MANAGING GROUND RISK FOR MAJOR RAIL ELECTRIFICATION PROJECTS

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ABSTRACT

The United Kingdom has embarked on a series of major rail electrification projects, for example the Great Western, Midland Mainline, Transpennine and the North West. The schemes require the installation of thousands (over twenty thousand on Great Western alone) of new deep foundations to support the overhead line equipment (OLE) foundations, which are primarily laterally loaded cantilever structures. This paper discusses geotechnical aspects of such proposals and is based upon the difficulties of obtaining quality geotechnical information within the confines of an operational railway corridor to inform design and construction risks. The paper details the necessary desk study sources of information that are available on such schemes (that are not necessarily initially appreciated), the recommended strategy of ground investigation with respect to types and spacings. Also detailed are specific recommendations in reducing risks in areas of very poor deposits with respect to the standard method of ‘allocating’ foundations in accordance with the electrification system design requirements.

1. INTRODUCTION

One of the major risks of rail electrification projects is uncertainty with regards to the ground conditions, particularly where ground conditions are variable along the route. Ground information is often limited, and opportunities to undertake ground investigation severely constrained as a result of often very restrictive railway possession and access windows. Other considerations for foundation design, placement and construction include the varying topography (embankments and cuttings), buried services constraints, and presence of other railway infrastructure such as signal gantries, culverts and bridges. Limited construction access available in the UK railway corridor, combined with limited opportunity and public acceptance for long term blockades (e.g. with bus replacement programs), present significant constraints to foundation options, which in turn can have significant impacts on the programme and project costs.

The foundations for OLE structures are a critical element in the design and installation process of Rail Electrification projects. Where the ground conditions are poorly understood, they can present significant risks to project budget and programme.

2. FOUNDATION SELECTION

Estimates of costs and construction programme made during the early stages of rail electrification projects will require assumptions to be made regarding the foundation system, e.g. it may be assumed that a driven CHS piled foundations will be utilised throughout. Should the ground conditions subsequently be found to be incompatible with the assumed foundation option, this can have a major impact on cost and programme. An understanding of the ground conditions and key risks to installation at this early stage will allow a more accurate assessment of the foundation types likely to be required and mitigate against cost and programme uncertainty.

2.1. UNDERSTANDING THE GROUND CONDITIONS

To maximise the relevance and cost efficiency of site investigation, a phased approach is advocated, with each stage of assessment building on the knowledge gained from previous stages. The first stage of the site investigation is to compile all readily available information in a desk study and visit the site. This will inform the requirements of the ground investigation (GI). Depending on the scale and complexity of the project, the commercial and contractual set up and availability of suitable possessions, the GI will also usually need to be phased, with early phases required before commencement of design work. In order to best manage risks and uncertainties, sufficient information should ideally be available at the right stages to inform the key decisions of the scheme as it develops.

The site investigation should establish the properties of the ground for design and identify ground hazards that may impact on the design and construction methodology. Key concepts include establishing the stratigraphy, understanding the geology of the site and establishing appropriate parameters for design, understanding the groundwater conditions, determining any contamination of soil and groundwater; and defining any particular ground hazards and risks.

The costs associated with dealing with difficult ground conditions tend to be far greater if these are not identified and known by the team before construction is underway within the railway, e.g. due to the delays to the programme if construction methods have to be changed or designs amended. Where risks are identified and understood earlier, there is a greater opportunity to consider them in the decision-making process, e.g. when considering OLE foundation options. The aspects and stages of understanding and managing ground risk discussed further within this paper are illustrated within Figure 1.

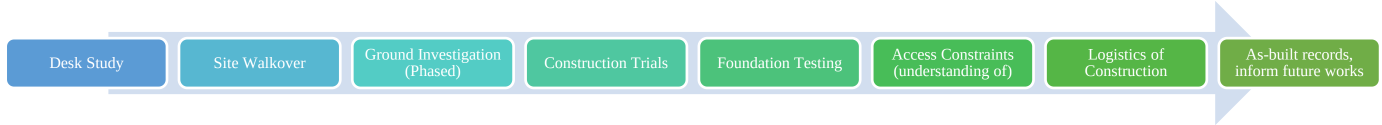

Figure 1 - Stages of assessment and management of ground risk

2.2. DESK STUDY AND SITE WALKOVER: KEY OBJECTIVES

The geotechnical desk study is usually undertaken at the Feasibility and Option Selection parts of the project lifecycle (known as GRIP stages 2 and 3 within the UK under operator Network Rail). Key objectives of the desk study include:

- Compilation of available information relating to ground conditions, topography, site history, site access points, ground hazards and ground risks. Defining the stratigraphy, groundwater conditions and geotechnical risks, and the implications of these for all scheme options being considered;
- Preliminary assessment of the most suitable foundation options. A focus should be defining the extent of the alignment which is likely to be suitable for the preferred foundation options. In the UK this may typically be. driven CHS-piled foundations. The desk study assessment should involve review of foundation 'refusal' risks, including presence of shallow rock and potential buried obstructions which may be associated with different strata (e.g. boulders/cobbles in glacial deposits);
- Informing the scope of ground investigation for each section of the route. This should provide the necessary data to develop the designs for the favoured foundation options and to mitigate any identified construction hazards and risks. The focus should be on areas of more limited information or greater uncertainty.

All desk studies undertaken should consider sources that provide details of site topography, the underlying ground conditions and any existing or known historical constraints. The British Geological Society (BGS) holds information on superficial and bedrock geology, which can be viewed via 1: 10,000 or 1:50,000 scale maps (and are also available in useful digital format for importing into models). Associated geological memoirs contain more detailed descriptions of geological sequences in particular areas, which support the geological maps. Recent advances in the information available through the BGS include superficial thickness contour mapping for certain areas, which provides indicative thicknesses and elevations of superficial deposits.

Historical maps and aerial photographs are useful for identifying potential buried obstructions within the ground, in-particular redundant foundations, buried retaining structures and underpasses, and previous track alignments. The construction of the railway often pre-dates the earliest maps available commercially in the UK, and local archives can be utilised to gain an appreciation of this. Commercially available digital terrain model (DTM) files can be supplemented by LiDAR surveys (which can be acquired efficiently using rail-mounted systems) to establish accurate profiles of ground topography, which are necessary for areas of containing cuttings and embankments.

As maintainers of the railway infrastructure in the UK, Network Rail have a number of additional sources of information that provide further detail to rail sites. The Linear Asset Decision Support (LADS) database allows for the review of track quality data and highlights areas where greater levels of maintenance have been or are anticipated to be required, which may be useful for identifying locations where underlying geotechnical issues may exist that may be targeted during ground investigation. The Network Rail earthworks inspection records describe routine inspections on earthworks (cuttings and embankments) over 3m in height, and include details of site topography, photographs at the time of the inspection and observations from the Inspector. The classification system used for earthwork inspections can highlight sections that may be more sensitive to the installation of foundations. The local knowledge of the Geotechnical Route Asset Manager (RAM) may include areas where remedial works have been or are planned to be completed, as-built records of retaining structures or bridges along the route, or previous ground information undertaken as part of previous projects. Where OLE foundations are immediately adjacent to or are interacting with existing assets, detailed records can significantly reduce or avoid intrusive works to establish the as-built geometry.

Site walkovers in advance of scoping ground investigation and selecting foundation types are highly recommended, ideally undertaken during daylight hours. Access may however be restricted within project timeframes due to the availability of suitable possessions, therefore it is recommended the project team allows sufficient time to allow this important activity to be completed. The key benefit of undertaking a site walkover is an appreciation of the site conditions, constraints to foundation installation and potential hazards first-hand. This includes gaining an appreciation of access and available locations for undertaking ground investigation. Subsequent site visits may be beneficial when the OLE layout has been confirmed, or for locations where more bespoke foundation solutions are required.

One aspect of undertaking a site walkover is to gain an appreciation of the current condition of the railway and lineside infrastructure, particularly where available information predates the commencement of the project. Works required to facilitate the electrification of the line, such as gauge clearance and signalling renewals, may be running concurrently to the electrification, and coordination of OLE foundations with these works is essential to minimise or ideally avoid knock on programme and cost implications.

Visual inspections of earthworks along the railway can identify any additional areas of slope movements or instability, which can be accounted for during foundation selection, design and construction. Where present, visual inspection of soil and rock cuttings can provide useful information about variations in the geological sequence and engineering properties. Areas of high groundwater may be observed adjacent to the railway corridor, particularly in low-lying areas or cuttings. The potential for contamination can be assessed during the walkover, particularly if any visual or olfactory evidence is encountered. Review of historical maps to allow assessment of former land uses can highlight particular areas of the site where an elevated level of contamination may be expected.

2.3. APPROACH TO GROUND INVESTIGATION:

The ground investigation should be based on the conclusions of the desk study and site walkover assessments. It should have clearly defined objectives and include a schedule of activities linked to a series of plans at a suitable scale. Ground investigations should be targeted at reducing potential risks associated with identified hazards and uncertainties to acceptable levels (which is to be agreed on a project by project basis). The information obtained should allow the most efficient, cost-effective design and subsequent construction methods to be developed.

