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ABSTRACT

Construction on soft ground commonly presents major project risks, notably regarding long term settlements and potential for instability. Geotechnical methods offer very substantial economies over expensive structural approaches, but normally need to be observational with scope to adjust to the very substantial uncertainties and variations in amounts and times of settlements. The technical issues are well-known to experienced geotechnical engineers. However, for others, too often the lessons are learnt by bitter experience. With time and experience, some very poor sites can be economically developed. Conversely, too many such developments have got into considerable difficulties. This paper reviews the issues and risks with reference to various case histories, some successful and many forensic cases. It offers recommendations for appropriate risk identification, reduction and management, and communicating these risks to other parties.

Keywords: Geotechnical risk, soft ground, early warnings, consolidation, predictions

1 INTRODUCTION

Construction on soft ground commonly poses major geotechnical and project risks, particularly regarding large and variable ongoing, long term settlements and potential for instability, even under relatively small loadings or changes in profiles. There is ever-increasing awareness of the importance of managing the geotechnical risks, but limited guidance suitable for engaging in appropriate identification and management, and communicating these risks to other parties. The paper draws on over 40 years of experience on numerous such projects. This includes over 80 forensic cases, of which more than half have involved significant soft ground issues (often several) and many with ‘unexpected’ large amounts and durations of settlements. Some selected examples are given including for a range of geotechnical approaches and ground improvement measures.

A recent International State of the Art Report on Integrating Geotechnical Risk Management in Project Risk Management and associated country reports (ISSMGE, 2013) gives much useful context. However it mentions settlements just a few times and gives no particular substance on this. The Country Report from China comments, perhaps rather perceptively

- In China all GeoRM steps fit entirely in the ProjectRM steps which may identify the potential risks. Nevertheless, a lot of times there is no continuous cooperation between the project risk manager and the professionals dealing with geotechnical risk. This implies that geotechnical risk is often (too) generally mentioned in project risk registers
- An example is the indication of “settlement risk” in a project risk register. What the settlement risk exactly is, and how to control it by a risk-driven monitoring programme for instance, is often not worked out. More integration of GeoRM in ProjectRM, by more cooperation between the respective managers and professionals, may overcome this hurdle.

2 RISK ISSUES

2.1 Geotechnical Risks on Soft Ground; Management and Observational Approaches

There are many useful papers on geotechnical risk generally. However, most current Standards and Codes do not address this topic particularly well; more risk-based approaches would be welcome in
the modern era, and perhaps particularly regarding soft ground. The recent ICE Manual, 2012, Chapter 100 discusses some code shortcomings in relation to the observational method (OM). Clayton 2001 gives much useful advice on Managing Geotechnical Risk generally. He notes a range of main causes of ‘failures’. Interestingly, issues with the soil model / boundaries are key main causes (nearly 30 %), and probably in many other cases are a significant contributory cause. This may rest with the investigations and/or the interpretations. For soft ground the variability and distribution of permeable layers are often major issues, often best address by an observational approach.

The author has attempted summaries of substantial soft ground cases from his experience, using somewhat different categories, Tables 1 and Figures 1 & 2. Of these, about 70 were relatively successful but about 40 (40%) are forensic cases, mostly involving some form of failure, litigation or dispute resolution (nearly 50% of the author’s cases, biased towards his interests and expertise). The data are clearly subjective and capable of more extensive analyses, as planned in due course. Most of the cases involved several potential risks; the proportions of these showing problems are indicated.

Table 1: Problems of construction on soft ground - overview

<table>
<thead>
<tr>
<th>Topic</th>
<th>All</th>
<th>% Problems</th>
<th>Problems a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>108</td>
<td>38%</td>
<td>40</td>
</tr>
<tr>
<td>Projects on soft ground</td>
<td>108</td>
<td>38%</td>
<td>40</td>
</tr>
<tr>
<td>Settlement</td>
<td>74</td>
<td>41%</td>
<td>25</td>
</tr>
<tr>
<td>Stability</td>
<td>34</td>
<td>68%</td>
<td>20</td>
</tr>
<tr>
<td>Ground Improvement</td>
<td>32</td>
<td>44%</td>
<td>11</td>
</tr>
<tr>
<td>Piling</td>
<td>20</td>
<td>40%</td>
<td>6</td>
</tr>
<tr>
<td>Shallow foundations</td>
<td>54</td>
<td>28%</td>
<td>13</td>
</tr>
<tr>
<td>Construction (other)</td>
<td>75</td>
<td>13%</td>
<td>8</td>
</tr>
<tr>
<td>Programme / Delays</td>
<td>75</td>
<td>35%</td>
<td>20</td>
</tr>
</tbody>
</table>

