestone bedrock is overlain by variable glacial deposits up to about 40m thick, necessitating the use of piled foundations for the piers on either side of the river. A study of the costs of deck structure and piers and foundations showed that, due to the relatively expensive foundations, the most economic span for this bridge was 80 to 90m. An arrangement of spans of approximately this length was therefore chosen to produce an aesthetically pleasing structure with minimum intrusion into the valley.

Stockley Park

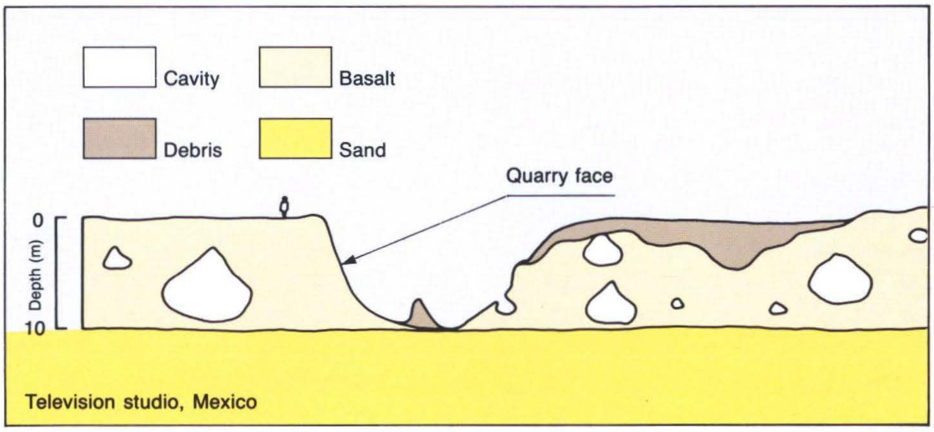
In this project a valuable site for commercial development and attractive parkland is being created from derelict land. The whole scheme has been greatly influenced by the original ground conditions and those which are required by the new land use.

The site was first exploited in the mid 19th century for brickmaking which involved stripping the near-surface deposits of clay. Subsequently, the underlying gravel was also worked to provide aggregates and, more recently, domestic and industrial refuse (landfill) was tipped into the old gravel workings leaving a derelict and contaminated site. The landfill was not only an unsuitable material on which to found, but contained toxic and decomposing organic material and was generating methane.

The scheme adopted for development was to transport the landfill to the northern part of the site and landscape this area to provide parkland for sports and recreation. The remaining unworked gravel was reclaimed to construct building platforms suitable for three storey buildings with pad foundations in the southern part of the site. These are surrounded by clay bunds to prevent infiltration of contaminated groundwater or methane from the adjoining landfill.

An important objective of the scheme was to minimize the import and export of materials to and from the site and to make the most effective use possible of the available materials. The ground conditions influenced the layout and form of the scheme and were fundamental to the feasibility, planning approvals and economic viability.


Stockley Park



Television Studio, Mexico

A difficult site, where ground conditions eventually led to the proposed development being re-sited elsewhere, was being explored for a prestigious new television studio complex in Mexico City. The site lies on a lava flow from a volcanic eruption about 2400 years ago, the lava having solidified to basalt rock.

The north east part of the site is an abandoned quarry, made into the basalt, and partly backfilled with demolition debris and rubbish; the remainder of the site is underlain by the full thickness of basalt. Although this is very strong it contains a large number of voids varying in size from a few centimetres across to large onion-shaped caverns up to 30m across. The origin of the caverns is not fully understood but is thought to be associated with steam generated as the lava, at an estimated temperature of 1000 to 2000°C, flowed across the underlying saturated alluvial deposits.

Many caverns were not visible from the surface and extensive probing would have been required prior to forming any foundation. At this site neither the option of stabilizing the basalt by grouting to allow pad foundations to be used, nor breaking through it (probably requiring blasting) to allow piles to be formed in the underlying dense sand deposits, was economically attractive.

Rangoon Hospital, Burma

The site for this new hospital is underlain by loose to medium dense clayey fine sand extending to a depth of at least 90m with groundwater level at a depth of about 6m.

The proposed hospital building consists of blocks ranging from one to four storeys in height, and pad, strip or raft foundations with an allowable bearing pressure of 100kPa would normally be suitable. However from a consideration of the seismicity of the area, the relative density and grading of the sand and the groundwater level, it was found that the sands were susceptible to liquefaction.

In order to avoid shear failure of the ground and associated excessive settlement during an earthquake if was necessary to reduce the net foundation loading. This was achieved by introducing a basement which substantially altered the form of the structure originally conceived.

Pan Pacific Hotel, Kuala Lumpur

This is a classic example where unusual and difficult ground conditions had a major influence on the design of the building. The project is discussed further in the report from Malaysia by Julian Wallace later in this *Journal*. In this case the layout of a multi-storey building had to be completely re-orientated because a 60m high buried limestone cliff was encountered during the site investigation running across the site.

Conclusion

Ground conditions always directly influence the form of a structure below ground level. Whilst this influence is generally not apparent in the completed structure, geotechnical factors can significantly influence the location, layout or form of a development above ground. In order to ensure that the best possible design solution for each project is developed it is important that the below-ground environment is understood as well as possible early in the design process.

Reference

(1) RICE, P. Soaring aspirations. *Royal Academy Magazine*. pp.29-30.Winter 1987.

London

Alain Marcetteau

In 1987, the name Arup Geotechnics was officially launched to give the geotechnical activity in Arups clear identity. This coincided with a dramatic growth in workload and staffing, in particular in our London Office where we now have about 80 technical staff compared with around 55 in 1986.

Arup Geotechnics London is now divided into seven sub-groups with about seven to 12 engineers per group. Each has a leader responsible for the day-to-day management, distribution of work and checking.

The structure of the geotechnical group in London has been developed and refined over the years to ensure that we deal with any new project with maximum speed and flexibility. We are now working on four new projects every day and up to 1000 new jobs last year.

Parallel with the sub-group structure, we have a systematic day-to-day checking system and specific design reviews at various stages of each project. These are aimed at increasing interaction and mobilizing pertinent experience throughout the group.

Our structure in Geotechnics is geared to encourage the development of personal talents in particular areas of interest. Ken Cole is our consultant on mining and subsidence problems, with Andrew Lord pursuing actively the redevelopment of derelict and contaminated land. Jack Pappin is now our specialist dealing with soil dynamics and dynamic soil structure interaction and recently Chris Humpheson took over the brief to co-ordinate our design approach to reinforced earth.

A lot of innovative work has been done by Arup Geotechnics this past year, in particular for a number of large caissons now being hand-dug in London Clay. We recently used base-grouted bored piles for the first time in the UK, for the new developments in East London such as South Quay Plaza and Blackwall Yard.

Much of the past two years has been dominated by major and exciting redevelopment in the City and in London's docklands. In future we would like to broaden our base of work overseas and see the Europe of 1992 as a particular challenge.

Royal Mint

Alain Marcetteau

We are presently redeveloping the site of the Old Mint in Cartwright Street in the City of London. The development comprises two office blocks with a maximum of seven suspended floors terracing down to four floors adjacent to a central courtyard.

The archaeological importance of the site together with the previous industrial use of the area transformed what could have been 'a standard' bored pile job into a challenging project.

Prior to 1350 the area was a Black Death cemetery. In 1350 Edward III established the Abbey of St Mary Graces on the site, which grew in size and prosperity until the Dissolution of the Monasteries in 1538. The Abbey buildings were demolished and the site occupied by the naval victualling yards until work began on the Royal Mint in the late 18th century.

Extensive studies of historical records, in particular those at the Public Records Office at Kew, revealed the presence of a number of tunnels and wells on the site. The wells were used to supply the Royal Mint steam engines with water. Water was originally collected from the Tower of London Ditch and distributed to the various wells by an extensive network of underground tunnels. The stagnant water in the Ditch caused, however, a spread of disease amongst the troops billeted in the Tower, and the Duke of Wellington ordered the partial filling of the Ditch. Consequently a deep artesian well was bored into the chalk to provide a supply of water to the Mint.

Prior to starting the piling work on site, an investigation of the wells and tunnels was carried out. The investigation was really made possible following the discovery of a survey report prepared in 1842 by a Mr Clarke of Tottenham, London, together with a plan of the Mint basement and drainage system.

The exploration work on the wells and tunnels was carried out by GKN Colcrete under our supervision. We had to share the site with up to 100 archaeologists who exhumed over 1000 skeletons while we were locating the wells. Work from the surface was very restricted with a number of areas not accessible to us until the end of the archaeological survey. The drainage plan and Mr Clarke's report proved very accurate. We located the central distribution well (well 1 on the plan) at an early stage.

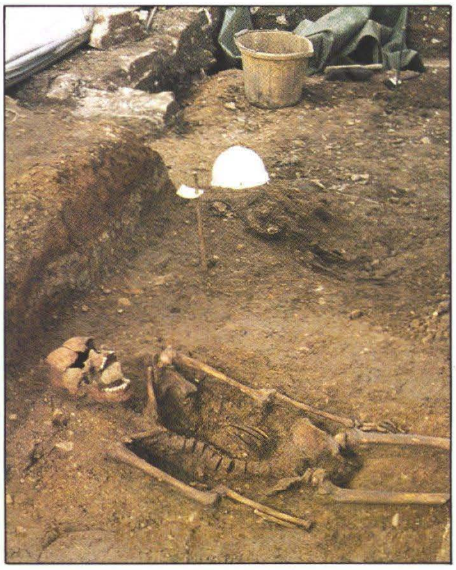
A Rovmarine mini-submarine controlled from the surface via an umbilical cord was lowered in wells 1 to 4. This submarine is about 750mm long and 450mm wide and is equipped with a low-light capability closed-circuit colour TV. The network of tunnels, however, was not discovered due to a 2m thick layer of mud and oil. This sludge was excavated using a special grab, which required the installation on site of a system of settling tanks to separate the oil, the mud and the water. As water was still flowing from the tunnel leading to the Tower of London, a grout plug was installed in the tunnel.

Well 1 was dewatered and an inspection by descent was made. At a depth of 15m, as recorded by Mr Clarke, we found four Gothic style brick-lined tunnels. They were partially blocked with sediment but, worst of all, the tunnels were curved so preventing any survey with a theodolite. We attempted to ascertain their alignment by using a small radio transmitter in a plastic sonde pushed in the tunnel with semi-flexible drain rods. The apparatus, however, was working at its maximum depth and the old massive foundations above tended to deflect the signal.

Dyno-Rod were called in to clean the tunnel with high pressure water jets. A Seer TV self-propelled survey tractor set off along the tunnels. This at last was successful, sending back clear colour TV pictures; the video tapes were used to map accurately the tunnels radiating from well 1 (drilling from the surface was not authorized) and finally well 1 was concreted. The other tunnels were located and grouted up from the surface using a rotary drilling machine and the remaining wells were concreted up, apart from the already-backfilled deep artesian well which was proved and grouted up in situ.

The 500 or so bored piles on this site revealed another old tunnel, which was located and grouted up from the surface at the beginning of March 1988. The piling work was successfully completed one week later.

1△ 2▽



1. Archaeological excavation
2. Skeleton from Black Death cemetery
3. View of the tunnel system

3 ▷

Earthquake engineering and soil dynamics

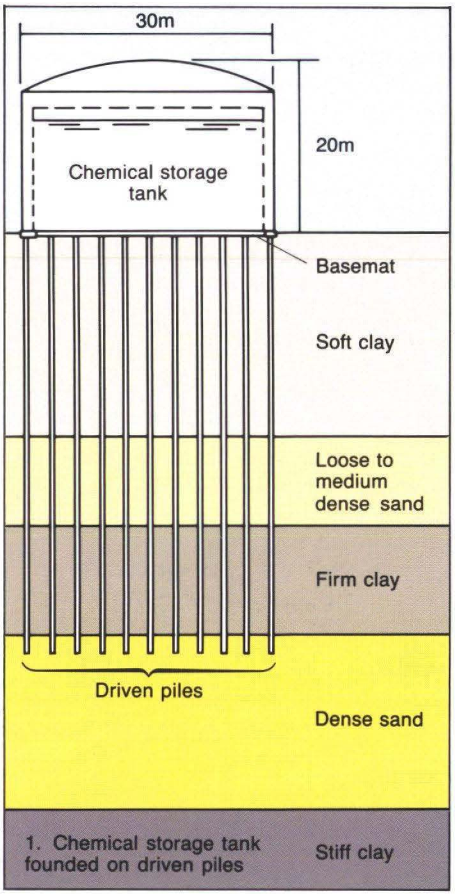
Jack Pappin

At present earthquake engineering and soil dynamics forms only a small part of the geotechnical workload, but it is an area that is steadily expanding. A recent project that illustrates our involvement has been the earthquake assessment of some hazardous chemical storage tanks in the UK. Fig. 1 shows a typical section through a tank, its piled foundation and the geological succession which consists of interbedded normally-consolidated clays and sand and gravels. Even without earthquake loading this site is a challenge to the foundation designer, given the large dead loads of the tanks and negative skin friction effects on the piles.

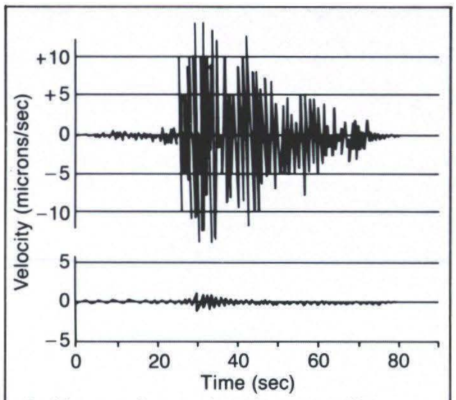
The geotechnical input into the earthquake assessment can be broadly classified into three parts:

(1) Site response study
(2) Dynamic soil/structure interaction
(3) Foundation design.

The site response study is necessary to investigate the likely earthquake motion in the absence of the tanks. It is well-known that deep soft sites of this type can lead to large amplifications of earthquake motions, especially at low frequencies. The 1985 Mexico earthquakes were an extreme example of this effect. The initial part of the study was carried out by a seismologist and entailed deriving typical underlying base rock motions. A computer model was then used to calculate how the ground would modify the motion, assuming the site to be a one-dimensional system with the earthquake motion being transmitted upwards from the base rock as a vertically propagating shear wave. Significant amplification was predicted at frequencies between ½ and 1Hz. To check the mathematical simulations, instruments were installed at the site to measure ground vibration. These instruments were in position for six months; during this time they measured motions from six earthquakes ranging from a magnitude 2.5 about 20 miles from the site, to a magnitude 8 on the opposite side of the planet in the Pacific basin. Fig. 2 shows a horizontal velocity-time history measured at the site compared with one measured at a rock outcrop a few miles from the site. The amplification of the motion by the soil at the site is clearly evident and was predominantly at frequencies between 0.7 and 1Hz, which agreed well with the numerical predictions. From the numerical studies and the site measurements a design earthquake motion at the surface of the site was established and represented as a design response spectrum.



1. Chemical storage tank founded on driven piles



2. Measured ground motions: at soil outcrop at site (top), and rock outcrop (below)

The dynamic soil/structure interaction study was necessary to determine how the flexibility of soil-pile foundation system affected the dynamic response of the overall structure. Very often seismic structural design assumes the foundation is rigid. When sites are relatively flexible, as in this case, this simplification is not valid. In this study the soil pile system was represented in the dynamic analysis of the structure as a group of frequency-dependent springs and dashpots. The dashpots are to model both material damping within the soil and radiation damping caused by the transmission of energy away from the structure by way of the soil. In this project it was evident that the dynamic forces applied to the structure were very dependent on the level of the radiation damping assumed. As the magnitude of radiation damping is not well established for large pile groups, special consideration was necessary when arriving at values for this parameter.

The foundation design involved assessing the ability of the piles to resist the additional loads induced by the earthquake motion. As it was possible that the upper sand layer could liquefy during the design earthquake, the piles also had to be assessed for their ability to carry loads through this layer.

Rising groundwater levels in central London

Brian Simpson, Tim Blower

The deep aquifer beneath London comprises the Chalk, Thanet Sands and the lower sandy horizons of the Woolwich and Reading Beds. In central London the aquifer is overlain by a relatively impermeable layer of London Clay and Woolwich and Reading Clay. During the last 200 years, abstraction of water from the deep aquifer has caused groundwater levels within it to fall. However, the rate of abstraction in central London has declined and since the mid 1960s a steady rise in groundwater levels has occurred.

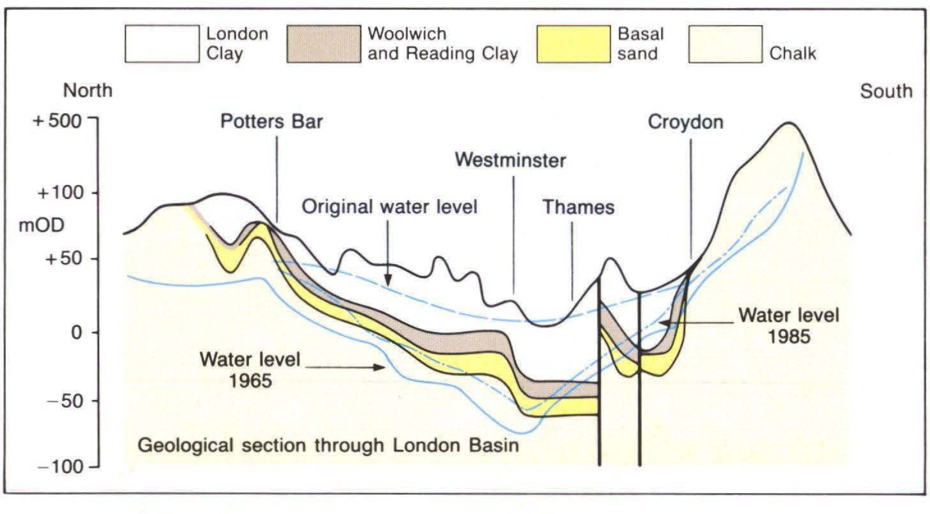
The fall of water levels in the aquifer has caused much of central London to settle by several hundred millimetres in the last two centuries. Basements, tunnels and foundations have been constructed in soil layers which had become dry or had low water pressures. The ground conditions will change markedly during the next few decades if the water continues to rise.

The future rise of water levels is difficult to predict and in central London depends crucially on abstraction from wells by private users, which is not predictable at present. However, if there are no major changes in the trend towards reduced abstraction from wells, reasonable estimates of future water levels suggest that damage could be caused to existing buildings and tunnels in central London within the next 20 to 40 years. The most common type of damage would be associated with swelling of clays, causing uneven heave of buildings, which would lead to damage to finishes and services. For a few major buildings, uncontrolled rising water levels could cause very serious damage or even collapse. Tunnels could suffer water ingress, distortion, cracking and possibly severe structural damage.

All of these problems for existing structures can be avoided by the simple process of controlling the rise in water levels. The quantities of water to be pumped are fairly small (of the order of 1% of London's water supply). It is possible that this will happen either by deliberate policy or by default as a few owners of buildings or tunnels operate their own local control systems.

In designing new buildings in central London the possible effects of rising groundwater in the deep aquifer should be carefully considered. The geometry of basements and foundations and the geology of the site should be reviewed, together with present and future water levels.

Arup Geotechnics have been centrally involved in a CIRIA Report on this subject. It is hoped that a summary of the findings will be published by CIRIA shortly.



Geological section through London Basin

Oil industry

Nick O'Riordan

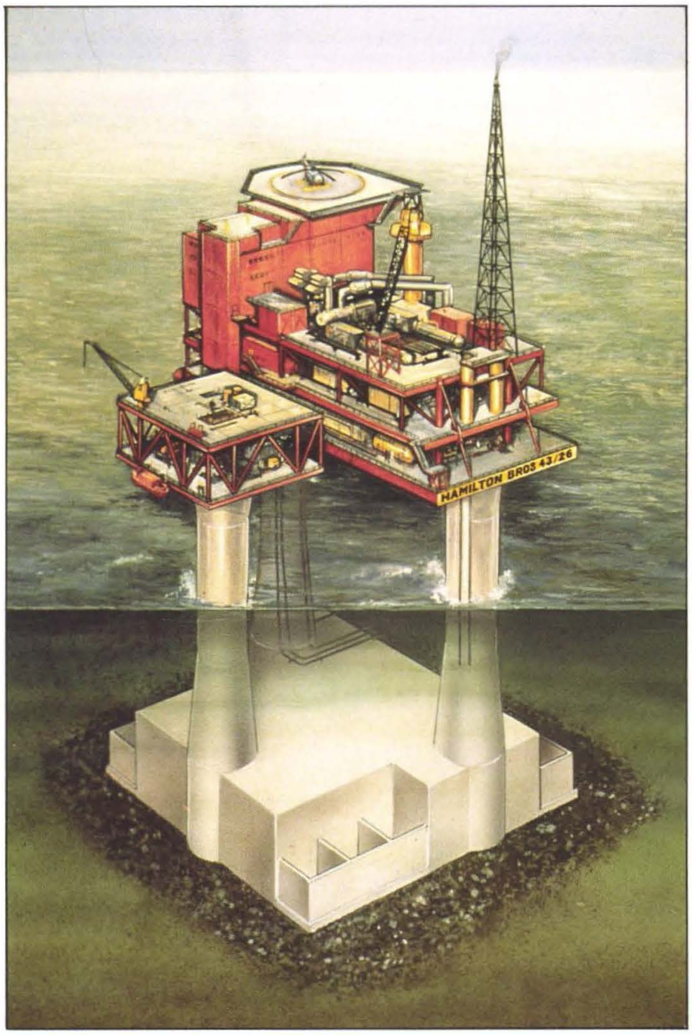
Arup Geotechnics has been involved in a series of feasibility studies, design checks, and hazard and operability evaluations for several offshore structures over the past 15 years. The latest and most extensive project in this series is the Concrete Gravity Structure (CGS) to support the main process facilities and compression decks of Ravenspurn North-Central production platform in the southern North Sea. The operator, our client, is Hamilton Brothers Oil and Gas Ltd. Arup Geotechnics has worked as part of the project team in the Industrial Engineering Division.