Given the difficulties in obtaining ground investigation information in the UK operational railway corridor, pre-existing information from earlier ground investigations (from either maintenance works or from infrastructure projects) is of huge value to such projects. Desk study should identify any existing information that may be available both with the railway land itself and adjacent non-rail sites. Pending permission to use this information, this should be considered when planning investigations and incorporated into the data sets for the design and reporting.

Enough exploratory holes should be undertaken, and to sufficient depth, to provide the required level of detail regarding the stratigraphy, geological structure, and groundwater conditions, and to allow design and construction risks to be understood. Suitable in-situ testing or lab testing on samples of soils and rock should be undertaken to allow characteristic parameters to be derived for design. Ideally exploratory holes would be sunk at each and every foundation location, but this is not generally practical, given the available possession windows and that the detailed OLE layouts may not be confirmed at the investigation stage. If a foundation is to be carried on a stratum known to have competent and laterally consistent properties, minimal investigation may be required. More closely-spaced exploratory holes should be considered in areas where significant ground variability is anticipated, and in such instances investigation at each foundation location may be merited.

The exploratory holes should be extended to the influencing depth of the foundation design, and hence the anticipated design requirements be understood when the ground investigation is scoped. For shallow foundations, e.g. for strip, pad or raft types, the depth of investigation below the foundation base should normally be at least 1.5 times the width of the loaded area below the base of the foundation. For piled foundations depths should extend below anticipated pile depth, e.g. typically 5m below the anticipated base of the piles, but this may be reduced if the piles are founded on anything stronger than very stiff/clay or very dense granular stratum.

Wherever possible, ground investigation techniques should be selected to allow these depths to be achieved; some typical methods include boreholes, window samples, CPTs, dynamic probes, trial pits and geophysics. Weak or voided strata may be present below more competent materials in certain rock types, and obstructions may be present at shallow depth such as made ground containing mass concrete. If investigation techniques cannot penetrate such obstructions, only limited information may be obtained, more conservative assumptions may need to be made during the design and construction risks and uncertainty will increase.

Phased investigations are considered for a number of reasons, e.g. limitations to budget or possession availability, where ground conditions are still poorly understood following desk study, or where the scheme proposals are complex. There may be insufficient information to fully develop a scope of investigation that provides all the necessary information efficiently in one phase, and an initial phase of investigation will help to focus subsequent phases. Additional information may also be required where unforeseen ground conditions are encountered, scheme proposals change or to verify certain design assumptions.

3. KEY GROUND RELATED RISKS

Key ground risks associated with OLE Foundations should be considered both in term of design risks and construction/installation risks. A summary of some of the main issues is presented within Table 2.

Design Ground Risks	Construction Ground Risks
Inability to install foundations to design depths In variable ground conditions, design ground models may conservatively assume a greater depth to bedrock. The implications of rock at shallower depths should however be considered when assessing installation risks. Natural or man-made obstructions may also be present (e.g. high cobble/boulder content or historical foundations). Both may result in difficulties achieving the required designed depths.	**Hard Ground** In areas of very dense soils or shallow bedrock, foundations still require some embedment into the dense strata /bedrock, to provide resistance against lateral loading. Driven piling may not be feasible, and pre-augering in advance of driving, or used of bored/augered foundations may need to be considered. Productivity can be significantly hindered due to slow progress boring through hard/strong strata.
Uncertainty regarding design parameters Design parameters may be derived from minimal information due to the difficulties in undertaking ground investigations. In such instances, more conservative parameters may need to be assumed, leading to larger/deeper foundations, slower productivity, and greater risk of installation refusals.	**Vibrations on Existing Structures** Pile installation can induce significant vibrations in the ground. Sensitive structures in close proximity to these piling activities or earthworks in poor condition are particularly susceptible to damage if vibration levels are not appropriately controlled and monitored.
Earthworks movements Earthworks may be in a poor or marginal condition, and it may be considered appropriate to either stabilise such earthworks or consider the potential for future movements within earthworks slopes when designing the OLE foundations installed within such earthworks.	**Track Movement** Vibrations linked with pile installation can cause instability with earthworks in a poor condition. Poor earthworks include those with over-steepened slopes, or the presence of animal burrows (voids within the earthwork). Such slope movements or instability or disturbance of loose materials within the track support zone can result in unacceptable movements beneath the track formation. Slope and/or track monitoring during and following foundation installation may be required.
Significant variations in ground conditions may be present, e.g. buried channels, which may not have been identified during the ground investigation or allowed for in the design ground models. This could result in insufficient foundation capacity and foundation failure. It is important to have some means of verifying the ground model design assumptions during construction, and for there to be a feedback mechanism to the designers, particularly where the potential for significant variation has been identified	**Buried Services** Located often in the cess running parallel with the track where OLE foundations are positioned. If in close proximity, clashes are an ever-present risk along with the installation process damaging services.