a Many of the soft ground cases experienced several problems

Major problems include actual failures and in some cases loss of life, serious accidents, near misses and major litigations. Clearly the risks must be managed by appropriate personnel and it is concerning how many problems relate to this. ICE 2013, amongst others, has tried to address this. The risk issues with soft ground are such that responsibility should normally lie at Geotechnical Adviser (GA) level, typically with more than 15 years’ relevant post-graduate experience. The absence of a GA can be linked to the majority of the problems cited, sometimes successfully claimed as a significant cause. Nearly 40% of the failures came back significantly to the client, notwithstanding in many cases contract conditions intended to pass all ground-related risks to the designers and/or contractors.

Key issue are project timescales, contracts, constraints and flexibility. Economies often require considerable time. For example, use of pre-fabricated vertical drains (PVDs) can commonly achieve 90% consolidation in 2 – 6 months. Faster timetables can easily double the drain requirements and costs. Contracts with little or no flexibility, including conventional Engineer, Design, Construct (EPC) and suchlike contracts, and cases where there are large programme or follow-on consequences, are frequently incompatible with geotechnical approaches and ground treatment methods. The project promoters need earliest possible geotechnical advise. Early works can greatly reduce risks and costs.
This is well known to some experienced clients especially with ongoing programmes of works, but sometime 'lost' with changes of personnel, and can be a mystery to others. Risk mitigation and management of construction on soft ground normally require an observational approach. The observational method (OM), as originally set out by Peck 1969, has evolved substantially, as described in CIRIA R185 and the ICE Manual, Chapter 100. Within this are many options, requiring considerable geotechnical input and working through in detail, with appropriate communication and understanding of all the parties. This can be difficult to achieve, particularly where some parties are unfamiliar with this approach. The 'fall-back' is the need for an expensive structural solution such as a piled raft, where the risks cannot be accepted or managed.

Many sites are simply not developed because they are, or appear, too expensive or uncertain. Time and programme are normally critical issues and the ranges need to be made explicit and acceptable. These are key components of feasibility studies. Examples include site developments where the follow-up works are time-critical and the possible delays are not acceptable.

Ground improvement options tend to carry significant risks and it is sometimes not clear who is in control or carrying the design and construction risks. This needs to be established from an early stage and through the procurement process. Surcharging, often with PVDs and staged construction are commonly the most-effective approaches, but also seem to experience substantial problems; perhaps the apparently simplicity can be deceptive. Several cases are discussed below. The theory for PVDs is well-established (Barron 1948, with numerous developments since) and implemented in various proprietary design charts and programs. Whilst various assumptions can be made, there is little practical alternative to monitoring and class B predictions (Lambe, 1973, see below).

2.2 Adequate investigations, case histories, variability and uncertainty

Inadequate investigations continue to give rise to undue construction costs, through parties having to price the risks and/or through subsequent claims (Clayton, 2001). Baynes, 2010, estimates that 20 to 50% of all infrastructure projects result in significant cost and time over-runs, with 1% of civil projects and 20% of mining projects having physical failures. Greater are likely for soft ground, Table 1.

Numerous codes and other documents give guidance on appropriate investigations (e.g UK SISG 2013); space precludes discussion here. A staged investigation approach is normally appropriate. Trial banks are particularly important to improve predictions and reduce risks (Tonks & Ameratunga, 2012), albeit these can mislead if not representative or not correctly interpreted, see examples below.

For soft ground it is particularly important to carefully collate and consider nearest comparable case histories. Charles 2001 & 2008 makes similar points regarding fills, which are commonly soft ground and included in present considerations. With the wealth of current knowledge, review of ‘comparables’ may be the most valuable, and cost-effective use of time and budget. Many of the relevant soil types and conditions are by their nature very variable, e.g. peat bogs / old drainage channels. This needs to be recognised and allowed for. It is different from uncertainty. The likely ranges of amounts and rates of settlements should be made clear, as well as the uncertainties.