The structure is shown here as an artist's impression. A feature of the CGS is its lightness, about 26,000 tonnes, less than one tenth of earlier gravity structures installed in deeper waters of the northern North Sea. The base caisson is 62m × 54.5m in plan and comprises repetitive, 16m deep, open and closed cells. Open cells are used for containing solid ballast which is necessary for both floating stability during towout and foundation stability in service. The base caisson is founded on 4m of dense sand overlying very stiff clay. The foundation is keyed into the sand by 2m deep skirts cast into the underside of the concrete base slab.

We have been responsible for the geotechnical design since the concept studies back in the autumn of 1986. This has led to specification and supervision of offshore geotechnical, geophysical and bathometric surveys, together with detailed laboratory testing and engineering evaluation of the cyclic behaviour of the sands and clays beneath the platform.

The water depth at the site is 43m. Close to the sea bed current and wave velocities around the base caisson are estimated to be 1m/s and would cause the sand to be removed by scour. After extensive analytical studies of the flow regime around the base, a 13m wide scour protection blanket of graded aggregate has been designed.

Artist's impression of Ravenspurn North-Central production platform



Technical appraisal of the structure has been carried out by Lloyd's Register and construction has now started in dry dock. As a result of our work on Ravenspurn North, interest in the feasibility of building similar structures in other shallow water locations has grown within the UK oil industry and has led to further commissions.

Geotechnical computing

Brian Simpson

Introduction

The major activity of geotechnical engineering is the study of the ground — what does it consist of, what are its properties, geology, history, and so on? Calculation is a relatively minor activity, but nonetheless a vital one.

Computers are used in Arup Geotechnics in three distinct roles, and Table 1 shows the computer programs we currently use.

Most of these programs now make extensive use of OASYS software, and all have been developed in house with the exception of PIGLET which was obtained from Dr Mark Randolph.

Traditional calculations

In principle, methods of checking the stability of slopes, piles and retaining walls and of calculating settlements in simple situations have not been changed by the advent of the computer. Using manual methods, however, some of these calculations were extremely tedious, time-consuming and prone to error.

Recent thinking about design methods, particularly the development of the limit state approach, has emphasized the importance of parametric studies which sometimes demand extensive computation.

Modern methods of analysis

As in structural design, there is a danger that idealized calculations which give safe structures in conventional situations cloud the understanding of actual behaviour and are misleading if applied to unusual problems. Arups are noted for their ability to tackle the unconventional!

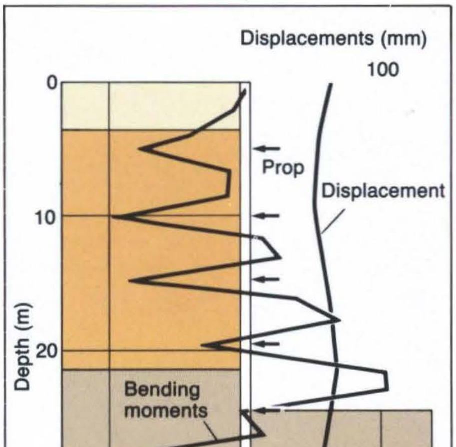
Our suite of finite element programs allows us to analyze ground movements and structural reactions, making the most realistic assumptions available about ground behaviour. We use SAFE extensively in the study of deep excavations and other soil-structure interaction problems, and we have developed a model of constitutive behaviour of London Clay successfully anticipating the university research of recent years.

Our most complex program is probably FREW, which is used for displacement and stress analysis of embedded retaining walls. OASYS software makes the program deceptively simple to use, and its cost is roughly $^1/_{10}$ that of an equivalent finite element analysis. However, it incorporates a series of assumptions and developments in soil mechanics, some of them somewhat speculative in nature. It is not a program to be used by the uninitiated!

Information processing

GRIN and GEOGEN are both data base systems, written in house, which allow information to be added in an ad hoc fashion and then interrogated and displayed. GRIN handles numerical data from ground instrumentation whilst GEOGEN is an attempt to augment our collective memory.

Geotechnical engineering relies heavily on experience and precedent, and Arup Geotechnics is very fortunate to have plenty of these because of its size and long history.



1. Flexible retaining wall analysis (FREW)

Table 1
Computer programs in current use

Calculations that are tedious and time-consuming by hand:

SLOPE
Slope stability analysis with a choice of eight different methods

PILE
Pile design for vertical loads on the basis of factor of safety against ultimate failure

VDISP
Settlement calculations for loads placed on the surface of layered elastic ground

STAWAL
Stability calculations for embedded walls such as sheet pile and diaphragm walls

GRETA
Stability calculations for gravity retaining walls

SISMIC
Probabalistic analysis of earthquake records for seismic hazard assessment

Method of analysis not practicable without a computer:

SEEP
Finite element steady state seepage analysis (the program considerably extends the range of problems manageable by hand)

SAFE
Finite element displacement and stress analysis, including non-linear behaviour governed by effective stress and pore pressures

PIGLET
Analysis of pile group interaction due to general loading

FREW
Semi-finite element analysis for embedded retaining walls

ALP
Beam and spring analysis for a pile subject to lateral loading

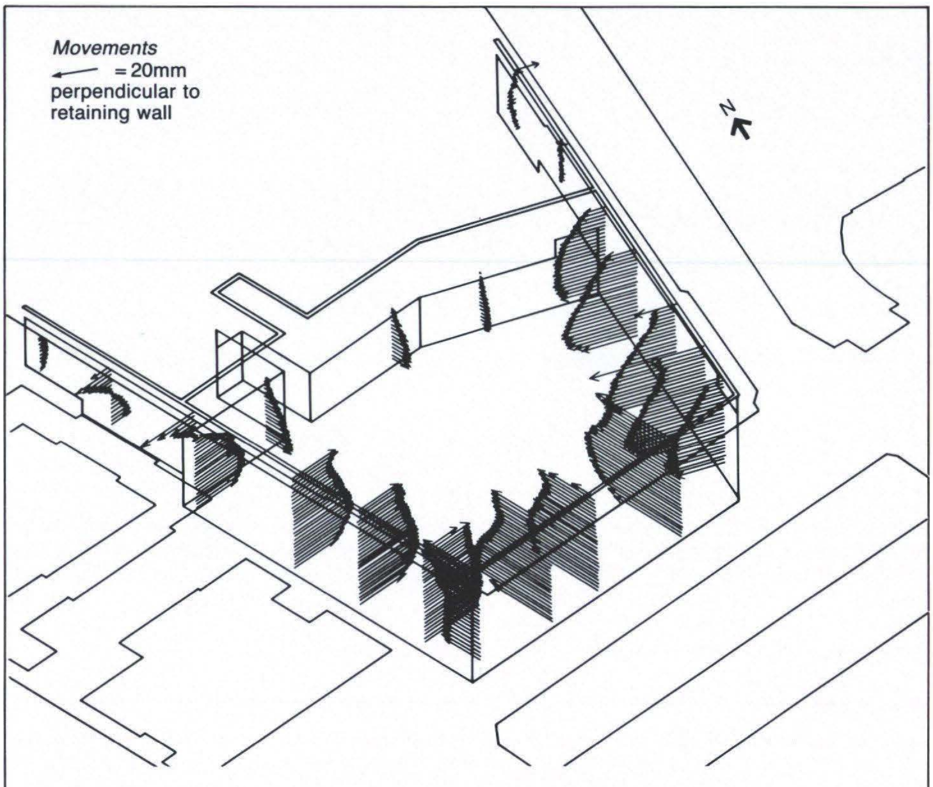
PILSET
Pile settlement analysis incorporating heave-induced tension

MINLIN
Displacement calculation within elastic half space using Mindlin integrals

Processing large bodies of information:

GRIN
Storage, processing and display of data from ground instrumentation

GEOGEN
Data base and search facility for geotechnical keyword information on Arup jobs



2. GRIN, retaining wall inclinometer movements, British Library Euston

GEOGEN was set up nine years ago to provide a keyword index to the locations, soil types, structural forms and geotechnical processes involved in Arup jobs. It does not contain very much hard information, but points the user to relevant job numbers in our archives. It is likely that it could soon be replaced by a more effective data base program, but the valuable data accumulated over the last nine years will not be lost.

The future

In some respects, computational ability has now overtaken our knowledge of geotechnical behaviour and further advances in analytical computing are likely to be modest. As computers provide more power and advanced software eases data preparation, more extensive use of finite elements, including three-dimensional work, can be anticipated, possibly supplanting more traditional methods of displacement and stability calculation.

We have barely started to exploit the computer's potential for manipulating information. In a speciality where experience is so important, expert systems could make a considerable impact. The ground is a complicated product of natural processes, however, and we must avoid over-simplification in order to meet the limitations of software.

Recent advances in piling

The last few years have seen several influential changes in the field of foundation construction. Turnover in the construction industry has increased, particularly for buildings in London, and this has resulted in most reputable foundation contractors enjoying full order books. A great deal of emphasis is presently placed on quick completion of buildings, and fast track construction is an overworked phrase. At the same time the sites under development are increasingly difficult, either because of poor ground conditions or because they are affected by their neighbours alongside, underneath or on top of the site.

These conditions have on many occasions led engineers to depart from the traditional suite of foundation techniques used for certain ground conditions, and adopt more unusual and innovative approaches. These have not always met with complete success.

Arup Geotechnics have been closely involved with several developments in the field of piling, and some of these are described below.

Hand-dug piles in London

Bill Grose

One such recent development in foundations has been the excavation of large diameter piles by hand. Whilst this technique was used extensively in Chicago from the turn of the century to about 1950, and is still popular in Hong Kong, there are only a handful of known examples where foundations have been hand-dug in London Clay. At the Shell Centre, Waterloo (completed 1960), several bored piles were required close to an underground tunnel and were excavated by hand. These piles were 1.4m diameter and under-reamed without support. The new London Bridge (built 1971) was founded on hand-dug, steel-lined under-reamed piles which were excavated from within a larger cofferdam. Our own job at Bond Street Station was supported partly on hand-dug under-reamed piles founded in the Woolwich and Reading Beds.

Arup Geotechnics have been involved recently in three projects where buildings have been supported on hand-dug piles: the Fenchurch Street Station development, completed 1986; Embankment Place, Charing Cross, due for completion in 1989; and Broadgate 11, Liverpool Street, also currently under construction. In each case the buildings are office blocks built over British Rail's London railway termini. They all involve large spans between columns, generating very high column loads. The first two of these projects involve Ove Arup & Partners as structural designers; for the third

Arup Geotechnics are designing the temporary works associated with the underreams for the contractor.

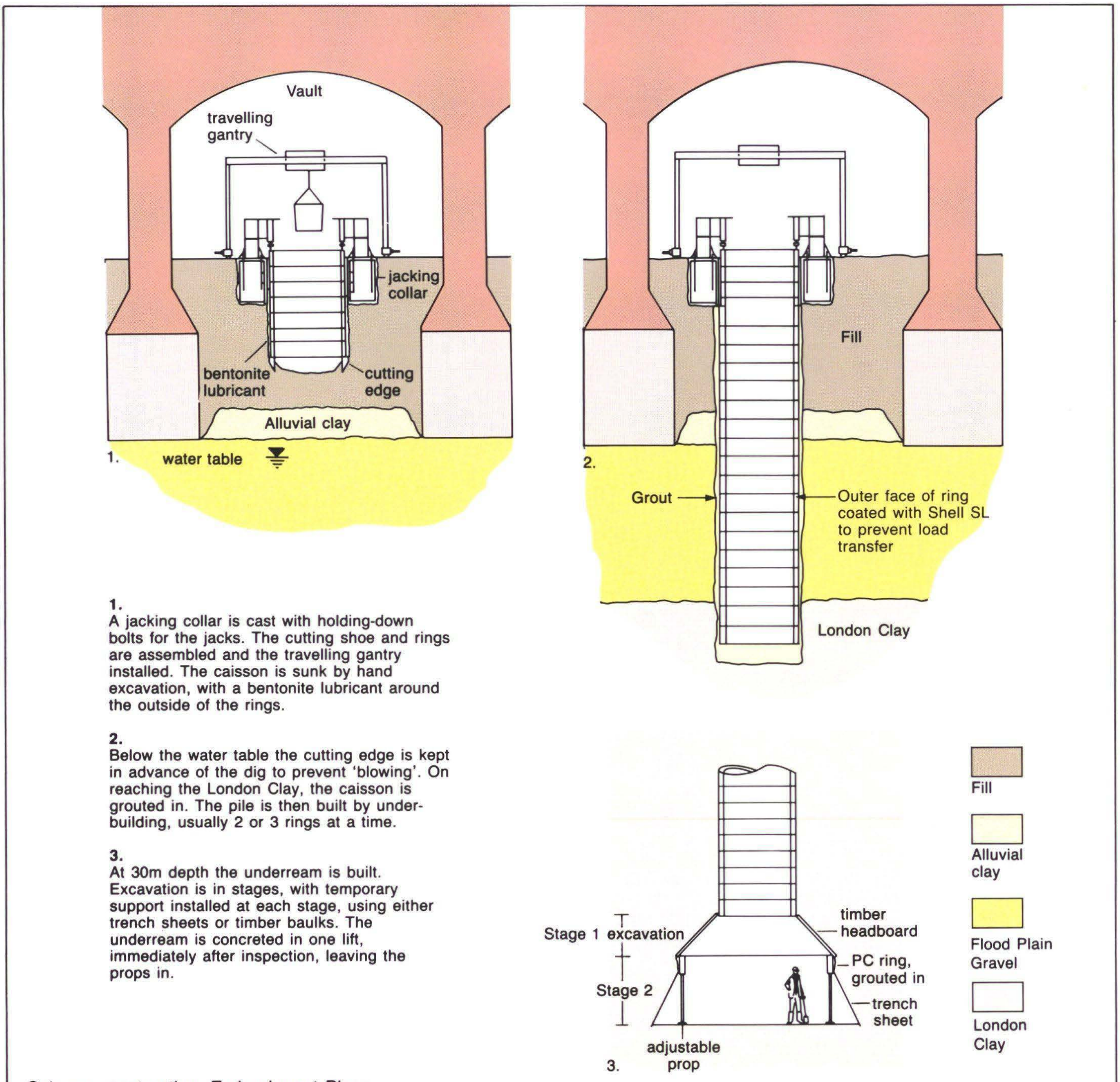
At Fenchurch Street Station the six storeys of offices span 27m over the railway, generating column loads in the range 700 to 1500 tonnes. The ground conditions, typical for much of London, consisted of 4 to 8m of fill, 4m of water-bearing dense Flood Plain Gravel, then up to 40m of London Clay. The foundation solution adopted was to sink a caisson to the London Clay at each pile position using precast concrete standard tunnel rings bolted together. Sinking was assisted by applying kentledge, and by using bentonite slurry as a lubricant in the annulus formed by the oversize cutting shoe. When the caisson was sealed into the clay, the pile was advanced by sequential excavation and installation of further precast concrete rings. Grout was then injected behind the rings to fill the annulus and bring them into contact with the clay, before starting the next increment of excavation. On completion of the shaft it was filled with mass concrete and capped with reinforced concrete.

The piles thus formed were straight shafted, 2.5, 3.0 or 3.5m in diameter and up to 40m deep. In order to limit settlement of the very stiff transfer beams, the piles were designed to carry all the load in shaft friction in the London Clay. One of the smaller piles was comprehensively instrumented in order to investigate its performance, and early results appear to show that much of the applied load is carried in the fill and Flood Plain Gravel, with an average skin friction of between 40 and 70kPa.

The construction methods used at Fenchurch Street Station were also used at Embankment Place (Charing Cross Station), as there were several similarities between the two projects. In both cases, high capacity foundations were to be built from within the confines of vaults beneath railway arches through essentially similar ground conditions. The column loads at Embankment Place, however, are considerably higher, ranging up to 2700 tonnes, and called for a different design approach to be adopted.

A preliminary assessment using conventional design methods showed that straight shafted piles 4.5m in diameter and 40m deep would be needed to support the highest loads. The volume of such a pile would be nearly 700m^3! As all the construction work was to be carried out in a confined space, the removal of this amount of spoil and its replacement with concrete would have been time-consuming and expensive. It was therefore decided at an early stage to consider the use of under-reamed piles. These proved to be significantly more efficient in volumetric terms, with the largest loads being carried on 2.5m diameter piles under-reamed to 6.6m at a depth of 35m. Piles of this size have a volume of about 240m^3, or 35% of their straight-shafted rivals. It was known that larger settlements would be associated with under-reamed piles, but a comparison carried out at scheme design stage showed that these movements could be tolerated by the new structure. The difference between the two schemes in terms of expected movement of the surrounding ground and existing structures was shown to be minimal. For these reasons under-reamed piles were chosen, and these were built between November 1987 and March 1988. One pile was fully instrumented by the Building Research Establishment, and it is hoped that the results will lead to a better understanding of the performance of these piles.

The back cover illustration shows a 6.6m diameter under-ream, one of the largest on the project, during the final stages of excavation.



Caisson construction, Embankment Place

Toe grouting of large diameter piles

John Mitchell

Bruce (1986) in his state-of-the-art review on 'Enhancing the performance of large diameter piles by grouting' published in *Ground Engineering,* describes the history of the technique. Early uses involved contact grouting as a method used in the Middle and Far East for underpinning piles not built effectively. We have our own experience with a job in Cairo, in the early 1980s. In addition there were a limited number of cases where toe grouting was used as part of the intended construction method. Cement or chemical grouts were applied mainly to fine to coarse sands or sandy silts.

The explosion of office development on the Isle of Dogs in London, and the ground conditions, have given the impetus to consider toe grouting as a technique for use in this country. Column loads can be typically 5000 to 20,000kN. The ground conditions consist of about 10m of fill, alluvial clays, peats and gravels, over about 20m of the Woolwich and Reading Beds, 15m of Thanet Sands and then chalk. The gravels are too thin to support column loads above about 7000kN because large groups of driven piles are needed. There can also be problems with pile interaction. The Woolwich and Reading Beds are very variable with interbedded silty clays and silty fine sands, and layers of limestone cobbles, and conglomerate. However, the Thanet Sands are generally a very consistent fine single size sand, with occasional thin silt layers.

The first Canary Wharf scheme envisaged about 10 to 15 storeys of office blocks with column loads having the magnitude mentioned above. We designed and executed a programme of three trial piles to test the applicability of the toe grouting method. 25m long piles were built under bentonite and founded in the Thanet Sands. One 900mm diameter grouted, and one ungrouted, and one 1200mm diameter pile were load tested. The grouted 900mm pile behaved twice as stiffly as the ungrouted pile.

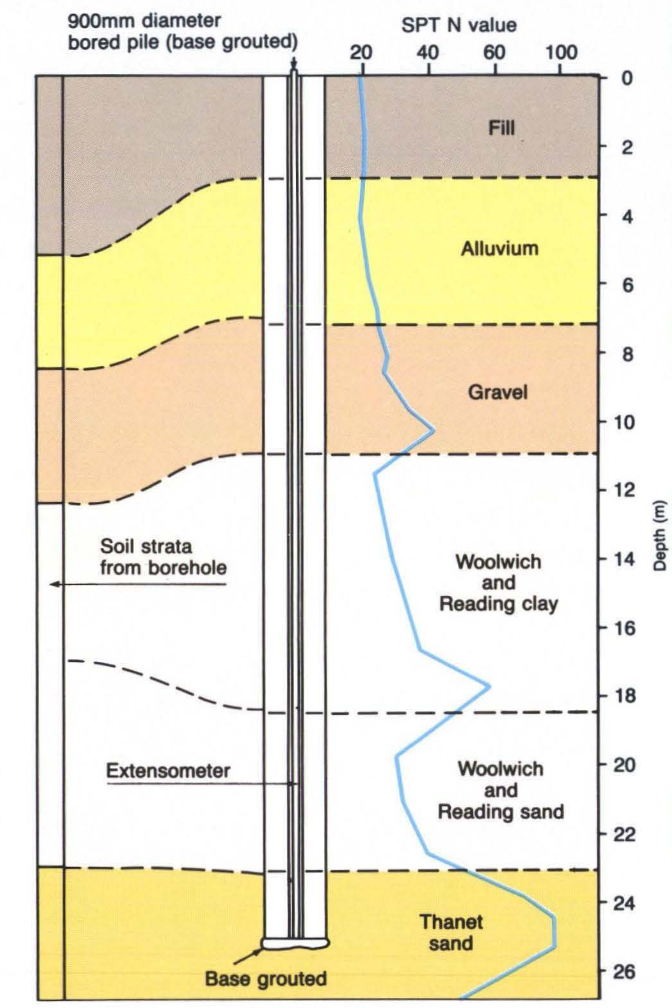
Following quickly behind Canary Wharf was the South Quay Plaza job nearby. Column loads for the 15-storey office block were between 6000 and 15,000kN. It was decided to use one pile per column with 1200mm diameter piles having a design load of 10,000kN, and 1500mm diameter piles having a design load of 15,000kN. The piles were built in the same manner as Canary Wharf, and again founded in the Thanet Sands. Grouting was carried out by casting a system of four 50mm diameter steel U-tubes within the pile. At the base of the U-tube, rubble sleeves or manchettes covered holes in the pipes. During grouting the sleeves acted as one-way valves allowing the grout to escape into the surrounding ground (see Fig. 2).