Table 2 – Key Ground Related Risks

3.1. EFFECTIVE COMMUNICATION OF GROUND RISK

Following completion of the desk study and ground investigation, the gathered information is usually captured within a series of reports including factual reports and interpretative Ground Investigation Reports (GIR) conforming to prevailing standards. Regardless of the standards adopted, the ground investigation reports for a major scheme will usually contain a significant amount of information, including exploratory hole logs, in-situ testing results, geotechnical and geo-environmental laboratory test results, etc. Factual reports may be in excess of 1000 pages long when combined. They can be complex to decipher and without graphical representation there is a danger that they are only viewed by the design engineers, or when something goes wrong on site! It is important that all parties; employer, principal contractor, contractor, and designer have access to a simplified interpretation and visual assessment of the ground, to allow the team to understand the issues and make their own assessment of constructability and ground risk. Use of hazard and risk registers can be an effective and simple means of communicating key ground related information.

Another effective method of communicating ground risk information is by means of a simplified engineering geology long section, with the various strata clearly identified. This requires an interpretation of the factual information by a ground engineering specialist. The accuracy and usefulness will be a product of the quantity and quality of factual information available. Such visual modelling of the ground conditions may be treated as a live document used by the construction team, updated when new ground information is acquired. Additional information may include both additional ground investigation and as-built foundation records. It also allows designers and contractors to easily identify transition zones between near ground surface bedrock and areas where bedrock is located below depths to which CHS stop becoming feasible, which often cause considerable difficulty in selecting the correct foundation type first time. The following should be considered when compiling and viewing such visual representations of the ground;

- Ground models are never definitive, and there will always be some uncertainty at foundation locations, even if an exploratory hole or record is undertaken at each foundation location – key is that areas of greater uncertainty and risk are highlighted to allow appropriate management of risks;
- The interpretation should consider the particular processes at work and depositional environments in which the various strata are deposited, including any ground hazards that may be associated with these strata. Ground models should be prepared by a competent ground engineering specialist;
- Long sections are typically completed with centre line being the centre of the combined track system. Across track ground changes can in some cases also be significant, and in such cases suitable cross sections may also be prepared to present a fuller picture;
- Boreholes can be some distance from track and also may not be representative of the track positions. The offset positions of exploratory holes should be indicated on long/cross sections;
- Track levels, and natural ground level prior to development of the rail levels should be shown to illustrate areas with cuttings and embankments and aid the interpretation;
- In-situ test results should be shown to assist in assessment of design parameters; and
- The drawings can be marked up with additional information including installed depths of foundations and construction records may be used to refine the interpretations. This may include pile driving records, records of depth to different strata in pile bores, pile test data, etc.

4. CONSTRUCTION RECORDS AND CLOSE OUT REPORTING

During construction of the OLE foundations, as-built records are required at each individual foundation. If properly recorded and presented, such records can be considered to be additional ground information, which can be reviewed and assessed by a competent geotechnical engineer to update the design and construction ground models. This allows a re-assessment of the surrounding foundations if required and use of the as-built records allows a much more complete image of the as-found ground conditions to be compiled. An example of the use of as-built records is by review of the driving rates of driven CHS piles. A simple assessment of driving rates of the CHS tubes (blow counts per nominal length, which is typically 250mm) provides a view of ground strength with depth. If provision of installation hammer energies and other key information is properly specified and recorded, this information can even be used to assess the dynamic capacity of the installed piles. When combining this information with nearby exploratory hole information, the engineering geology long sections may be updated and designs potentially refined during construction. The works may be phased in such a manner to supplement GI information and allow greater understanding of installation risks in identified high risk areas, such as transition zones between deep superficial soils and shallow rock. This can be a powerful tool when completed in good time to verify design assumptions, and to allow remediation of existing designs in previously unforeseen ground. Other benefits of maintaining good construction records and using these to verify or refine ground modelling assumptions include opportunities to reduce instances of construction remedial works, e.g. in the event of foundation refusals.