3 SOME TECHNICAL ISSUES

3.1 Settlements, differential and post construction settlement PCS

Most aspects of settlement prediction are well known. Various computer programs allow these to be traced through and sensitivity explored. The starting point for most practical cases is realistic stress distributions, which is often not well established or monitored. A few particular points are made here.

Primary consolidation. Clearly consolidation theory comprises a key pillar of soil mechanics and has been known since Terzaghi’s 1923 classic work. Defining rates remains a major uncertainty, largely because these are so greatly affected by the natural variability of ground and permeabilities; hence the value of in situ testing, trial banks and an observational approach.

Initial Settlements. Most soil profiles include some strata which will settle quickly, including sands and silt layers and unsaturated or partially saturated strata, above the normal phreatic surface. This
can be particularly important in cases involving peat. These, in some forensic cases, have not been allowed for, or wrongly interpreted as primary settlements, leading to some serious misinterpretations.

**Creep / Secondary Consolidation.** It is most important to consider and make estimates from the outset. The author finds the Bjerrum 1967 formulation and time lines model most useful, not least for conceptualising the behaviour, including the effects of delayed consolidation.

**Post construction settlements (PCS)** should be estimated from the outset and updated regularly as information improves, taking due account of the various aspects outlined above. It is surprisingly common for PCS not to be specified. PCS of the order of 50 mm is likely to be practical; less may be too demanding. For example in one forensic case the specification was for better than 10 mm PCS, for which a piled solution was always necessary and the surcharge scheme was ‘doomed to fail’.

**Differential settlements** are particularly difficult to predict and assess. ICE Manual, Chapter 26 gives some latest guidance and definitions in relation to movements and distortions for buildings. For some structures and slabs a gradient around 1 in 500 may be required. This equates to only 2mm per metre or 10 mm over 5 m which is seldom achievable where ground conditions and loadings vary significantly, unless there is very substantial ground treatment. Other works such as road, rail and pipelines can have very different criteria. The case studies below give some examples.

### 3.2 Predictions and sensitivity analyses

Lambe 1973 gave useful guidance on types of prediction. Table 2 develops these ideas and notes the possible uncertainties in relation to amounts and progress of consolidation settlements on soft ground. Clearly the quality of prediction should generally improve with knowledge and time.

<table>
<thead>
<tr>
<th>Case</th>
<th>When</th>
<th>Stage</th>
<th>Uncertainty factor - Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-0</td>
<td>Before Event</td>
<td>Original – Desk Study</td>
<td>0.2 to 5</td>
</tr>
<tr>
<td>A-1</td>
<td>Before Event</td>
<td>Site Investigations</td>
<td>0.2 to 5</td>
</tr>
<tr>
<td>A-2</td>
<td>Before Event</td>
<td>Case Studies</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>A-3</td>
<td>Before Event</td>
<td>Trial Banks</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>B-1</td>
<td>During event</td>
<td>Early</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>B-2</td>
<td>During event</td>
<td>Mid</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>F</td>
<td>Final</td>
<td>Note also variability</td>
<td>0.5 to 2</td>
</tr>
</tbody>
</table>

(1) Possible range – actual are case specific. These should be attempted from the outset and refined with time.

Sensitivity studies are particularly important for assessing and ‘bounding’ the uncertainties and risks. They can be easily be done by use of programs and with several methods. An obvious simple check on settlements is using the mv and Cc methods for credible ranges of parameters. The ranges found initially can be alarming, but provide a basis for going forwards with sensible risk management and communication, reducing uncertainties, but recognising likely real variations in many cases.

### 4 CASE HISTORIES

#### 4.1 Embankments over dredgings and peat

Manchester Ship Canal has over 100 years’ experience of constructing embankments on soft ground over very soft peat and alluvium, and subsequently over dredgings. Over 20 km of such banks have now been built mostly in several stages and some to over 10m height. Some of these used to encounter problems during construction (Rowe 1972). Many lessons were learnt and used to great economic advantage in an ongoing development programme.