After South Quay Plaza, toe grouted piles were used at Heron Quay, just to the north, and Blackwall Yard to the north east, above the Blackwall Tunnel north portal. The piles at Blackwall Yard proved particularly demanding because they need to be about 38m deep to be founded in the Thanet Sands. Fig. 3 presents load test results from all four jobs normalized to allow comparison. A relationship between load and deflection appears to be emerging. The load test results have also demonstrated that the Thanet Sands probably have an ultimate bearing pressure in excess of 20MN/m^2. This is

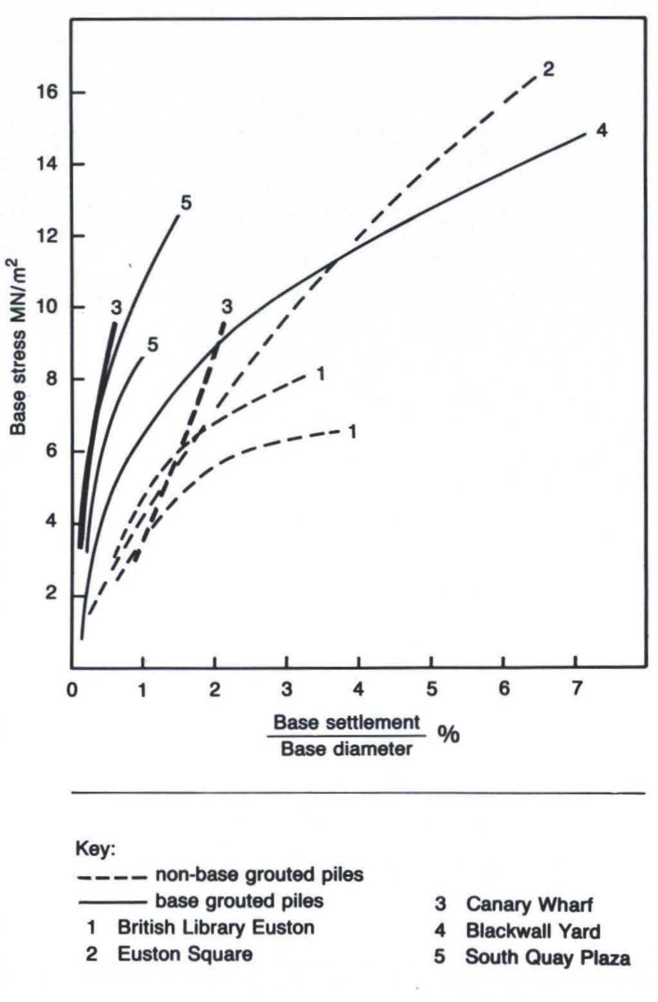
2. Detail of manchette assembly

about twice the limiting value recommended in the literature for piles.

We are now considering the use of toe grouted piles for a job in Ilford which will start in the near future. Other engineers are also taking an interest in the technique, and it may well be applied to a bridge in Scotland, founded on glacial gravels. Rock sockets can also be improved by toe grouting.



1. Canary Wharf: Geological section through base grouted pile and SPT profile from borehole investigation



3. Comparison of load test data for base grouted and ungrouted piles

Scotland

Andy Woodland
Paul Gough

In recent years we have been involved in a wide range of large and small building and civil engineering projects throughout Scotland and the North of England.

A selection of jobs is described below.

RGC Offshore Ltd. plc, Methil
For many years we have been involved in civil engineering work at RGC Offshore's Methil Works on the Fife Coast, where oil production jackets are fabricated.

In 1984 a scheme was designed for infilling two disused load-out docks each 35m wide by 120m long and 10m deep to provide additional fabrication space. The docks had a tidally fluctuating water depth of between 3m and 9m and wave heights of up to 4.5m had been recorded nearby. Consequently a new high modulus sheet piled seawall was installed across the mouth of each of the old docks to prevent the washout of infill material and provide a new quay for RGC's operations.

Colliery discard originating from a nearby disused coal mine was available in stock piles on the site and was an obvious and economical choice for the infill material. The discard consisted of fragmented mudstone but contained approximately 8% silt sized particles. Although the old docks would remain tidal once the sheet pile walls had been constructed, model tests showed that only very small quantities of the fines would be washed out of the infill.

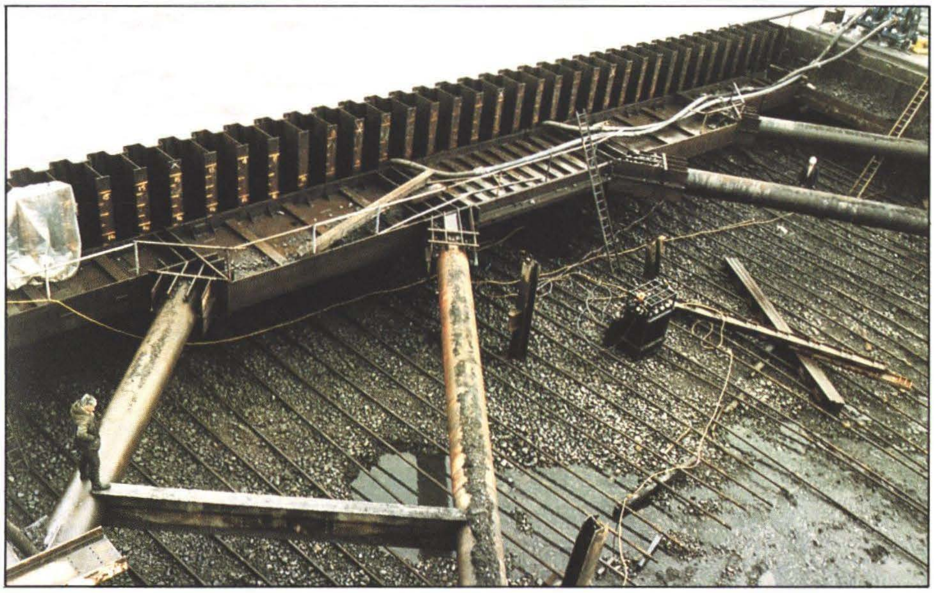
It was essential that only small settlements of the fill occurred under high applied loads from jackets during fabrication and load-out and large mobile cranes. Cone penetration tests showed that on completion of infilling the discard was in a very loose to loose state. To increase the relative density it was compacted by a combination of dynamic compaction and rolling in layers. Dynamic compaction was carried out on a 5m triangular grid pattern using a 15 tonne, 2m diameter tamper falling through a height of 22m.

After completion of the works large scale load tests were carried out on the surface of the compacted fill using kentledge and a 3.5m × 3.0m loaded area. These confirmed a load carrying capacity of 350kN/m^2 with acceptably small settlements.

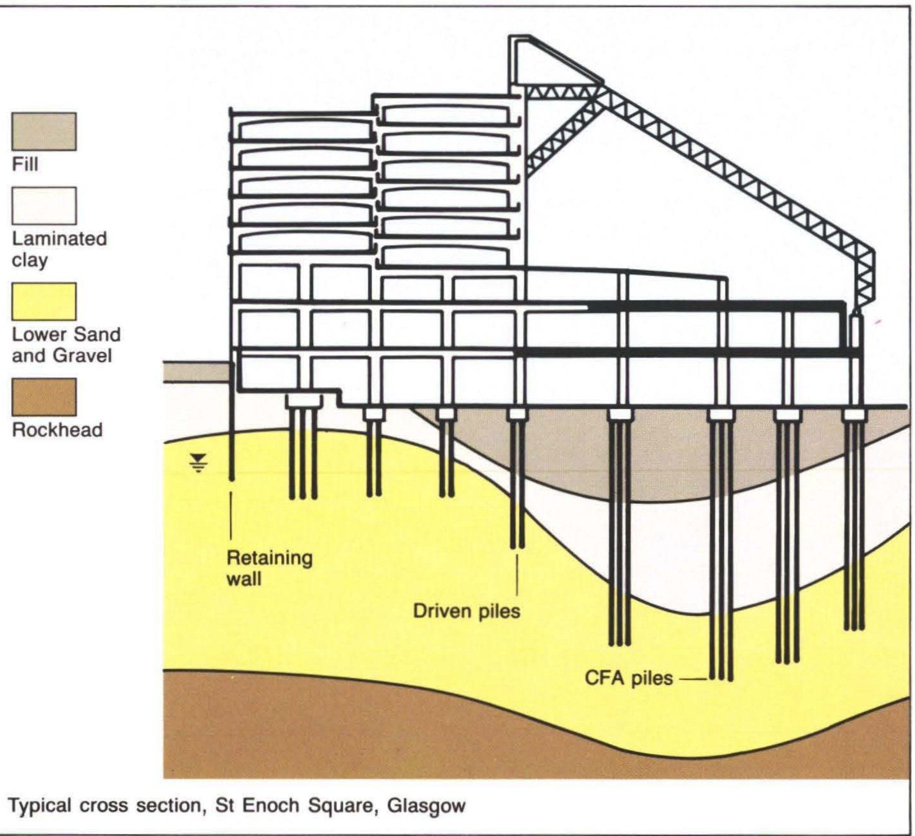
More recently we have been involved in lowering the tie rods of the sheet pile seawall to allow clearance for the feet of the jacket while it was being launched.

Other work at the site includes the installation of offshore anchorages to hold transportation barges in place during loading-out of jackets. The anchorage loadings were assessed by testing a model of the transportation barge and jacket in a water tank capable of reproducing wind and sea conditions expected at the site. From these tests it was determined that the anchorages were required to resist lateral forces of up to 3000kN. The system designed comprised four 1m diameter, 50mm thick steel tubes with padeyes, drilled and grouted approximately 9m into the seabed sandstone bedrock.

St Enoch Square, Glasgow
The St Enoch Square Commercial Development is located in the centre of Glasgow close to the north bank of the River Clyde

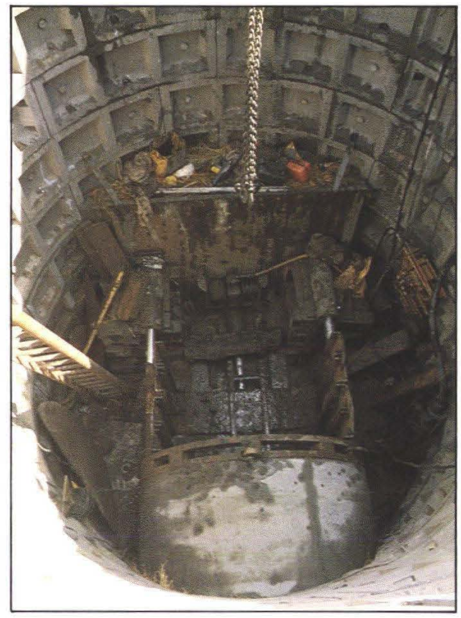


Methil: Sheet pile wall and below: Load test on compacted fill

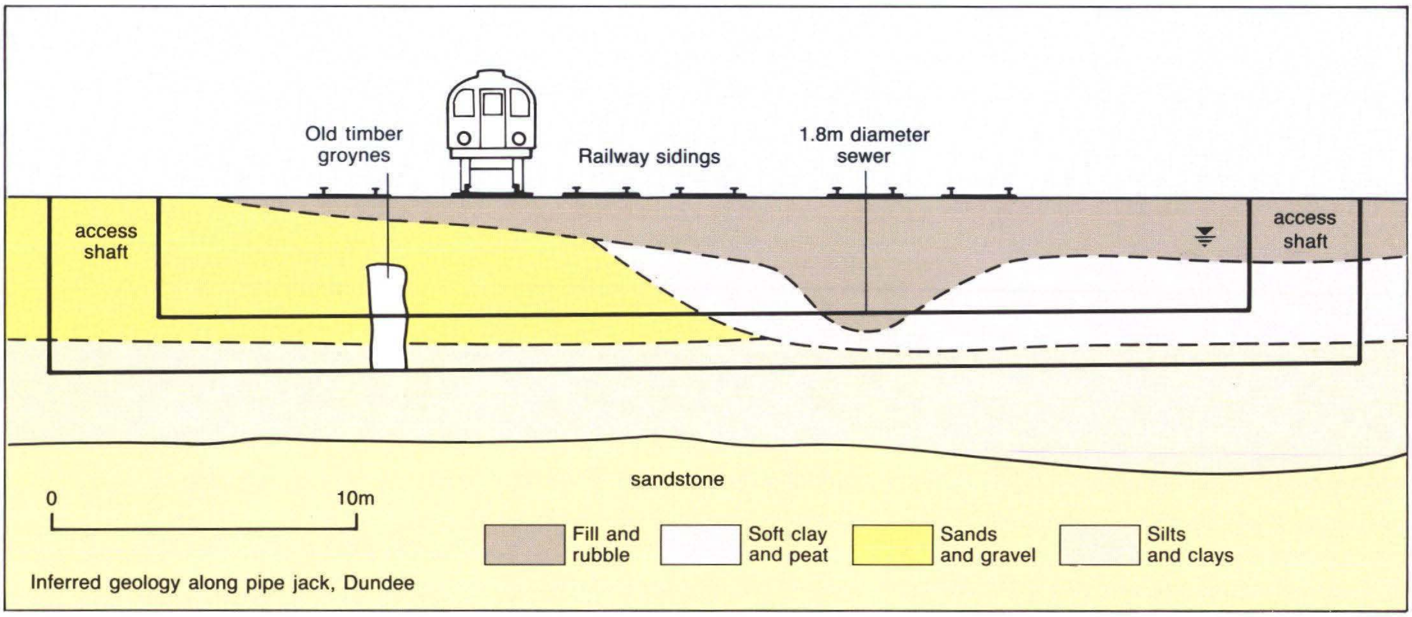


Typical cross section, St Enoch Square, Glasgow

Continuous flight auger piling, St Enoch Square, Glasgow



Access shaft, sewer installation, Dundee



Inferred geology along pipe jack, Dundee

The development, which is currently under construction, includes a department store, 70 shop units, an ice rink, a fast food court and a car park for 750 cars. The entire development is surrounded by a glazed canopy. The structure is built in reinforced concrete and rises to eight storeys with one basement level. At foundation level the column loads range from 1MN to 9.6MN.

An extensive site investigation, including 27 boreholes and 38 Dutch Cone tests, revealed a complex and variable sequence of fluvio-glacial deposits including sand, gravel and soft clay overlying bedrock at a depth of 35m.

Railway tunnels and old brick sewers are present beneath the surrounding streets. The building is supported on approximately 1700 piles founded in the Lower Sand and Gravel, in groups beneath each column. A piled foundation was selected because of the thick, compressible stratum of clay and the variability of ground conditions across the site. Roughly ⅔ of the piles are driven cast in situ. However, driven piles were unsuitable for use close to existing structures, tunnels or sewers, and could not be used where the Lower Sand and Gravel stratum was more than 17m below formation level. In these areas Continuous Flight Auger (CFA) piles were specified.

The CFA piles installed are 600mm in diameter and carry working loads of up to 1200kN. Piles were installed using a 28m drill string with 100mm internal hollow stem.

Two trial piles were constructed and tested before the start of contract piling. These piles failed at 1.67 and 1.75 times the design load. Investigations showed that soil inclusions and weak concrete within the pile shafts had caused the failures. The reasons for the inclusions in the pile shaft are complex. The main reason appears to be that the volume of the bore created by lifting the auger was on some occasions formed faster than concrete was being pumped in to fill it. This allowed soil and fluid concrete to drop off the auger flights at the base of the stem, and contaminate the concrete.

The results of the failure investigation led to our requirement that the actual volume of concrete being pumped into the pile must be monitored during construction by the rig operator so that a positive volume flow is maintained at all times.

A further seven trial piles were successfully constructed using the new monitoring system and tested before contract piling was allowed to continue.

Sewer installation, Dundee Waterfront

We have been involved in various projects concerned with the development of Dundee Waterfront area. A recent project was the installation of new sewers, the line of which crossed the main rail lines in and out of Dundee Station.

In view of the importance of the rail line, the only feasible construction method was to tunnel under the railway using the pipe jacking technique.

Three pipe jacks were required of diameter 1050mm, 1800mm and 1500mm. The 1050mm and 1800mm pipes were relief foul and storm sewers for central Dundee, the 1500mm pipe contained two 600mm diameter inserts which are sewers for a development site in the waterfront area. The pipe jacks were driven northwards, under the railway, from large access manholes at the south side of the tracks. The drives were between 42m and 46m long, from where cut and cover construction could continue. The pipes were made of precast concrete in 1.25m long sections, and at least 3m of cover was provided to all three pipes.

The sewers run through an area reclaimed from the Firth of Tay, and a number of old timber groyne obstructions about 2m long were encountered and removed during tunnelling. Ground conditions were complex, consisting of fill material, which included large boulders, overlying alluvial deposits consisting of soft organic silts and peat deposits.

The water table was close to ground level, and it was necessary to install a large number of dewatering points though the made ground. Settlements of the rail tracks were monitored during the contract and were within the tolerances acceptable to Scotrail.

Birmingham

Alan Turner
Peter Braithwaite
Christina Jackson

Introduction

While Birmingham is involved with similar geotechnical problem-solving to our other offices, we are particularly associated with urban regeneration initiatives involving work both below and above ground.

The Black Country to the north west of the City of Birmingham was the industrial heartland of Britain during the 18th, 19th and early 20th centuries, but has suffered with the rapid decline of its traditional heavy industry during the late 1970s and early '80s. However, over the last few years various Government and private incentives have raised the spark of regeneration.

Before redevelopment of derelict sites can take place, a range of economic, access and geotechnical problems have to be resolved. We have been involved in a number of major schemes which have developed our expertise in handling various reclamation problems, particularly involving mining instability, chemical contamination and foundation problems caused by steel furnace slag.

Abandoned limestone mines

The largest of the derelict land schemes we are involved with relates to the investigation and treatment of abandoned limestone mines in the Black Country and also in the eastern part of Shropshire.

Limestone was extensively mined from the beginning of the Industrial Revolution up to about 1920, to provide a flux for ironmaking and agriculture. The mines, often up to 10m high, were left open when they were abandoned, not being stowed or infilled. Since then the mines have gradually degraded and collapsed to varying extents.

On behalf of the Department of the Environment and the local authorities affected, we have carried out desk studies of archive records, and have collated information on 38 abandoned limestone mines. In Dudley, Sandwell, Walsall, Wolverhampton and Shropshire an area of about 10km^2 is affected.

The problem posed by the abandoned mines can be categorized into two different effects. The collapse of deep mines (deeper than about 70m) can cause general subsidence in the form of a dish-shaped depression over a wide area. Such a collapse occurred in Sandwell in 1978, in the abandoned Cow Pasture Limestone mine (140m deep). This resulted in subsidence over a wide area with a central settlement of 1.5m, causing considerable damage to overlying buildings. With shallow mines (less than 70m deep) 'crownhole' collapses can occur, causing a dramatic, but localized effect, on the surface.

A three-stage approach to the investigation and treatment of the mines has been adopted, which can be simply summarized as follows: Stage 1 involves preliminary investigation by direct inspection if the mines are accessible, or drilling investigation if not. Stage 2 comprises further drilling investigation, if necessary, to provide design data for Stage 3 treatment works.

The drilling work involves the innovative use of down-the-hole geophysical logging, and CCTV, sonar and laser surveying of open workings encountered. Geophysical logs have been correlated with the lithology of the overlying rock, so that the use of cost-effective probe drilling by openhole techniques can be maximized. Using sonar and laser surveying, the geometry of open mines can be recorded up to 100m from the borehole position, supplemented by CCTV surveys indicating the condition of the mine in the immediate vicinity of the borehole.

If the mine is found to be open or partially collapsed, stabilization by infilling is often recommended. After stabilization, or if a mine is found to be already fully collapsed, the detrimental effect of the presence of the mines on planning, development and existing property values is removed. Thus confidence in the use of the overlying land is restored.

Infilling schemes

The particular treatment option chosen for a mine depends on many factors including the condition of the mine, depth of mine and the land use of the overlying ground. The mines may be infilled with rock-paste, grout, sand, pulverized fuel ash, or a combination of materials depending on access and the cost of supply of the materials.

We have been involved with the development of one particular method, using rock-paste, which is appropriate for bulk infilling of mines with large interconnected voids which are either air or water-filled.

Development of rock paste

Rock-paste is basically a mixture of colliery spoil and water and is designed to be a cheap infilling material which initially flows and then has a modest gain in strength.

During 1985 a trial infilling contract was undertaken to fill a 30,000m^3 section of Castle Fields mine, Dudley, to prove that it was possible for a civil engineering contractor to mix and pump rock-paste and that the flow characteristics of rock-paste in the mine were as theoretically predicted.

Littleton Street

After successful completion of the trial, we were engaged by Walsall Metropolitan Borough Council to design and supervise the infilling of Littleton Street mine, Walsall, which is a completely water-filled mine. The pillar and room mine lies about 70m below Walsall town centre and covers a plan area of some 13ha. A two-year contract was let in October 1986 to infill the mine with approximately 450,000m^3 of rock-paste, consisting of colliery spoil, water, lime and pulverized fuel ash. The lime and pulverized fuel ash have been added to the colliery spoil and water to ensure a gradual increase in strength with time and also to reduce the amount of consolidation as compared with the rock-paste used in the Castle Fields mine trial.

The contract is still in progress with more than half the mine having been filled. The contractor has been achieving pumping outputs of around 2,000 tonnes of rock-paste per hour. On completion of the contract, two colliery spoil sites will have been restored and a third tip reduced in volume. Redevelopment of 21ha of town centre land will also be possible.

Ironbridge

One infilling contract, at Lincoln Hill, Ironbridge, Shropshire, has already been completed. A different form of rock-paste, based on pulverized fuel ash, cement and water, was used as the infilling medium.

During 1982 a crownhole formed in the mine roof which broke through the ground surface in the public road leading up Lincoln Hill. Our examination of the mine workings, made possible by descending down an open shaft, revealed considerable deterioration of the mine workings, which would eventually lead to further crownholes forming.

In order to safeguard the road and existing buildings, Shropshire County Council were advised, and accepted the need, to infill the mine workings. Due to the close proximity of Ironbridge Power Station the infill material chosen was pulverized fuel ash mixed with water and 1% to 1.5% of cement. In total 16,000m^3 of infill material was mixed and placed by conventional batching plant and pipeline within the mine.

Surface dereliction

The western end of the Black Country Route, a major highway connecting the M6 motorway with the western part of the Black Country, involved crossing land previously occupied by the former Bilston steelworks. Prior to the development of the steelworks, the area had been extensively mined for coal and ironstone.

The operation of the steelworks had left its own legacy of dereliction in the form of furnace slag waste and fused slag/iron masses.

A railway and canal run past the former steelworks site and in order to carry the Black Country route over these, a four-span viaduct was proposed. Following an extensive site investigation to determine the nature and condition of the superficial fill material and the underlying worked mineral horizons to a depth of 110m, we were able to design the viaduct foundations.

The foundation system adopted for the bridge piers was to use large 1.2m diameter piles, founded within the mudstones and sandstones of the Carboniferous Strata beneath the fill deposits.

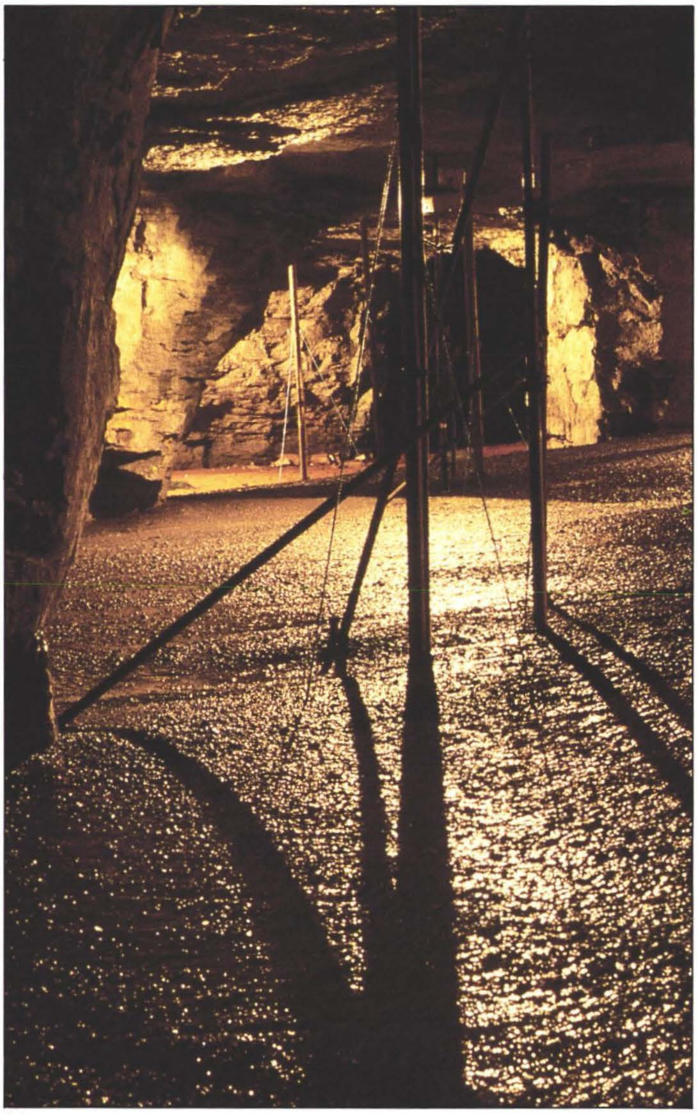
Prior to the construction of the pile foundations the worked mineral horizons were grouted to a depth of 90m with a mixture of pulverized fuel ash and cement to ensure that voids present within the horizons were filled and to minimize future settlement of the bridge structure. To accommodate any future movement that may arise, the bridge spans have been designed as simply-supported structures.

The use of large diameter piles was chosen to enable large inclusions of fused slag and iron/slag ingots to be removed from pile excavations should the need arise.

To ensure the integrity of the pile shaft within the zone of superficial material, all the piles were permanently lined with a light gauge steel liner.

1△

1. Crown hole, Dudley Cricket Pitch
2. Castle Fields Mine during infilling
3. Infilling plant at Littleton Street
4. Lincoln Hill Mine
5. Castle Fields Mine
6. Section through Springvale Viaduct
7. Bored piling at Springvale Viaduct



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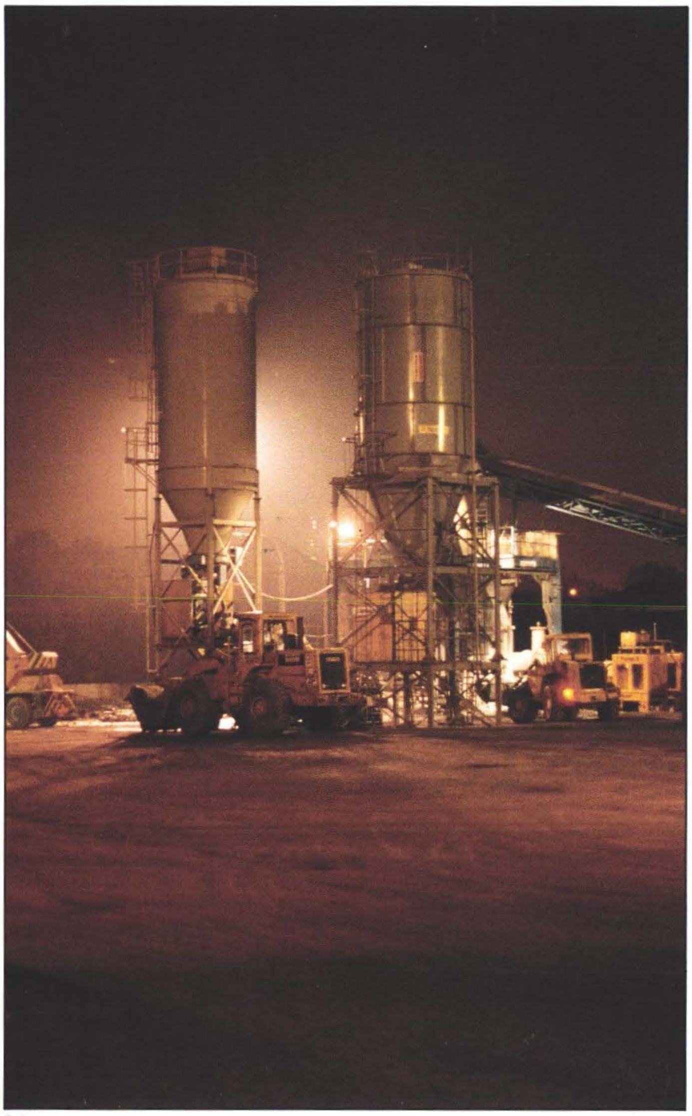

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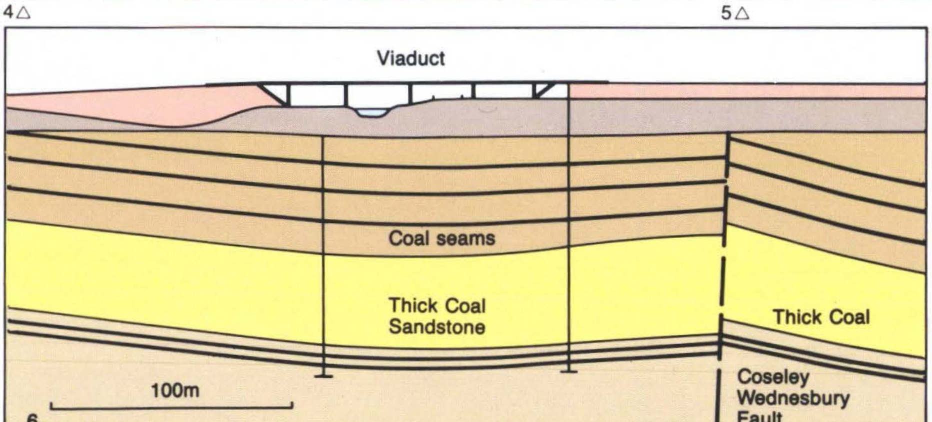

Viaduct
Coal seams
Thick Coal
Sandstone
Thick Coal
100m
Coseley
Wednesbury
Fault

6.

Abandoned mining hazard in South Wales

Ian Statham
Gabe Treharne

Introduction

Abandoned mining, especially by early partial extraction methods, has long been seen as presenting a risk of instability, due to progressive upwards collapse of the workings after abandonment. The severity of the hazard, however, is not well understood and this is of concern to the Department of the Environment and Welsh Office. In particular, as they have overall responsibility for the planning process, they saw a need for simple guidance maps easily understood by planners and developers. Consequently, we were commissioned to carry out a programme of research aimed at developing a method of preparing risk maps suitable for use by planners to take better account of subsidence hazards.

The study

The original objective was to test a traditional desk study approach for a 25km² pilot area near Ebbw Vale, South Wales. The intention was to prepare a mining map from available records and then to apply a back analysis of subsidence incidents to define the risk area. In the event this approach proved to be impossible because:

(1) The past mining areas could not be readily identified due to incomplete mining records, e.g. the first mining lease dated 1778 was issued almost 100 years before the earliest surviving mining plan.

(2) Insufficient subsidence incidents were traced within the pilot area for reliable back analysis, i.e. only one.

An alternative strategy had to be developed. We saw that the only practical way forward was to concentrate on the potential rather than the record of abandoned mining. We speculated that potential could be developed from an overall appreciation of the mining history of an area and the reputations of local seams for old workings. To allow this idea to be tested, the study was extended and we collected all readily available records of subsidence incidents for the whole of the South Wales Coalfields. We also examined the present condition of mined ground and reviewed the experience of stabilizing abandoned workings by grouting.

Subsidence incidents

388 incidents were traced, of which only a few were before 1960. Over 75% were collapses of mine extrances or through a cover of drift deposits. The remainder propagated through rock to the ground surface. The upper limit of propagation varied with the dip of the strata and was equal to H/T = 8 for gentle dips, increasing to H/T = 18 for steep dips (H/T = thickness of rock cover/estimated height of original void). Incidentally the majority related to roadways and not the workings themselves.

Present condition of abandoned workings

The present condition of abandoned workings was examined in exposures found at opencast coal sites, small coal mines still working using traditional methods and a few accessible, abandoned ironstone mines. Indirect evidence was collected from grouttakes for a selection of drill and grout contracts. These all showed that the following general conclusions applied to the original pilot area:

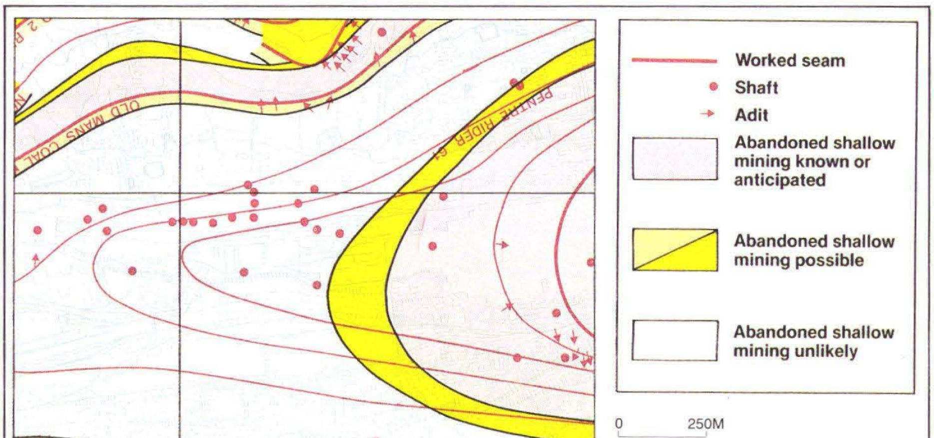
(1) That old abandoned workings would generally be completely collapsed or backstowed.

(2) Any remaining voidage would be higher in the ironstone horizons.

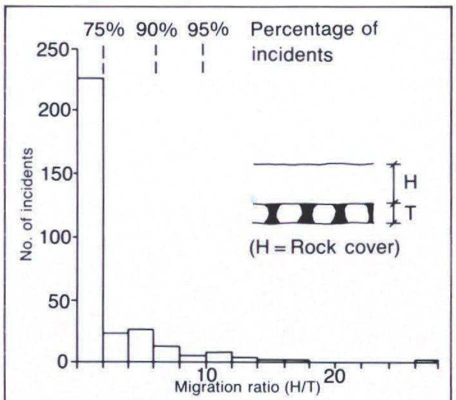
(3) Roadways would be frequently open, especially those that provided cross-measures connections (i.e. from one seam to another).

The development advice map: mining subsidence

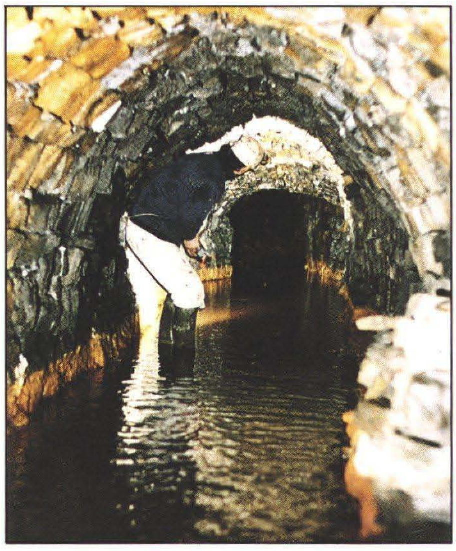
The results of the coalfield study were applied to the pilot area and enabled production of a 1:10,000 scale Development Advice Map: Mining Subsidence. An extract of this is shown above. The map is zoned to show areas where specialist advice is necessary in support of a planning application. It also shows all mine entries traced in the desk study. The method used is general for the South Wales Coalfield with minor adaptions to suit local conditions. We believe it is a method which can be extended to other coalfields, although of course new background appreciations and subsidence incident data would need to be collected.



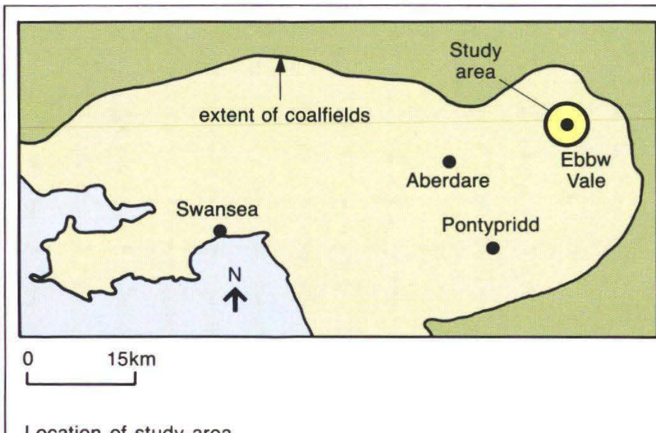
Extract from Development Advice Map: Mining Subsidence



Subsidence incidents histogram



Cae Harris ironstone workings: above, condition survey; below, roadway



Location of study area

Bristol

Martyn Duffin

Arup Geotechnics in Bristol currently comprises five engineers and geologists providing geotechnical advice on a wide diversity of projects. These range from small housing schemes through major office and retail developments to predominantly civil projects such as marinas, infrastructure and enabling works involving large volume earthworks.

The office is presently working on large commercial and retail developments in Bristol, Gloucester, Winchester and Birmingham. More details of a large development currently under construction in the centre of Bristol are given below.

Bristol's Broadmead shopping area was first developed in the later 1950s and early 1960s, largely over sites cleared by the Blitz of the early 1940s. The regeneration of the area is to be spearheaded by a three-level shopping complex occupying the south-east quadrant of the central area.

Interpretation of old maps, geological and archaeological information permitted efficient location of boreholes and trial pits within a very congested site. The ground conditions consist of a variable thickness of fill overlying predominantly firm becoming soft, silty clayey alluvium. This in turn overlies loose to medium dense sand becoming very weak to weak Keuper Sandstone at depth.

The development incorporates a basement, housing servicing areas, storage and retail facilities. This will be constructed well below water table level in the soft alluvial deposits, adjacent to the culverted River Frome. The basement will be constructed using 'top-down' techniques within a diaphragm wall taken some 4 to 5m into the weak Keuper Sandstone found at around 12m depth beneath the site.

Some column loads within the basement will be carried on barrettes but the majority will be taken by large diameter piles socketed into the Keuper Sandstone. These will be concreted to basement level and steel stanchions set accurately into the wet concrete to support the superstructure above.

Prior to construction of the diaphragm wall and piles, approximately 250 mainly driven piles remaining from the earlier developments will need to be removed.

Outside of the basement area, support will be provided by groups of small diameter bored piles.

Whilst the group is based within a regional office of Ove Arup & Partners, it can be seen from the above that geotechnical work is carried out on a wide range of sites, not only within the south west but throughout the country in response to appointments from Bristol-based developers and architects. In recent years projects have been as far afield as Cairo and Papua New Guinea.

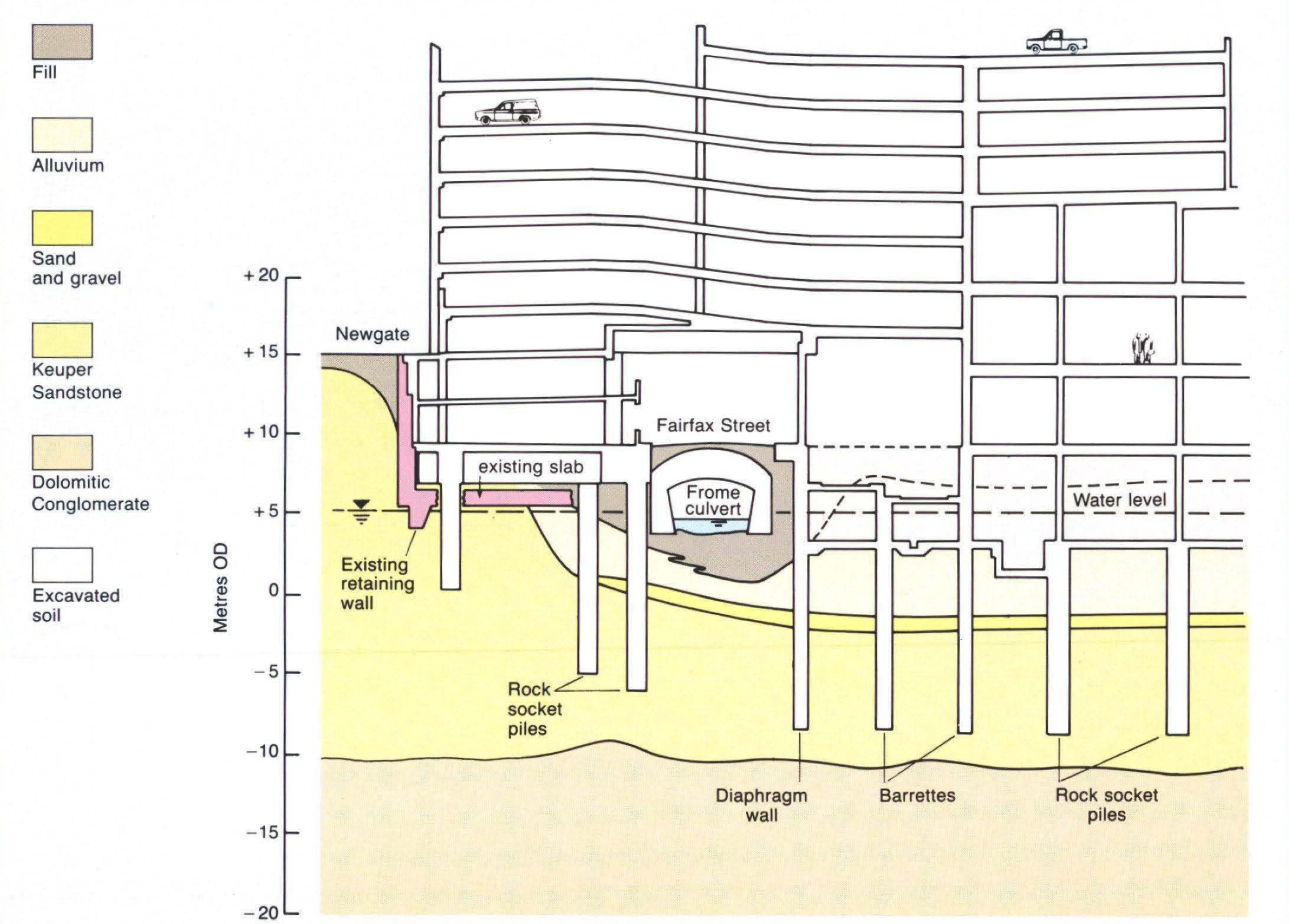
Not only have the sites varied geographically but also geotechnically, particularly in the south west, reflecting the rapidly changing and interesting geology of this part of the country. This latter aspect is exemplified by the foundations and groundwork required for the redevelopment of Brunel House which is a few hundred yards from the Bristol office.