Recent works proceeded over many years since the late 1980s using staged construction and geotextile reinforcement developed principally through trial embankments (Tonks 1989) and then successfully rolled out for the main sites. The timetables and contractual arrangements have been very flexible, implemented by simple plant hire contracts to dry and improve the very poor local soils
and dredgings for re-use. This has provided highly economic solutions for many km of new banks and raising of existing banks and other developments (Tonks et al 2002).

4.2 Forensic – housing on peat
A development of more than 200 houses in NW England was built over a peat bog, with up to 7 m of peat and another 7 m of very soft alluvium. The houses were piled, but not the infrastructure. After nearly 10 years, settlements were approaching 3m and still continuing at over 200 mm / year, with some remarkable management works by the developer.

![Figure 3. Housing with impossibly steep drive – after over 2.8 m settlement on peat](image)

The very substantial court case included a key claim of failure to employ a suitable qualified geotechnical engineer. Some rapid initial settlement of unsaturated peat was mis-identified as primary consolidation, leading to seriously inadequate predictions. The site had been purchased as a bargain, but in fact had substantial ‘negative value’. Eventually some 40 houses had to be demolished and the remainder of the estate required an expensive piled road to maintain access and use.

The writer has since been involved in several rather similar but less dramatic cases on peat. More positively, many similar, but less onerous sites have been economically developed by surcharging. Space precludes further details here, but essentially just by appropriate use of geotechnics.

4.3 Forensic Platform for hospital. Stability and Settlement Risks
A major new medical facility was to be built on very soft ground. Site preparation required up to 5 m of fill over peat and very soft clays. Earthworks costs for staged construction with PVDs were around £1M. By contrast a piled platform was likely to have cost over £4M. These figures were small in comparison the to several hundred million pound facility which was time critical.
Figure 4. Failure of staged construction of fill platform on peat
Figure 4 shows stability failure of the earthworks at about 1 m below full height. Forensic studies by experts found that during the 3rd stage of raising (of 4), monitoring showed pore pressure rising well above trigger levels, i.e. failing to dissipate as fast as predicted. Two-dimensional effects were not well understood, with some areas having insufficient PVDs and a pore pressure wave developing in the critical toe area. Inclinometers also gave due warnings, but results were not being duly processed. Timely stopping of filling was required, but the contractual responsibilities were disputed and there were ‘risks of delay!’ These of course then became far worse on failure, with over 2 years delay, an expensive structural solution and litigation. This was nonetheless second order to the costs and consequential delays to a major public facility, which needed to be factored into the risk profile.

The observational geotechnical approach chosen was reasonably practical and economic, but needed far more geotechnical work, limited changes and perhaps just 6 months more time than was provided. There was, however, little scope to alter programme and no-one of Geotechnical Adviser experience.

4.4 Settlement risks for housing and during construction

A development for some 400 houses and other facilities was planned over very deep soft ground. Extensive desk studies and SI showed very variable ground conditions with more than 10 m of very variable fills over variable alluvium, including much soft clay, to a total of around 25m depth in places. Loadings were specified at up to 40 kPa, plus fill raising of up to 1.6 m (30 kPa). PCS was required to be within 50 mm following about 18 months construction programme. Surcharging with PVDs was proposed and put out to tender, for the contractor to assess the geotechnical risks.

![Figure 5. Highly variable settlements in trial bank](image)

An initial trial bank used for the original basis of design was interpreted to show limited settlements, and proposed quite limited surcharges and PVDs. The Contractor’s reviewer identified high risks of much greater settlements, up to about 500mm, and the likely need for considerably more ground improvement. In particular the trial bank showed large local variations and differential settlements even within its limited footprint (which was little more than the depth of the compressible strata). Some issues were due to 3 dimensional load spread effects, the bank not fully loading the lower strata. Other variations reflected probable local prior loadings, not well defined. Assessments using the program SETTLE-3D (Rocscience, 2013) were particularly valuable in addressing these issues. Table 3 shows the progressively improved predictions as works progressed, with scope to adjust.