Brunel House is located at the foot of the south-facing slope of Brandon Hill which overlooks the City Centre. The redevelopment involved excavation into the toe of the hillside which had a history of instability in both the superficial and bedrock strata, whilst retaining the original 15m high facade dating from the 1820s.

Desk studies and site investigations proved that the hillside was underlined by a veneer of fill and colluvium, various Triassic deposits and alternating sandstones and mudstones of the Quartzitic Sandstone group. These latter Carboniferous rocks dip out of the hillside at angles of between 20° and 30°. Carboniferous rockhead is complex with a variable depth of weathering, steep slopes and buried cliffs. The front of the site is underlain by a substantial thickness of made ground, colluvium and weathered Trias; the latter including gravelly clays and uncemented sands with high ground water pressures.

Most of the new structure was founded on bored cast in situ piles, although a few columns at the rear of the site were founded on pad footings where bedrock was shallow. The piles were socketed into the Carboniferous strata at depths between 5m to 20m. Difficulties were experienced in penetrating the alternating hard and soft bands as well as restricting the inflow of sands under high water pressures.

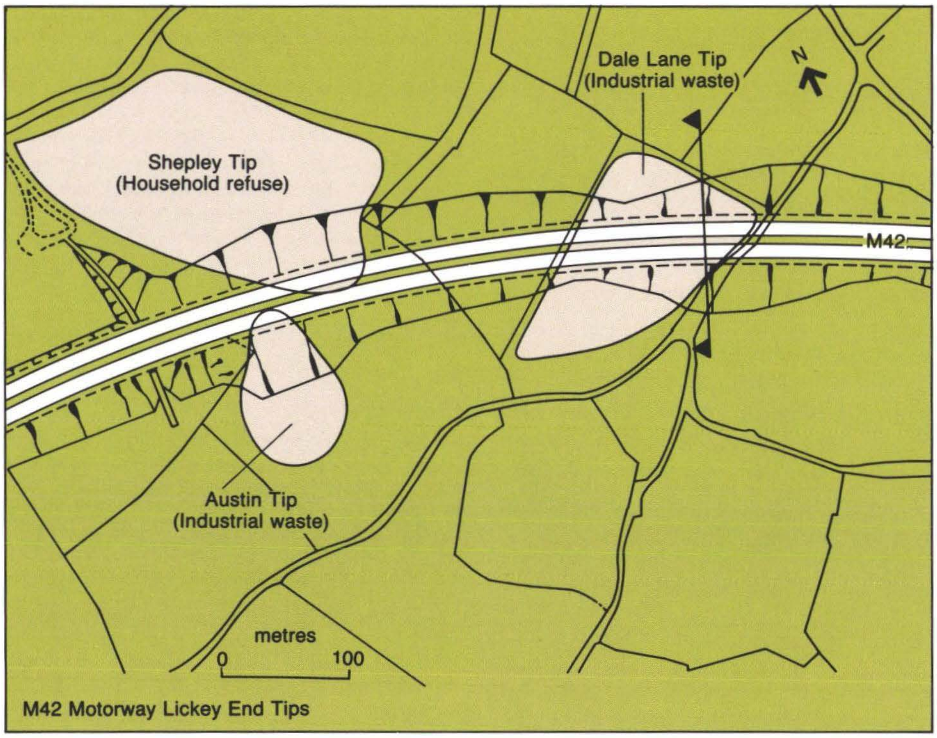
In order to maintain the stability of the hill slopes above the site, small bore shallow inclined adit drains were installed to prevent build up of water pressures within fissures in the rock. Temporary works carried out to ensure stability of the hillside during construction included rock anchors, drainage, a contiguous bored pile wall and underpinning to existing retaining walls.



Broadmead shopping area

Warwick

John Gabryliszyn



M42 Motorway Lickey End Tips

M42 Motorway: Landfill sites

To minimize the environmental impact of the M42 to the south of Birmingham, the preferred route had to pass through a number of old landfill sites. This restriction posed a number of geotechnical problems which are illustrated by the three tips at Lickey End.

Tipping at the Lickey end site was under way in 1946 and was completed in 1979. The tips contained both industrial and domestic waste, part of which was placed before regulations controlling the disposal of hazardous waste came into force.

The tips are former sand and gravel pits, underlain by Bunter Sandstone, which in this area is an important aquifer with an abstraction point some 2km from the site.

Investigation

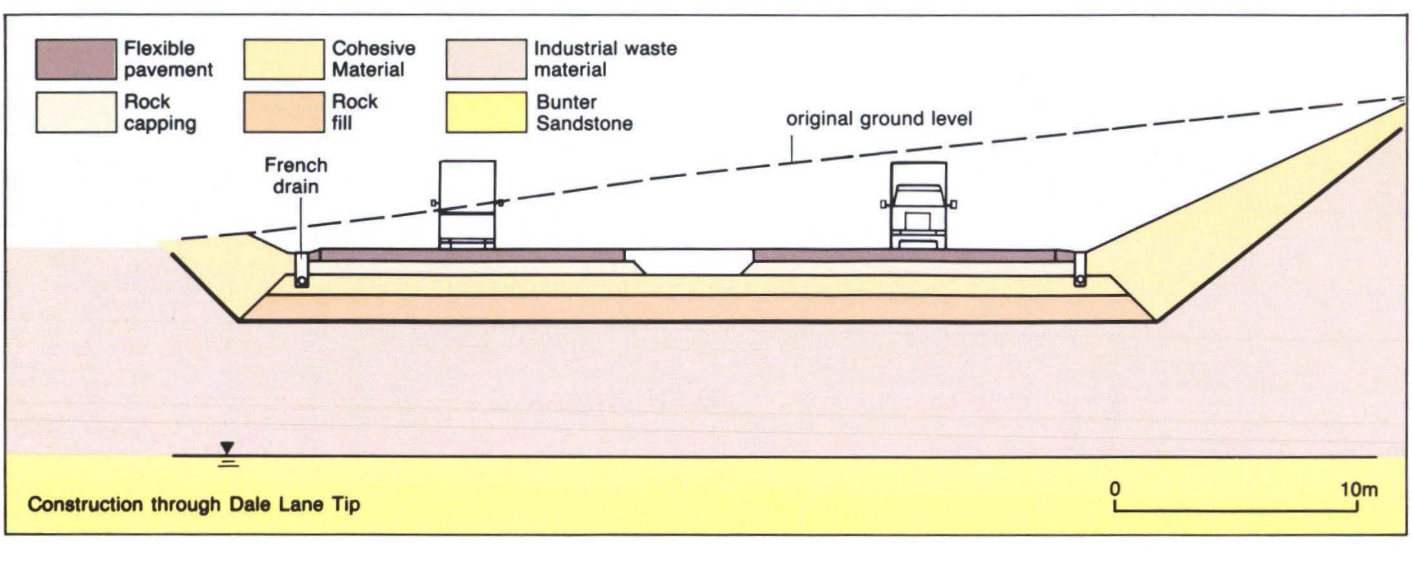
The first step in establishing the nature and age of the tipped material was to carry out extensive desk studies, in which aerial photography played an important role. It was estimated that the Dale Lane Tip alone contained 120,000 gallons of oil, 2,500m^3 of putrid waste from wholesale food markets and 46,000m^3 of old tyres. Ground investigations followed and confirmed the extent of the tips and a chemical investigation was carried out in an attempt to establish the level of contamination of the tipped material.

Further investigation at the start of construction encountered significant contamination 'hot spots' including 147 drums of cyanide compounds, which had not been identified in the previous investigations. A resident chemist was appointed to the site to inspect the industrial waste as it was excavated and to identify any materials requiring neutralization and special disposal processes. (Photos show typical tips.)

Construction

The vertical alignment of the motorway required the removal of considerable volumes of waste material. It was possible to re-deposit the domestic refuse on that area of the tip lying outside the motorway but all the excavated industrial waste had to be disposed of in licensed tips off site. The contractor obtained license for his own tip adjacent to the motorway some 3km from the site. This greatly reduced disposal costs and as the tip was reached by travelling along the motorway route, the nuisance of carting waste on public roads was avoided.

To minimize the volume of waste to be moved it was decided to 'float' the motorway across the tip material on a 2.5m thick layer of natural material. This consisted of rockfill to even out local differential settlement; and a 1.0m layer of cohesive material as a leachate barrier to isolate the motorway drainage from the groundwater regime within the tip. Regular levelling checks made on this section of motorway show that since its opening in 1986 a maximum settlement of about 70mm has taken place and that movement has now virtually ceased.



Construction through Dale Lane Tip

Ireland

John Higgins
Sean Mason

Traditionally, geotechnical work in Ireland has been carried out as much as possible by our versatile civil and structural engineers, with back-up from London's Geotechnics Division when necessary.

The appointment as consulting engineers for the £200 M redevelopment of Dublin's Custom House Docks Site at the end of 1987 allowed a permanent geotechnical presence to be established within the Dublin office.

The Custom House Docks Development scheme is the largest and most economically significant project to reach our shores for many years. The first phase comprising 27 acres is to be completed within 5 years.

The site lies to the east of the elegant Customs House built in 1796, and 'Busaras' (Dublin's central bus station), Arup Ireland's first job, built back in the late 1940s.

The site contains two large interconnected docks covering seven acres. The original old dock to the west has now been backfilled.

There are associated warehouses to the docks with basements formed in brick quoin arches which date from 1816 to 1825. The International Financial Services Centre will be the initial development sited west of George's Dock, and incorporating the vaults of Warehouse C.

About 5m of loose fill cover the entire site, including a layer of very soft contaminated silt, in the area of the old dock. Dense glacial tills and gravels underlie the fill and silts which extend down to depths ranging from about 10 to 22m below ground surface. The underlying bedrock is carboniferous 'Calp' limestone, with some soft mudstone layers, and occasional calcite veins.

Groundwater is at about Datum and has a modest tidal variation. This is probably due to the high quality of the dock walls. There is also a masonry arch culvert 3.6m wide by 2.7m deep surrounding both docks, which drains into the River Liffey via flap valves.

The work started in April 1988, with sheet piling and dewatering necessary for the excavation of up to 7m of till to enable basement construction.

We are the designers of the temporary works for McInerney's, the substructure contractor. Two large scale pumping tests have also been carried out in order to design appropriate dewatering measures.

Pad foundations are planned for the West Block and adjoining underground parking areas, bearing on the glacial gravels and tills.

Bored pile foundations bearing in the glacial tills and gravels are planned for the north and south blocks over the vaults to Warehouse C.

Design will be based on a preliminary pile test programme using both precast and auger bored piles. The adjacent George's Dock will be serviced with a floating platform to help develop the waterfront amenities within the site. Included in later phases are an International Trade Centre, offices, residential accommodation, an hotel, museums, an entertainment centre and shops.

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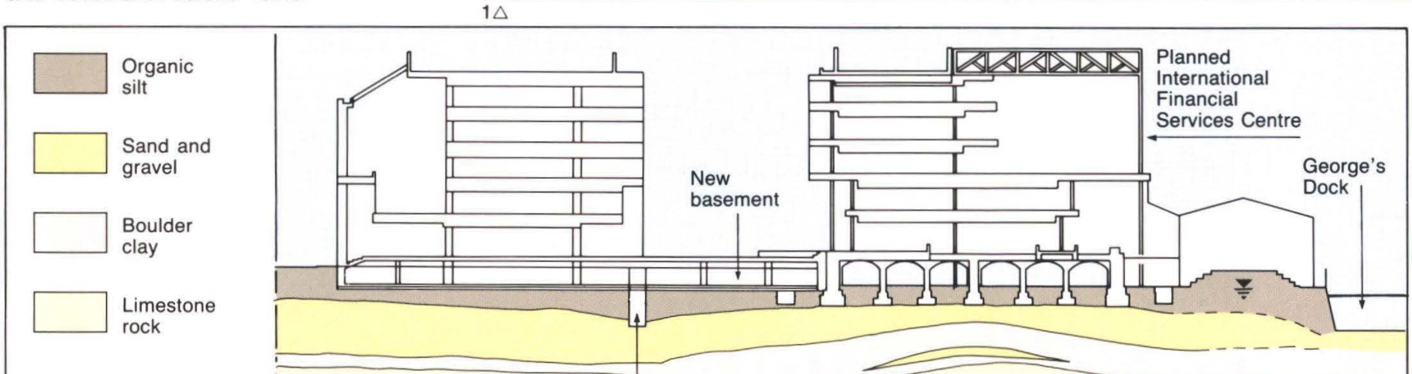

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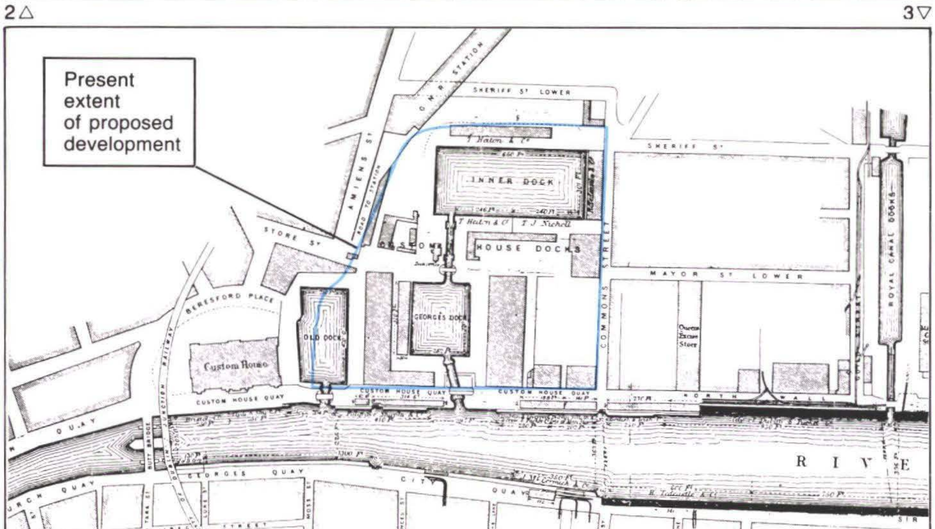

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1. Dublin's Custom House Dockside: Aerial view
2. Cross-section through proposed structure
3. Site map, c.1896
4. Warehouse C vaults

Turkish roads

Andrew Lord

Over the past 10 to 15 years Geotechnics have had considerable involvement in most of Civil Engineering's highways and bridges work overseas; notably the 600km of the Trans Saudi Arabia Expressway (SARA) and the Bukit Timah Expressway in Singapore. The scene of our overseas motorways design and construction has now moved to Turkey.

Turkey is attempting to develop its unique geographical position which straddles Europe and Asia by construction of an extensive motorway network from Europe across the Bosporus into Eastern Turkey. Arups are currently involved in supervising the construction of some 180km of the Kinali-Sakarya section of this motorway in partnership with the local Turkish firm of ENET and the American firm De Leuw Cather. This motorway will be extended westwards by 150km to the western border of Turkey with Bulgaria and Greece in a separate design and construct contract won by the Turkish contractor Dogus. In partnership with Turkish consultants Botek we are currently providing the design input — construction was due to start in August 1988.

Although for many Turkey is seen as a sun-drenched Mediterranean coastline, the climate of the comparatively narrow strip of land between Europe and Asia, along which the motorway passes, and which includes Istanbul, is dictated by that of the Black Sea. This climate has been described as 'six months heat and dust, six months rain and mud' and it is the latter which has proved to influence strongly much of the geotechnical design of the motorway.

The Kinali-Sakarya Motorway project has been divided into four sections as shown opposite.

(1) From Kinali to Mahmutbey, on the outskirts of Istanbul, the motorway is 62km long, including a 2.2km long viaduct at Karasu.

(2) This 37km section starts from the city suburbs and crosses the Bosporus on a new suspension bridge.

(3) The Camlica-Gebze section starts just to the east of the existing Bosporus crossing, and amounts to 65km of road including two links to the existing E5 expressway.

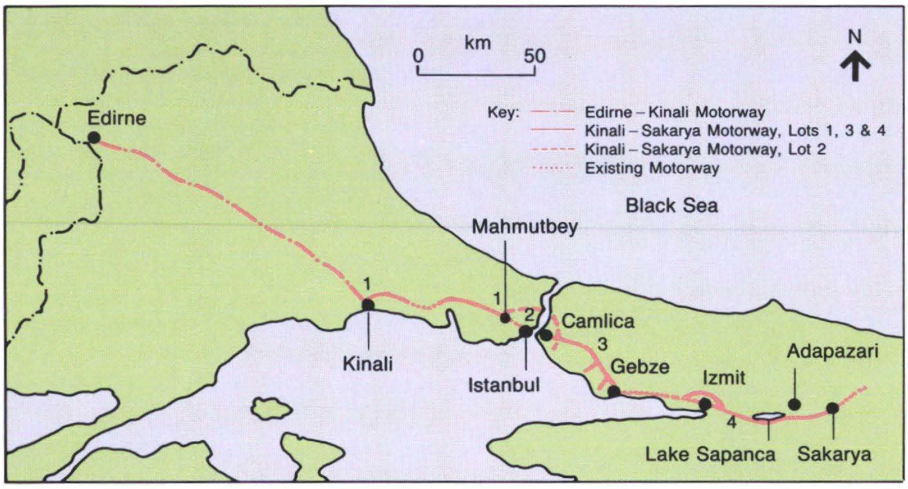
(4) The Izmit-Sakarya section which is 73km in length has been split into two sections:

(a) The Izmit by-pass, starting from the eastern end of the existing motorway and skirting through the steep hills to the north of Izmit by a series of spectacular viaducts, up to 85m high, and three tunnels with a combined length of over 2000m.

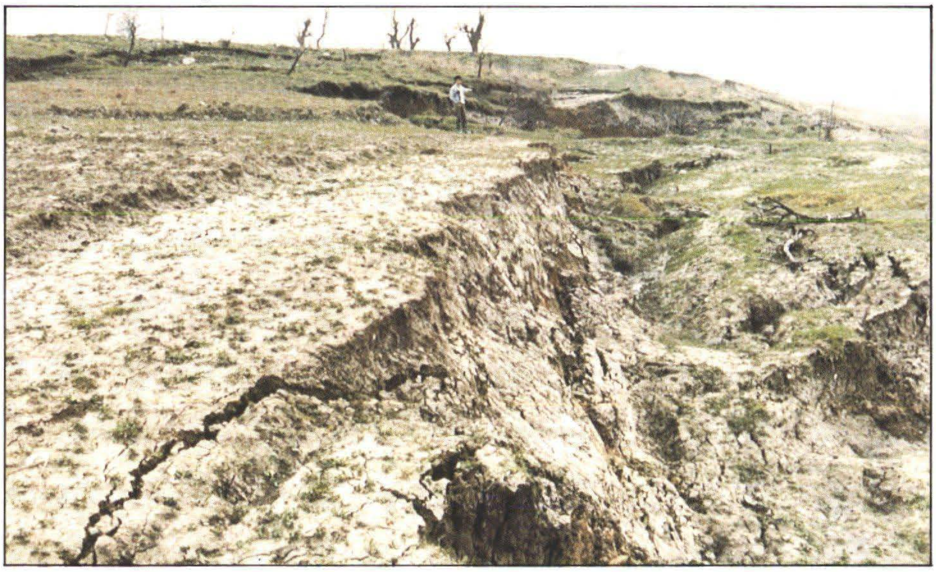
(b) The remainder of this section crosses the very low-lying area to the south of Lake Sapanca before crossing the Sakarya river on a viaduct 400m long.

Arups with our partners are currently supervising the construction of sections 1, 3 and 4. Together with ENET, we were also responsible for the design of section 3 of the motorway.

In May 1986 construction started on sections 1 and 4B of the motorway. Within a month or so of commencement of excavation of one of the major cuts in section 1, the cutting side slopes had slipped at least twice. Furthermore, following the excavation of another cutting, the wells supplying a nearby army camp dried up. As a result Ove Arup & Partners were asked by the Turkish Ministry of Public Works and Settlement (KGM) to undertake a geotechnical appraisal of section 1, and this was extended to include section 4. Working in conjunction with Bogazici University, we undertook this work between September and November 1986.



Above and below: Slope failure.



The section to the west of Istanbul passes through considerable areas of a geological formation known as Istanbul Green Clay; this formation was present in the cutting which had experienced landslipping during construction. Examination of aerial photographs showed a history of slope instability in the worst affected area; natural slopes were inclined at 1:6 to 1:9, whereas the cutting slopes had been designed at 1:3. Examination of the strata exposed in the cuttings in the areas of land slipping indicated that the Istanbul Green Clay Formation was much more complex than had been assumed by the original designers. It would appear to consist of an overlying stratum of sand which contained a number of thin continuous seams of clay which prevented downward drainage of surface water. At the base of the sand is a band of Green Mudstone which rapidly weathers to a clay on exposure, and beneath this is a thinly bedded, almost varved, black very silty clay or clayey silt. The ground water level throughout the whole area is very high, being at or just below ground level. It would appear that land slipping had taken place predominantly in the zone of Green Clay due to rapid weathering of the formation and the low effective stresses resulting from the high water table. Slipping was also observed in the underlying black very silty clay. The problem appeared to be further compounded by seepages from the overlying sand layers which feed water into the tension cracks and rapidly promote mud flows. Analysis indicated that the stability of intact slopes which are undrained could be achieved with a side slope of 1:6; if slope drainage was introduced, which was considered to be essential to prevent erosion of the face of the slope, slope angles of 1:4.5 could be adopted. In our report for section 1 we subdivided the earthworks cuts into three types:

(1) Cuts in areas of relic landslipping in which re-activation of slips had occurred soon after excavation of the cut.

(2) Cuts in intact Istanbul Green Clay in which we predicted that slipping would take place within a very short period of completion of the cut — certainly considerably less than the design life of the road.

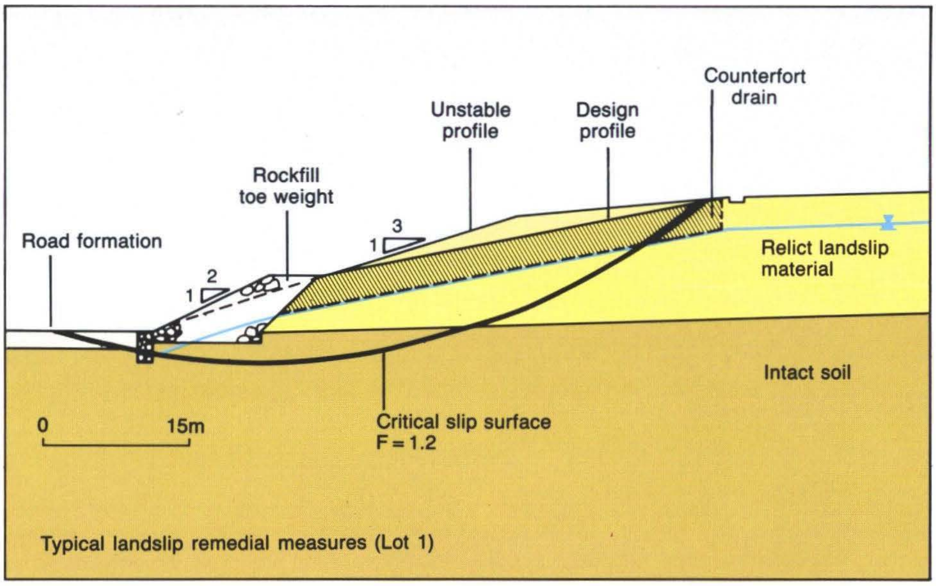
(3) Cuts where there was a dearth of borehole information.

In the cases of 1 and 2 we recommended that the cut slopes be re-graded and that slope drainage installed. In the case of 3 we recommended that further site investigation be undertaken. Needless to say our report was not received enthusiastically. However, we were considerably heartened in terms of our prediction capabilities by the occurrence of landslips in every cut over a 34km length of the motorway, where it passed through the Istanbul Green Clay, during the winter of 1986/87. Consequently in spring 1987 we were asked to undertake complete re-design of those sections of the motorway through the principal landslipped area, about 7km in length, and to recommend slope re-grading or drainage measures for those cuts listed under (2). In addition, further boreholes were carried out in the summer of 1987 at the western end of the route where the previous site investigation was deficient in geotechnical information.

It also proved necessary to undertake further boreholes and Dutch Cone testing along the length of the Karasu Viaduct in order to determine the lengths of the 1.5m diameter bored piles, constructed under bentonite in groups of four beneath each pier, which were socketed into mudstone at depths exceeding 40m.

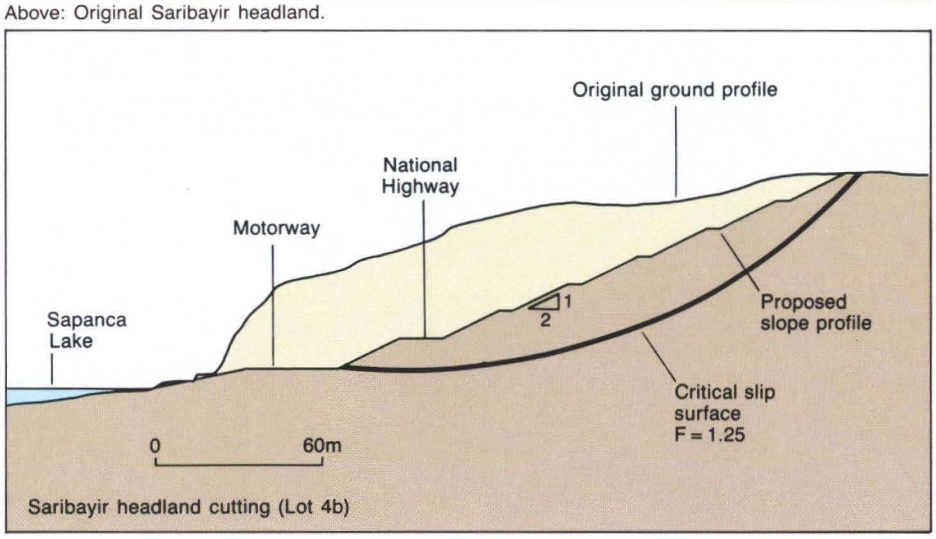
To the east of Istanbul in section 4A, we undertook a geological assessment of available borehole information in order to identify potential problems in the construction of the tunnels on the Izmit By-pass. As a result the alignment of the motorway was moved further north to avoid tunnelling through conglomerate. In the course of these studies we discovered a major fault which could not be avoided at the western end of the alignment. The city of Izmit itself lies on a major east-west trending Graben fault which passes through the Sea of Marmara — our joint studies with the Kandilli Observatory of the Bosporus University showed that earthquakes with a magnitude of 7 on the modified Mercali scale occurred every 20 years in Izmit! However the Observatory's microseismic records indicated no past movement on the fault that crossed the alignment — it was therefore concluded that this fault was no longer active.

In section 4B the principal geotechnical problems arose from the low-lying, waterlogged, silty shoreline along the south side of Lake Sapanca, with its consequential problems of embankment construction, and the possible re-alignment of the route through the Saribayir headland at Sapanca. In the case of the latter the alignment had been designed to follow the course of the existing railway line which itself was to be constructed further out into the lake on a new fill. However, in view of the soft sediments on the lake bed and the high risk of seismic activity, this design was considered to pose unacceptable problems. Accordingly we were asked to re-design the alignment slightly further inland which involved cutting away the majority of the headland, so forming a cut about 75m deep on one side.



Typical landslip remedial measures (Lot 1)


Above: Original Saribayir headland.



Saribayir headland cutting (Lot 4b)

Further appropriate site investigation work was undertaken under Bill Addington's direction in the summer of 1987 — construction will start in July 1988.

Our work on the Edirne-Kinali section of the motorway started in autumn 1987 with the requirement that we completed our design of the 20km long 'priority' section by February 1988. Insofar as we had to investigate 5 to 10km beyond either end of the priority section in order to identify the basic geology of the area, we were just able to complete the boreholes for the earthworks before the weather closed in and access became impossible. With the improving weather conditions in the springtime, boreholes for the structures on the priority section and for the earthworks on the eastern section of the route have now commenced and by the beginning of May eight boring rigs should be at work. Much of our work has been spent in trying to identify the basic geology of the areas through which the motorway passes. The same formations appear to have been given different names in different areas — it is only when faced with such a situation that the work of the British Geological Survey in the UK can be fully appreciated.

Pakistan

Asim Gaba

Sui gas field compression project

Natural gas is Pakistan's major source of domestic energy. However, demand outstrips supply, and production is limited by inadequate capacities to produce, treat, and distribute gas. Sui Gas Field, located some 500km north of Karachi in a remote seismically active part of Baluchistan Province, has the largest reserves of natural gas in the country and is crucial to the economic development of Pakistan.

The Sui Gas Compressor Station is a vital component in the first stage of gas supply to the national distribution network in Pakistan. In March 1984 Ove Arup and Partners were sub-contracted to provide geotechnical advice to Foster Wheeler Energy Ltd. for the construction of the gas compressor station (value: £260M) for Pakistan Petroleum Ltd. Initially, this involved the supervision of fieldwork for the geotechnical appraisal of a large site. However, in September 1984 during excavation for the foundations of the gas compressor station, a number of open cracks or fissures, up to 1m wide, were encountered in the bedrock over much of the site. These fissures were not visible at the surface nor on aerial photographs taken prior to initial site preparation, nor were they encountered during earlier phases of site investigation. We returned to conduct geological and geophysical investigations at the site and following reconnaissance studies, we concluded that the rock fissures discovered beneath the site were likely to be tensile features of tectonic origin.

We considered that the presence of the fissures beneath the site would alter the seismic response of the ground and that potential ground movements across untreated fissures due to a design seismic event would cause damage to the pipework and structure.

Four options were considered as possible solutions to the hazard posed by the presence of the fissures:

(1) Move to another site

(2) Adjust the arrangement of the plant within the site to avoid the fissures

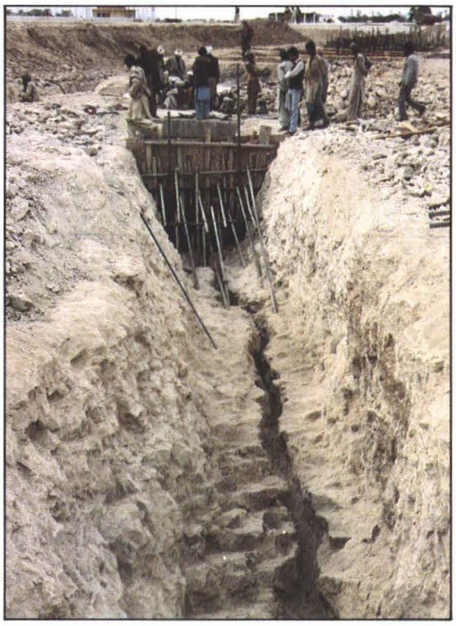
(3) Design the pipework to accept the anticipated ground movements due to the presence of the fissures

(4) Treat the fissures.

The first option would have involved considerable delay, a new programme of site investigation and the possible presence of fissures of a similar nature beneath the new site. The second and third options of adjusting the plant arrangement within the existing site or redesigning pipework to tolerate additional movement would also have involved considerable delay and substantial cost penalties. It was decided to adopt the fourth option and treat the fissures. The objective of the remedial action was to restore the surface layers of the site to a condition which existed prior to the opening of the fissures. This was achieved by plugging, with concrete, the top of each one to a suitable depth below rockhead to ensure that the ground surface on each side of the fissure would move in unison. Between October 1984 and July 1985 we maintained a geotechnical presence on site to design, specify and technically supervise remedial works.

The late discovery of the fissures necessitated rapid implementation of remedial measures and complicated phased construction to minimize costly delays to the main civil works on site. The situation on site required constant assessment as new fissures were discovered. The fissure remedial works were completed in October 1985 at a final cost of about £3M.

This project is our first major involvement in Pakistan. The Sui Gas Compressor Station was formally inaugurated by the President of Pakistan, General Zia-ul-Haq, in June 1987.



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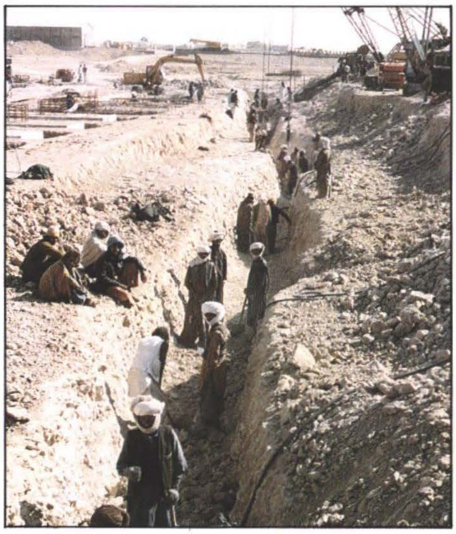

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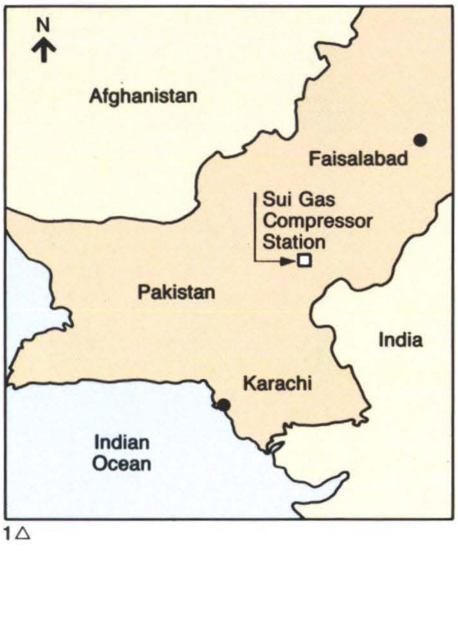

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1. Location of Sui Gas Compressor Station

2-3. Remedial works to fissures

4. Satellite image showing tectonic structure of Northern Pakistan

Nigeria

Peter Elumeze

Man-made chemical weathering of tropical soils

Guinness has been a considerable problem for geotechnical engineers in West Africa for many years. The difficulty centres not so much in its consumption as in the bottling process.

Between 1976 and 1980, we investigated the presence of cavities and subsidence occurrence at the Guinness Brewery, Ikeja. Similar problems were experienced at the Bendel Brewery at Benin City and the PZ soap factory at Aba. Later in 1982, a similar subsidence occurred at the Guinness Brewery in Benin City. Extensive investigations showed that cavities were indicated in areas under the stout bottling hall, the stout process building and the lager bottling hall. Caustic soda solution, used to clean the bottles, which was leaking from the drainage system, was implicated; and at the end, grouting of the cavities and changing of the drains from subsurface to surface was recommended. The former was carried out successfully, while the subsurface drains were not changed, with subsequent re-occurence of the problem.

Late in 1986, a bund wall within the stout bottling hall and around the buffer tank failed. This led again to a series of investigations which showed that the subsoil below most of the structures and machinery within the brewery had deteriorated, with the soil losing between 25% to 50% of its original strength.

The factors which control the flocculation or dispersion of clays are complex, but David Henkel showed in his Rankine Lecture of 1982, that caustic soda is very effective in breaking down the forces of attraction which exist between individual kaolinite particles. The clay therefore tends to de-flocculate and in this condition, clay particles may be eroded from the surface of the soil or from the sides of drainage channels.

We recommended that micro piles be introduced to take loads off the soil, weakened by the caustic soda seeping into it. The subsurface drains will also be changed to surface drains to make maintenance and leakage control far easier.

Above: Unwashed soil
Below: Soil washed in caustic soda

Arups have advised on very similar cavity problems at the Guinness Brewery in Duala, Cameroons.

Botswana

John Henry

Nata-Maun Road

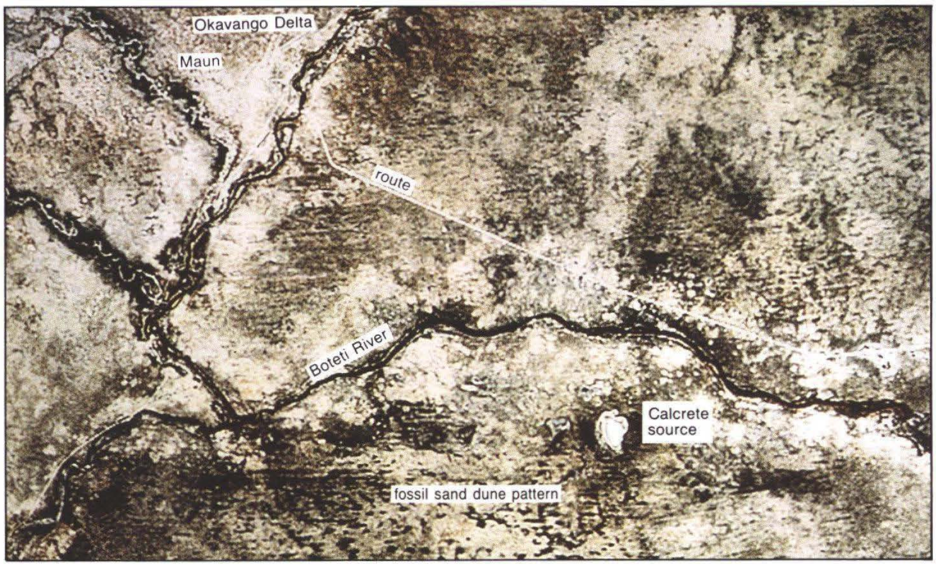
Since the initial Botswana Feeder Roads Study which involved satellite interpretation of 4100km of route scattered around the nation, we have had frequent involvement in new route location studies although none has been connected with the original work. Certain themes recur — shortage of suitable material, shortage of water, vast distances and monotonous terrain and vegetation that make locating oneself accurately a problem even when 1:50,000 maps exist. With very few settlements to connect, the guiding principle is to route through or near materials sources, which are first identified on aerial photographs and/or satellite imagery.

The proposed Nata-Maun route had all these characteristics. Independent materials exploration surveys over its 300km length had not located materials of adequate strength. Using newly commissioned 1:50,000 photography, an 11km corridor was studied in detail. Available Landsat satellite imagery enabled forays into promising areas outside of this corridor.

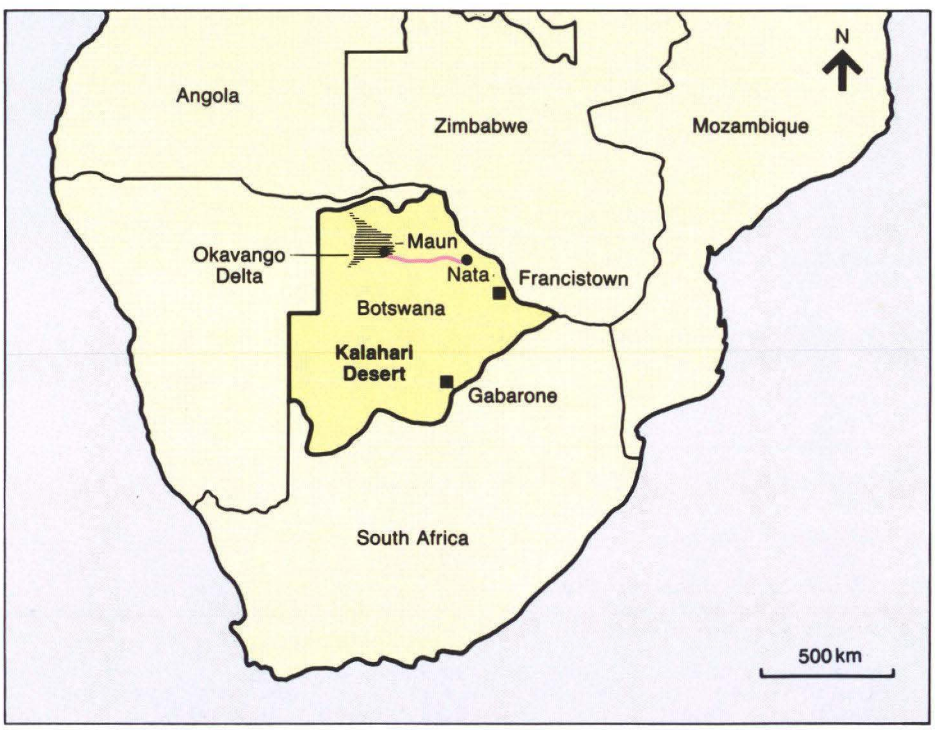
On the thick Kalahari sand cover the only rock or gravel materials are calcretes, less commonly silcretes. Both are recent evaporate deposits forming relatively thin crusts in some localities. Calcretes are recent calcium carbonates varying from chalky powders to hard nodular and tabular limestones. Silcretes are flint-like rocks often found in association with calcretes. Nodular calcretes are the best local source of road stone but were uncommon in the Nata-Maun corridor. These are most frequently associated with terraces around pans and fossil drainage systems.