These concerns were confirmed by a larger trial bank through the first few months of contract on a part of the site without much prior loading. Figure 5 shows the very large variations and ‘edge effects’ demonstrated. The design was developed by an observational approach, with extensive monitoring and review through the scheme. Surcharging was generally raised to 2 - 3 m above finished (raised)
ground levels, with PVDs at 1.5m centres in time-critical areas and 2 m centres elsewhere. The required consolidation was achieved in times varying from 1.5 to 4 months dependent on conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Stage</th>
<th>Smin (mm)</th>
<th>Smax (mm)</th>
<th>t 90 min a</th>
<th>t 90 max a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tender Case</td>
<td></td>
<td>100</td>
<td>200</td>
<td>1.5 months</td>
<td>3 months</td>
</tr>
<tr>
<td>A-0</td>
<td>Desk Study</td>
<td>200</td>
<td>500</td>
<td>1.5 months</td>
<td>2 year</td>
</tr>
<tr>
<td>A-1</td>
<td>Site Investigations</td>
<td>200</td>
<td>500</td>
<td>1.5 months</td>
<td>2 year</td>
</tr>
<tr>
<td>A-2</td>
<td>Trial Bank</td>
<td>200</td>
<td>500</td>
<td>1.5 months</td>
<td>1 year</td>
</tr>
<tr>
<td>B</td>
<td>Observational</td>
<td>300</td>
<td>450</td>
<td>1.5 months</td>
<td>4 months</td>
</tr>
<tr>
<td>C</td>
<td>Final</td>
<td>200</td>
<td>450</td>
<td>1.5 months</td>
<td>4 months</td>
</tr>
</tbody>
</table>

a t 90 based on PVDs. Design revised post tender to increase and accelerate settlements, see text.

An important point here is the variability of final settlements (see figure 6), not uncommon in such circumstances. The surcharging was managed by progressively developing ‘Class B’ predictions, including use of the Asaoka 1978 method, with refinements proposed by Sasar M and Haeri S M, 2013, which give some improved predictions, allowing for creep. Significant corrections also needed to be made for immediate compression and for 2 and 3-dimensional effects. In this mixed ground some of the compressible strata, especially some of the made ground, were relatively permeable and in places accounted for up to about 150 mm of settlement in the first week or two. It is of course important to separate this out from the consolidation behaviour. It was found that this could practically be addressed by using duly corrected consolidation curve fitting, following Taylor, 1948.

![Figure 6. Surcharging scheme for housing and main road – settlements on cross section](image)

An interesting feature was an adjacent new road and buried high pressure main. Angular distortions had to be kept within 2°. Risk assessments showed settlements could be up to 350mm, as later proved to be the case. The ground variability left substantial uncertainty in local differential movements. Pre-surcharge surveys showed up to 1° existing distortions in places, attributed to original construction issues and settlements over the years. This led to protracted negotiations with the developers and the asset owner, eventually accepting a closely controlled, observational approach, with weekly level monitoring and assessments of almost every joint, with emergency provisions should movements appear likely to exceed trigger levels. The surcharging actually changed the distortions by less than a further 1°, the greatest values not coinciding with previous maxima. The scheme was successfully completed, saving substantial time and costs over alternatives which would have required major pipeline relocations, delays and costs.

5 CONCLUSIONS
- Construction risks on soft ground are high and require particular judgement, normally supported by extensive monitoring and an observational approach. This may include controls on works and early warnings. It is crucial to monitor the right things and maintain full control.
Cost-effective geotechnical approaches needs suitable time and resources, managed and acceptable to all parties, with scope to adjust the design and programme to suit as work proceeds. Otherwise a more expensive structural approach should be used.

The geotechnical risk management (GEORM) must rest with suitably experienced specialists, with extensive experience of soft ground, consolidation and appropriate geotechnical works. He/she must be empowered to vary works if necessary, including stopping / delaying work in some cases.

Workshops and peer reviews are particularly useful and may substantially increase confidence.

Adequate investigations should normally include specialist methods such as CPTUs and Trial Banks. These all need considerable care to ensure valid interpretations.

Good risk communication with the client is particularly important for an observational approach.

Surcharge must be left on long enough – various methods to evaluate this are discussed.

Pro-active Risk Management is required, including use of risk registers and team review meetings.

Peer / independent review can greatly assist identification and management of risks.

Predictions should be made and the ranges of uncertainty and risks assessed and communicated from the earliest stages. These should be regularly reviewed and improved through the works.

6 ACKNOWLEDGEMENTS

The author is grateful to numerous colleagues and clients with whom he has worked on the projects described and numerous others which have contributed to the work presented here, particularly Dr M Wymer, project engineer, who carried out many of the analyses described.

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