These are features which are readily identifiable from the air. A large source was located 11km south of km270 near Maun. Although the material quality was less than ideal, it was the best available in the whole corridor and in sufficient quantity to justify a new river bridge and link road in order to haul it to the proposed route.

The loan agreement to finance construction was signed in February 1988 and work should begin in the near future.



Above: Satellite image shows calcrete source and existing route
Below: The proposed route of the Nata-Maun Road



South East Asia

Julian Wallace

Arup Geotechnics has had a continuous presence in this region since 1982. Before then, geotechnical staff were provided from London on a project basis, for example on the 65-storey Komtar Centre in Penang and the east-coast highway in Peninsular Malaysia and the United Overseas Bank Building in Singapore. Currently we have four geotechnical engineers here, one in Kuala Lumpur and three in Singapore.

Singapore

Our work has included major building developments and a wide variety of civil engineering projects. On the buildings we have generally been engaged by the developer. However, in civil engineering we often work for contractors on design-and-build projects; in some cases as part of an Arup design team and in others purely as geotechnical consultants.

Recent civil engineering projects include roads and bridges, an underground railway station, bored and cut-and-cover railway tunnels, port expansion works, and terminal structures for a precast undersea cable tunnel. Two projects are described below.

Newton Station

The design and construct contract for this underground station was awarded to Dragages Sembawang Construction for whom we carried out both pre-tender and final design. The station is about 180m long by 21m wide by 15m deep. The contract included a section of cut-and-cover crossover tunnel about 120m long by 7m wide by 15m deep.

Ground conditions at the site were highly variable comprising soft marine clay up to 20m deep overlying fluvial sands and clay over completely decomposed granite. A detailed site investigation comprising 56 boreholes, 25 Dutch cone tests and pumping tests was carried out to supplement the information provided with the tender documentation. During the course of the work four buried channels in the granite infilled with soft marine clay were identified.

The station was constructed using the top down method with 0.8m thick perimeter diaphragm walls. Jet grouting was used in a deep buried channel to stabilize the marine clay below the base slab. A pumping system was designed and installed to dewater the fluvial sands and decomposed granite below the excavation whilst a system of recharge wells was used to maintain the groundwater level beneath the marine clay outside the site to control consolidation settlements.

The station was only about 10m away from three adjacent buildings and it was therefore very important that the design limited ground movements outside the excavation. Ground movements were monitored throughout the work and compared with the design predictions. This enabled the performance of the works to be continuously reviewed and the construction sequence to be optimized.

Mass rapid transit tunnels

We were engaged as geotechnical consultants by a contractor boring several kilometres of supposedly soft ground tunnel. The 6.5m diameter tunnels, in a heavily built-up area of the city, went through some particularly difficult ground, ranging from very soft marine clay to unexpected extremely strong dyke rock. There were road collapses, damaged buildings; a whole gamut of problems. We were called in when work was already under way to give advice.

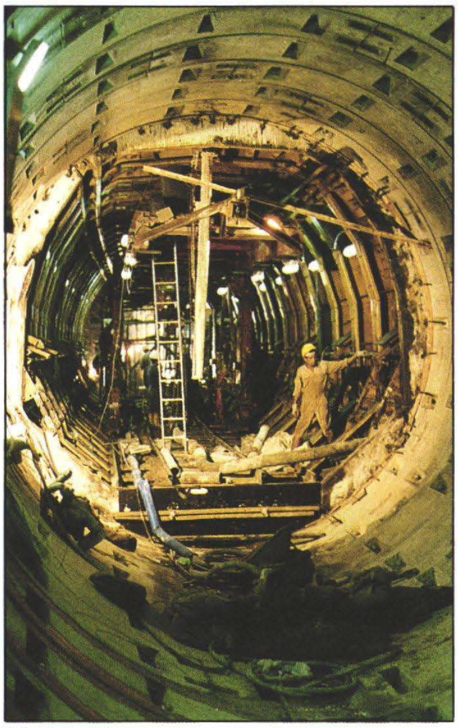
Three tunnels were excavated using a shielded tunnel boring machine with a full face cutting wheel, installing a temporary lining of steel ribs and timber lagging, followed by a permanent cast in situ concrete lining. A fourth drive was bored with an open-shield backhoe machine, installing a permanent segmental precast concrete lining immediately behind the shield.

Groundwater inflow and settlement along the tunnels was generally controlled by compressed air. This method could not be used safely in one tunnel for fear of pressurising underground structures in permeable ground further back. Instead, a system of recharge wells and grouting was used to restrict face losses and settlement.

Another problem was consolidation of the marine clay squeezing the temporary circular ribs into unstable egg shapes while the permanent support was still hundreds of metres back along the tunnel. Close monitoring and local strengthening works were required.

The trains started operating in November 1987; but that is not the end: unresolved tunnelling claims run into millions of pounds.

Indeed, the outstanding lesson on this job was the crucial significance of ground information at the time of tenders.



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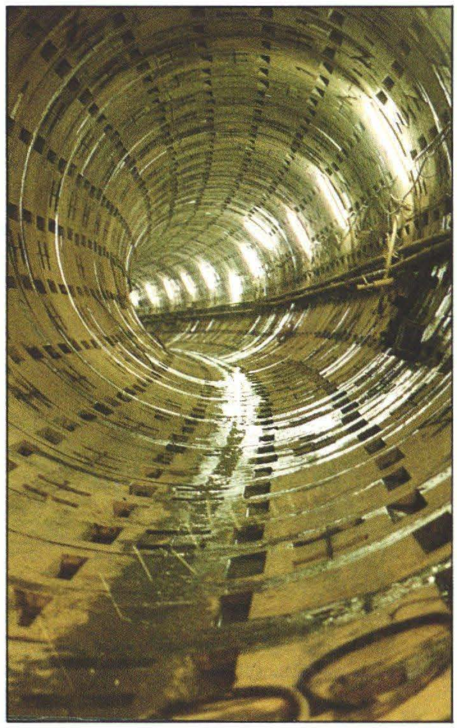

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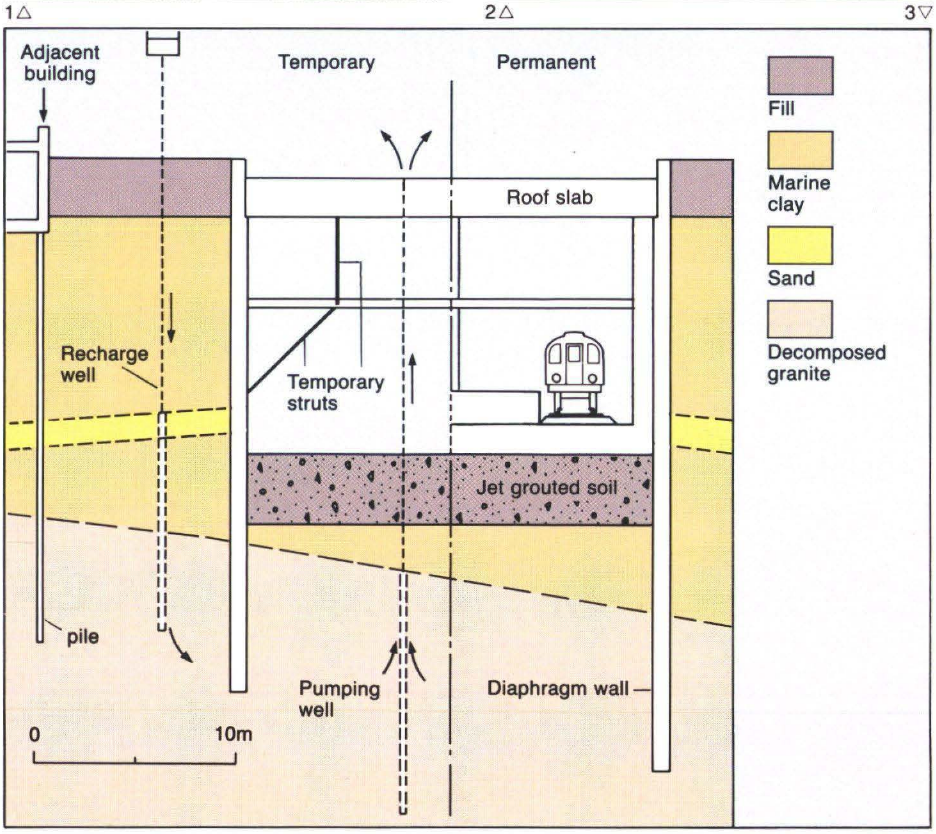


MRT tunnels

1. Cast in situ concrete lining
2. Completed segmented precast lining

3. Temporary and permanent construction Newton Circus Station

Malaysia

Much of our building work is in Kuala Lumpur, and here many sites are underlain by soft alluvium over limestone bedrock. The elevation of the rock surface can vary dramatically over short distances and there are often solution cavities within the rock mass itself, sometimes tens of metres in size. This makes for considerable problems in the design and construction of foundations to high-rise buildings. One such project was the Pan Pacific Hotel described below.

Foundations to Pan Pacific Hotel

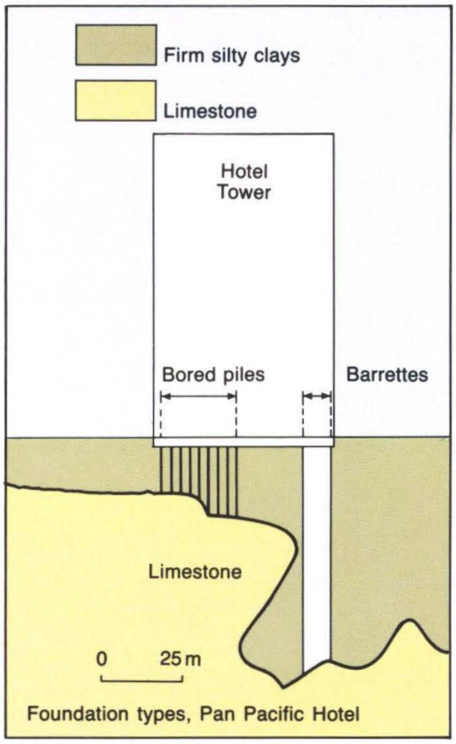
Pan Pacific Hotel is a 30-storey tower block built entirely using precast wall and slab units, with in situ stitching. Such a potentially brittle structure needed a rigid foundation. Almost 100 borings showed that the building was sited over a limestone 'cliff' about 50m high overlain by the silty clays or clayey silts of the Kenny Hill Formation.

The 'cliff' was in the form of a 15m overhang. This is shown in the geological section A-A, which indicates the foundations adopted in the 'deep' and 'shallow' areas of limestone. Because of the nature of the structure, all foundations were taken to rock, but avoiding the overhang. Large pile caps were used to span the structure across the cliff, and overhang.

Where about 20m of the Kenny Hill clays overlay the limestone, foundations consisted of groups of 1.2m diameter bored piles, with 1.5m long rock sockets. A working load of 6000kN was used. Every pile was probed for cavities for at least 6m below the base of the rockhead. Where cavities were found, the pile was underpinned with four 180mm diameter micropiles taken 6m below the lowest cavity. Three 50mm diameter high tensile steel bars formed the reinforcement for the micropiles, which were up to 40m deep. 156mm diameter permanent steel casing was used through the cavities themselves to control grout losses and minimize the risk of buckling in the void.

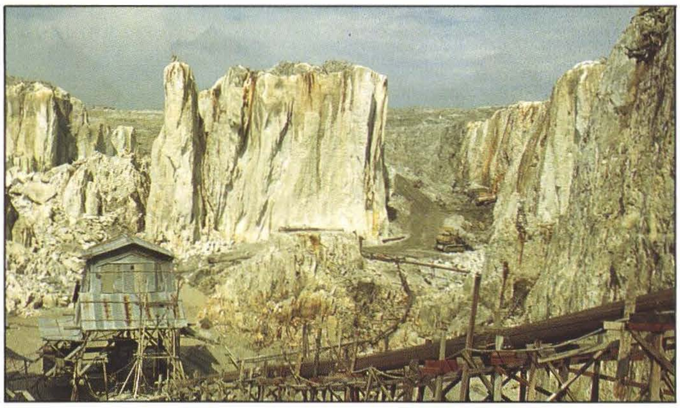
Where about 75m to 90m of Kenny Hill clays overlay the limestone, foundations consisted of groups of barrettes or rectangular piles. The barrettes were 2.7m by 0.6m with a working load of 9000kN. Excavations under bentonite took three to four days and were completed with a 0.3m deep rock socket in the limestone. Where cavities were encountered beneath the barrettes they were filled with grout. Typical consumptions of grout were about 160 bags or 6m^3, but several barrettes needed between 700 and 5000 bags of cement.

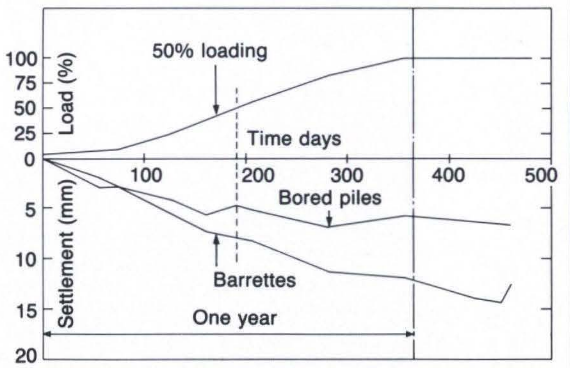
Settlement behaviour of the building was also monitored. The measurements indicate a differential movement of about 6 to 7mm between the structure on bored piles and barrettes. This represents angular distortions of about 1/1200. The results of load tests on a trial pile and a barrette are shown on the plot of settlement against time for comparison.



Foundation types, Pan Pacific Hotel

Below: limestone cliffs exposed in a tin mine near Kuala Lumpur



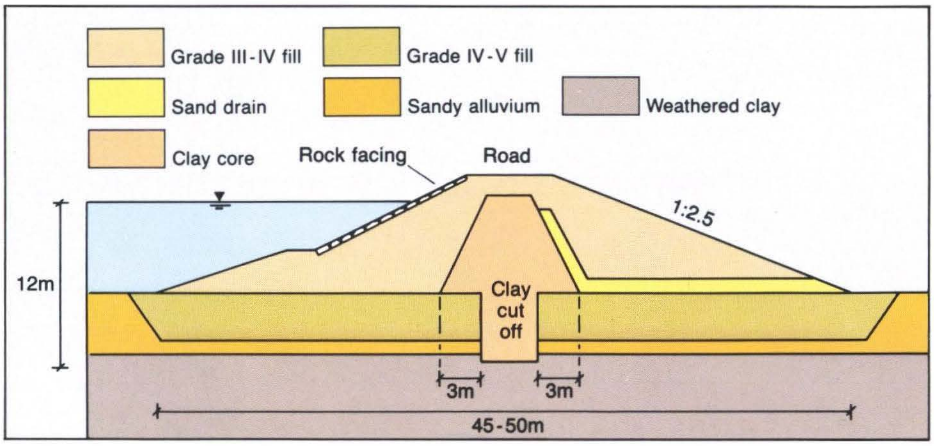


Settlement monitoring data, Pan Pacific Hotel

Indonesia

Our jobs have been in widely scattered parts of the archipelago, from Sumatra in the west to the far-flung eastern territory of Irian Jaya (the western half of New Guinea). We work with less reliable data than we are used to, and a keen awareness that our engineering solutions must make allowance for local practice and construction standards. There are also earthquakes to contend with.

On one of our completed projects we worked for a turnkey contractor, designing foundations for a number of diesel generating stations — each serving one town or village. Ground conditions and foundation solutions varied from place to place.



The photo shows an earthdam we designed, on Pulau Bulan, an indonesian island south of Singapore. The dam, 185m long by 8.5m high, stores water for a farm of 100,000 pigs.

We have been involved in site selection, site investigations and design of earthworks and foundations for several mills and factories for one of the government palm oil companies. One is a 60 tonne/hr mill, now under construction, in seismically active Irian Jaya, a remote and fascinating part of the world.

Above: Cross-section through dam

Left: Pulau Bulan embankment dam

Current projects in Jakarta include a 10-storey shopping/entertainment complex with a 1 to 2 level basement. It is to be supported on piles which penetrate soft alluvial strata, common in low lying Jakarta, to found on a layer of lahar — partially cemented volcanic soil transported in ancient mud flows.

We recently gave advice to the Jakarta building authority in connection with settlement and structural damage to the adjacent Russian embassy; an interesting case in which the geotechnics was a great deal more straightforward than the politics.

Hong Kong and China

John Davies

Introduction
Since establishment of our office in Hong Kong during the mid 1970s, geotechnical engineering has been a central part of our activities. Early projects ranged from the Mid-Levels slope stability survey to design of deep excavations and foundations for the Mass Transit Railway.

More recently, the 1980s have seen a shift in our workload towards the private sector in Hong Kong and an expansion of our field of activity to include the People's Republic of China, the Republic of Korea and many other parts of Asia. Illustrated here is a selection of projects representing the type of work we do, with the emphasis on more recent jobs.

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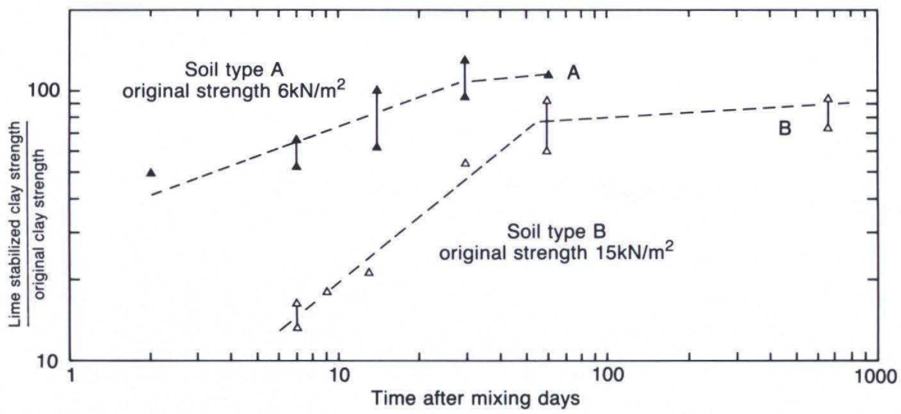
1. Hand-dug caisson wall: Happy Valley
2. Large bored piles: Heng Fa Chuen
3. Site formation: Hong Kong Barracks
4. Mixing quicklime and soft clay



5. Increase in shear strength with time: Prototype lime column, Shatin Racecourse

Hong Kong

Hong Kong's hilly terrain and large population ensure that developable land is constantly at a premium, despite a continuing programme of land reclamation. A large part of our work concerns the geotechnical problems associated with the design of high-rise buildings (up to 60 storeys) on restricted sites: site formation, slope stability and deep foundations, often with deep basements in the reclaimed coastal areas.

On steeply sloping sites retaining walls are often formed of a row of hand-dug caissons, anchored or propped in the temporary case with long-term support provided by the completed building. At one such site in Happy Valley (Fig. 1) a row of 1.1m diameter caissons supports a 17m deep excavation for two 25-storey residential blocks.

Our largest site formation project to date was originally intended as a barracks for Hong Kong's 5th Battalion but is now to be the site of the University of Science and Technology. Completed in its original form (Fig. 3) in 1985, the scheme provides 28 platforms and 3.5km of roads on a large hillside site underlain by decomposed volcanic rocks.

Deep foundations for heavy structures generally consist of hand-dug caissons or machines bored piles, founded on the granite or volcanics bedrock, or driven piles founded in the overlying decomposed rock. At Heng Fa Chuen a residential development of 23 towers is being built on 10ha of reclaimed land, part of our site formation design for MTRC's Chai Wan Depot. The buildings are founded on more than 600 bored piles up to 2.5m in diameter and 60m long (Fig. 2).

The conventional reclamation technique of end-tipping fill often causes mud waves in the soft marine clay on the sea bed. This often produces a variation in thickness of marine clay over the reclaimed area which can result in differential settlement as the disturbed clay consolidates.

One method of reducing settlements is the installation of lime columns, a technique which involves the in situ mixing of quicklime with the soft clay using an auger (Fig. 4). This was demonstrated at the Royal Hong Kong Jockey Club's racecourse at Shatin in the New Territories where a prototype trial illustrated how the resulting lime columns increase in strength with time compared to the clay and reduced settlement of the ground (Fig. 5).

In recent years a growing area of our work has been in preparing alternative basement and foundation designs for contractors tendering for projects. The strict discipline in time and cost-effectiveness that this type of work requires also aids our ability in the conventional consultant's role. A project where this was demonstrated was a foundation design for a flyover at Rumsey Street in Hong Kong's Western District where bedrock is more than 75m below ground level and the engineer's design required piles to be founded in the decomposed granite rather than end bearing on bedrock. Our alternative design changed the bored piles to barrettes constructed with diaphragm wall equipment and proposed using higher shaft friction values.

The performance of the trial barrettes under test met the engineer's requirement and the foundations have been constructed to our design.

People's Republic of China

Two of our largest projects in the People's Republic of China are located in Guangdong Province close to Hong Kong.

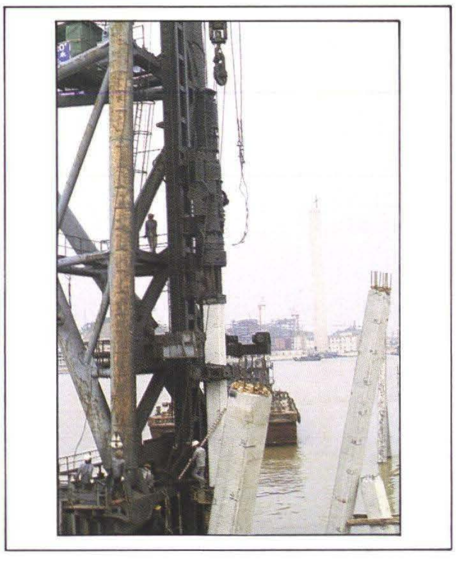
Shajiao Power Station

The winter 1987-88 issue of *The Arup Journal* gave the background to the design and construction of this 700MW power station on the east bank of the Pearl River between Hong Kong and Guangzhou.

The programme for the design and construction of the £60M civil works for a power station to an overall construction programme of less than two years was itself a challenge, particularly as 75% of the site was formed by reclamation using soil and rock obtained by removing a 60m hill. The importance of geotechnical factors to the completion of this station in a record time was recognized before the commencement of the civil design. The turbine hall with its very heavy loads was identified as being on the critical path for construction so the station layout was designed to allow the use of shallow foundations on rock for this structure.

For other structures a total of 30km of steel H-piles were driven through the reclamation into decomposed granite rock. We were able to achieve a saving of some 30% in the steel quantities by adopting working stresses of more than 0.4 times the yield strength of the steel. Four hundred 600mm square hollow section precast concrete piles up to 35m long (Fig. 6) were used to support the 1100m

6. Shajiao Power Station:
Precast concrete piles, unloading jetty

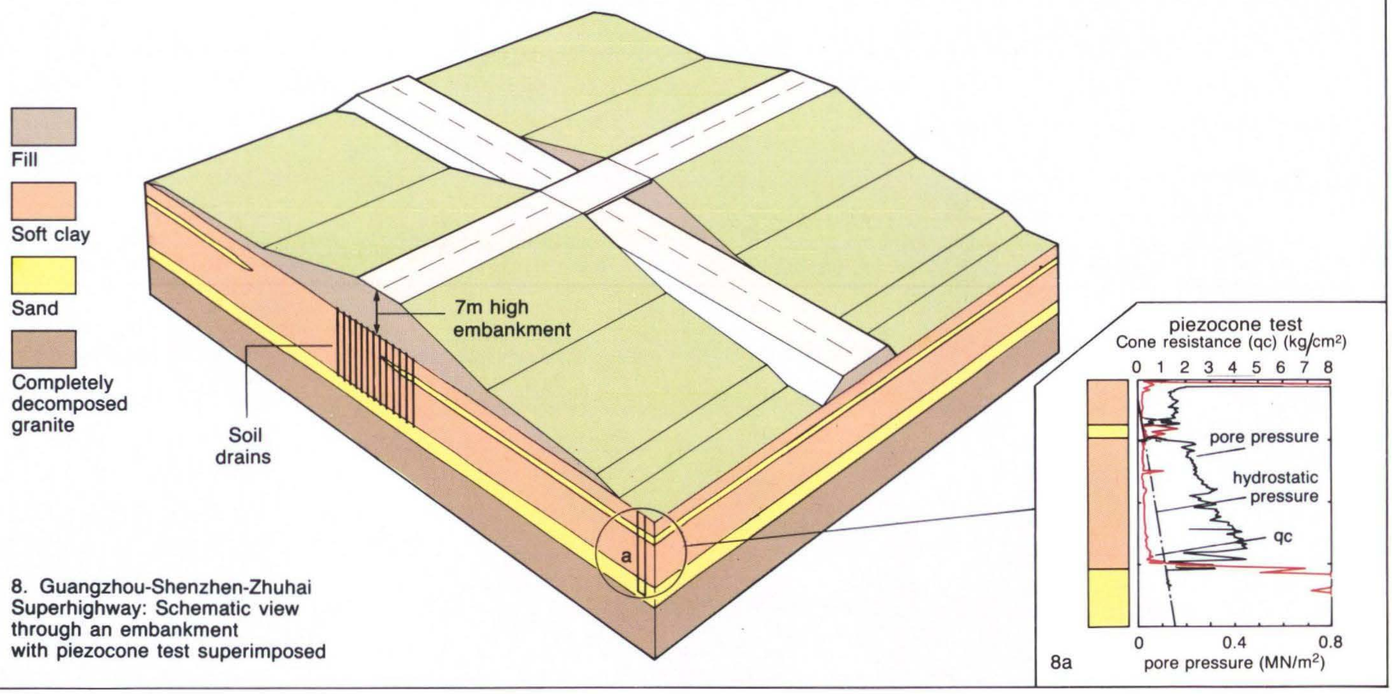


access arm to the coal unloading jetty. The heavier loads associated with the coal unloaders and berthing forces for 39 000 tonne ships required the use of two hundred and thirty 900mm diameter tubular steel piles up to 45m long.

The 12 intakes for the cooling water were located on precast box culverts 700m offshore placed in a shallow trench dredged in the soft river bed. The offshore section of the culverts was connected to a stilling basin and pumphouse by a 200m length of in situ box culvert constructed 12m below ground level both in open cut and within a sheetpiled coffer dam.

The 75m long, 25m wide by 14m deep stilling basin (Fig. 7) was constructed using a 1.2m thick diaphragm wall with a floor slab and isolated struts at 5m centres near ground level so as not to impede water flow through the basin. Flotation forces, when the basin is dewatered, are resisted by barrettes as well as friction on the outer face of the diaphragm wall.

7. Shajiao Power Station: 1.2m thick diaphragm wall for stilling basin



8. Guangzhou-Shenzhen-Zhuhai Superhighway: Schematic view through an embankment with piezocone test superimposed

Guangzhou-Shenzhen-Zhuhai Superhighway

Construction of the first section of the Guangzhou-Shenzhen-Zhuhai Superhighway commenced in 1987. This 19km length of road crosses very variable terrain which requires the formation of cuttings up to 50m deep and embankments up to 15m high.

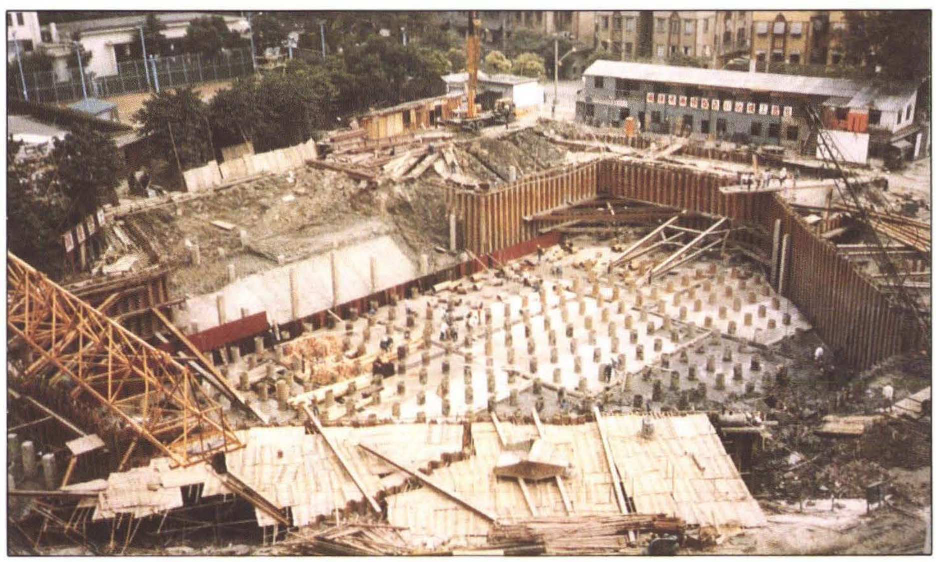
Special problems occur where 4km of 5 to 7m high embankment is being built across submerged land underlain by deep deposits of soft clays and silts. Soil drains are to be used to accelerate the settlement of the soft clay while berms alongside the embankment will provide stability (Fig. 8).

A recently developed site investigation technique, the piezocone test, which has rarely been used in China, was mobilized for the project. This test measures pore water pressures during probing. It is particularly useful in identifying thin layers of sand in clay deposits (Fig. 8a) which are significant because they have a considerable affect on the consolidation behaviour of the soil mass. Pore pressure dissipation tests using the piezocone provided useful information for the design of soil drains.

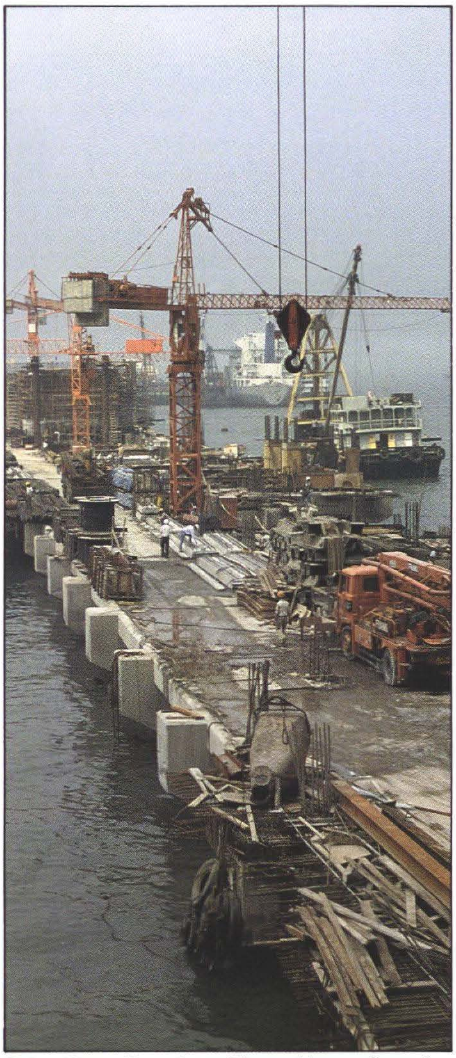
The field behaviour of the soft clay is being investigated by constructing an instrumental trial embankment, the results of which will be used to refine the design of the highway embankments.

Shanghai

In Shanghai particularly challenging geotechnical problems are presented by two hotels founded over several hundred metres of highly compressible alluvial clays. The 42-storey Shanghai Hilton International was completed in 1987 whilst the 33-storey Jin Cang Mandarin is presently under construction. The foundations comprise 40m long steel pipe piles (see photo below) driven to a thin sand layer within the alluvium. Consolidation of the clay is expected to result in 150mm settlement of each hotel tower.



Jin Cang Mandarin Hotel: driven steel piles



China Hong Kong jetty (Photo: Martyn Stroud)

Sea water tunnel construction, Hongkong Bank (Photo: N. Farrin)

Hong Kong housing authority, slope remedial works (Photo: Martyn Stroud)

Australasia

Tony Phillips

Early days
Arup Geotechnics was established in Australia in 1980, by Tony Phillips who had previously worked for Arups in the UK and Nigeria. Within a week of arriving he was deeply involved in a power station siting study in central Queensland which was to last for four months.

That study still rates as one of the most intensive working periods we have been involved in, with over 20 possible sites being identified and examined at four different locations before choosing Stanwell, near Rockhampton, for development. Work was undertaken by a multi-disciplinary group of engineers working together with the client, the State Electricity Commission of Queensland, on a daily basis. Geotechnical input involved detailed air photo interpretation, carried out by a geomorphologist seconded from London. This assisted geological mapping and the subsequent assessment of geotechnical design parameters to enable preliminary designs and costings to be undertaken. For each alternative site, roadworks, railways, earthworks, foundations, water and ash disposal dams were considered. The study team's recommendations were accepted by the client and the power station is being constructed on the chosen site.

Once the Queensland study was complete the task of establishing Arup Geotechnics in Australia and defining its aims and objectives began in earnest. Unlike the arrangement elsewhere in the world at that time, Arup Geotechnics in Australia was given a separate identity. It was expected to provide specialist advice to Ove Arup & Partners, but in addition it was a stated policy that it should seek its own commissions independent of the rest of the practice.

Growth
During its first year the practice developed and expanded from undertaking geotechnical investigations for office and housing developments through to major projects in Sydney including the 52-level Grosvenor Place development, and the 22-level Intercontinental Hotel. On each of these projects geotechnical involvement continued through the design phase into construction, where various specific problems had to be solved to facilitate progress. As staff numbers increased over the next few years the geographical spread of projects extended rapidly across the continent and included jobs in Perth, Canberra, Melbourne, Brisbane and several more remote locations including the Yulara tourist resort at Ayers Rock.

True to our original intention Arup Geotechnics began to generate its own work independent of any other involvement by Ove Arup & Partners. One of the first major jobs which we undertook in this regard was at Port Kembla. We were commissioned by the Maritime Services Board of NSW to undertake the geotechnical engineering design for a new grain handling terminal.

In addition to the design of a stable underwater revetment slope 20m high, advice was given on dredging requirements and the design of tubular steel driven piles.

In the last few years, growth within the firm in Australia has resulted in new staff adding expertise in the fields of engineering geology, rock mechanics, dam design and underground engineering. This complements our established skills in ground engineering, foundation and excavation design, highways, bridges and maritime works.

Grosvenor Place Development, Sydney: Hawkesbury Sandstone

Yulara tourist resort, Ayers Rock

Proposed Bennelong Point underground car park: In situ permeability testing

New offices: The future

In January 1988, Paul Wallis, our Senior Engineering Geologist, moved to Brisbane from Sydney to open successfully our first geotechnics office outside Sydney. We intend to continue this expansion of our operations throughout the Australasian region to establish a network of regional offices, each with a core group familiar with local conditions and respected by the local community. In this way we can pursue business opportunities throughout Australia, ensuring a personal approach, while having the wider resources of the group at large and our overseas colleagues to draw upon for any project requiring particular specialist skills.

In summary, with our growing strength and sound track record covering substantial projects, we are aiming for continuing success in building engineering but also for a deeper involvement in the resource development sector and large-scale civil engineering work.

Skills and projects

The range of skills which we have available today is best demonstrated by specific reference to some completed projects throughout the region.

Australia

In Portland, Victoria we undertook raft foundation design, overall stability and settlement analysis for 14 coke silos constructed on fill placed over compressible sands and clays overlying weathered basalt. Our brief also included design and installation of a settlement monitoring system and interpretation of ground movements during construction filling.

A comprehensive investigation has been undertaken for the Department of Main Road, NSW, through an appointment to the Snowy Mountains Engineering Corporation. This involved site investigation and geotechnical design for an 18km section of the Hume Highway between Gunning and Yass in the Southern Tablelands region of NSW. Work included an assessment of construction materials, slope stability, rippability assessment in deep cuttings, drainage requirements and an assessment of subgrade conditions for pavement design.

In a commission from the Public Works Department of NSW, Arup Geotechnics carried out a site investigation in the Botanical Gardens for the proposed Bennelong Point underground car park to be constructed beside the Sydney Opera House. Sufficient geotechnical information was provided from a site investigation for tenderers to assess tunnel roof stability, groundwater flow rate and to develop a satisfactory excavation programme. Arup Geotechnics' involvements extended to providing input into the environmental impact statement for the scheme with particular reference to the effect of groundwater levels in the overlying Botanical Gardens and to assessment of the technical aspects of submitted tenders.

The Darling Harbour Development, one of Sydney's prestige bicentennial projects, consists of the redevelopment of an area of derelict industrial land at the western end of Sydney Harbour. The project faced Arup Geotechnics with the challenge of designing large foundations, many excavations and roadways on a site where ground conditions were made difficult by a high water table and the presence of up to 15m stratum of alluvial clays and fill overlying sandstone bedrock.

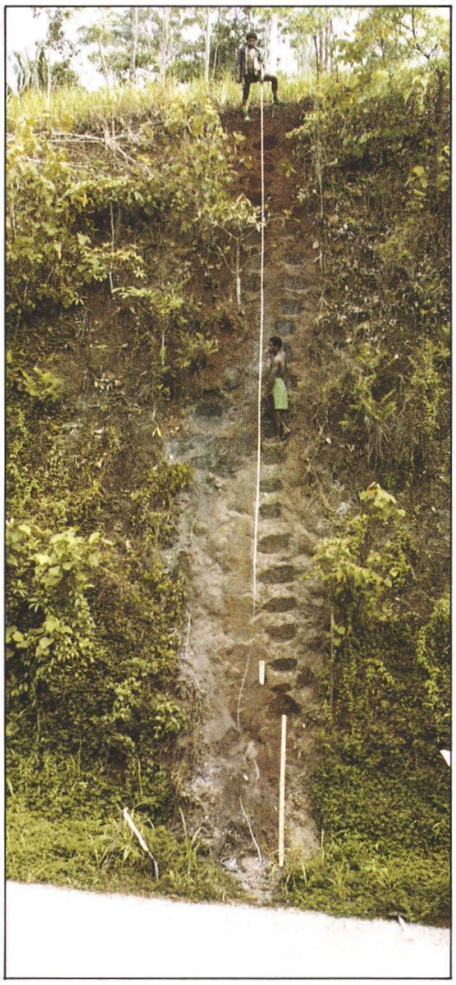
An important feature of the work was our success in using rock coring techniques in order to justify the very high stress levels adopted for both bored and driven piles constructed onto the sandstone bedrock. In all, we supervised construction of over 2000 piles for the development.

Papua New Guinea

Site investigations and foundation design advice has been given for projects in Papua New Guinea. These included the tallest building yet constructed in the country, the 17 storey Atlas Apartments in Port Moresby, which was located in a particularly difficult fault zone in a seismically active part of the world.

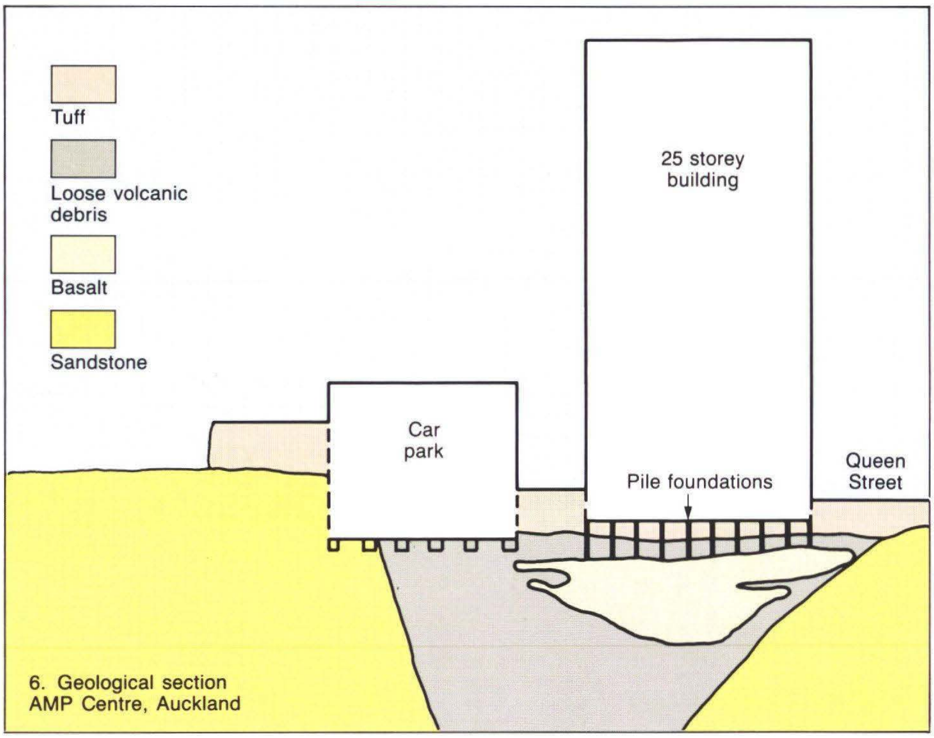
A piled raft with driven cast in situ piles driven into sheared mudstone between 9 and 18m below ground gave the best compromise between foundation cost and settlement performance.

A two stage investigation was also undertaken for the reconstruction of a 28km long section of the Hiritano Highway to the north-east of Port Moresby. The investigation included the use of air photo interpretation and helicopter reconnaissance to locate potential borrow areas and quarry sites. Subsequent site investigation work consisted of hand-dug trial pits, and rotary boreholes at quarry, bridge and causeway sites. Seismic traverses were also used to provide additional information for quarry selection.



Above: Hiritano Highway, Papua New Guinea: site survey

Left: Hume Highway, NSW, Australia: site investigation



6. Geological section AMP Centre, Auckland

New Zealand

In Auckland, Arup Geotechnics have been involved with a particularly difficult development proposed by the AMP Society on three adjacent city centre sites. The buildings themselves are not unusual, but the site is underlain by a crater which is infilled with agglomerate, a volcanic debris, and partially buried under a number of basalt flows. Site investigation drilling, carried out under our direction, led to a revision of our understanding of the local geology. The behaviour of the volcanic agglomerate under earthquake loading was of major concern, since it has an extremely loose granular structure. Advice was sought on this occasion from a leading Canadian authority on the subject and the problems were solved to everyone's satisfaction. Detailed design of the three structures is to start soon, but future geotechnical input to various stages of design and construction will still be necessary.

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