Bored piles and shallow foundations involve the extraction of ground hence the ground conditions can be recorded during excavation and transferred back to the geological long sections, providing further confidence of the ground conditions at that location and the surrounding positions. The type of information that can be obtained during construction is summarised in Table 3. The information typically received is often not as good quality as targeted ground investigation, because the arisings may be heavily disturbed by the installation process, making confirmation of the in-situ properties difficult in practice. Foundation installation is also usually conducted by different engineering professionals (who are primarily there to construct and not log ground conditions). Despite often lower quality, the information can be invaluable to the project, particularly if it is carefully specified to allow maximum value to be gained. The presence of a ground engineering professional whom is informed of the design, geotechnical parameters and anticipated ground conditions during the installation, can significantly aid in flow of sufficient information between all parties.

Provision of suitable quality as-built information can be used for verification of piles that were not installed as per original design requirements, if they indicate stronger than anticipated ground conditions than those assumed within the design ground model. This may help to avoid expensive and time consuming remedial works (either during construction or operation of the railway), as it may provide the necessary information for the designer to justify the use the foundation 'as-installed'. As-built information can also highlight areas of weaker ground than anticipated, and should this be found during construction, remedial works can also be specified during construction when this is the case. This is safer, and less costly than an increased maintenance programme or remediating during railway operational periods post works. A variety of methods can be utilised by these types of assessments, e.g. qualitative assessment can be undertaken where the driving records allow refinement of the depth of rockhead. Dynamic pile driving analysis may be undertaken to back-analyse driving rates and provide updated axial capacities of the as-built foundations if adequate information is provided. The required construction records should be carefully specified and discussed with the installation contractor prior to works commencement.

Foundation Type	Ground Information Obtained
Driven CHS	• Depth of pile installation achieved by vibratory means only (As vibratory hammers cannot install piles within more competent soils/rock); and • Percussive hammer records, including record of rate of penetration/No of blow counts per nominal length, typically 250mm). This gives a measure of the ground strength/density with respect to depth of foundation.
Single Bored pile and group bored mini-pile group foundations	• Ground type with respect to foundation depth as material extracted; • Ground strength when boring rates are provided with the as-built records; • Depth of the casing required provides depths of superficial deposits; • Ground water levels; and • Ground contamination.
Shallow Foundations	• Ground type with respect to foundation depth as material extracted; • Ground water levels; and • Ground contamination.

Table 3 – Information that can be obtained during construction for different foundation options

Once all ground investigation is complete and as-built records reviewed and combined, this dataset will provide an extensive assessment of the ground conditions beneath the scheme. This dataset will provide the maintainer and geotechnical route asset managers with indispensable ground information for the life of the asset. The compiled information may be used to inform future infrastructure works. This should be captured in the form of a geotechnical close out report summarising the geotechnical works undertaken, including investigation, construction, testing and any post-construction monitoring. This forms an essential part of the construction verification process and provides useful information relevant for maintenance, demolition or re-use for ongoing management of the asset.

5. SUMMARY OF LESSONS LEARNED AND RECOMMENDATIONS

Risks including cost uncertainty and programme delays may be mitigated by ensuring adequate assessment and communication of the geotechnical risks associated with the particular ground conditions anticipated for the scheme. Recommendations are summarised below for the various project stages;

5.1. CONCEPTION (FEASIBILITY)

Preliminary geotechnical desk study to be undertaken by a competent engineering geologist or geotechnical engineer. An understanding of the buildability of different foundation options and experience with the available types of OLE foundations are essential for this stage. Early involvement by a competent installation contactor is of huge benefit to define the focus of the preliminary desk study assessments. [OUTPUT] A clear summary of the anticipated ground conditions, ground hazards, and associated risks and uncertainties will allow a suitable scope of ground investigation to be developed. Initial estimates of foundation types should be based on a sound understanding of the construction limitations. This will allow preliminary pricing and program estimates to be as accurate as possible.

Review physical constraints such as investigation and construction access, clashes with existing infrastructure and condition of existing assets. This should be a coordinated assessment undertaken by a team knowledgeable in ground risk, foundation design and construction and OLE layout design, and should include the foundation designer and electrification designer and installation contractor. This should be based on desk study review, cab ride videos and other readily available sources of information. Site visits should be undertaken to understand these constraints. The electrification layout should take into account these constraints and be modified to eliminate any onerous civil/geotechnical requirements, and also eliminate any identified health and safety issues where identified. [OUTPUT] A understanding of highly constrained areas, practicable efforts to eliminate difficult or dangerous construction works, based upon a multi-disciplinary approach to layout design and identify optimum locations for the OLE foundations.

Ground risk workshop to include stakeholders, planners, commercial managers and representatives of the foundation design and construction team. [OUTPUT] A shared project appreciation of the anticipated ground risks. These could include a summary of ground variability, ground conditions, expected foundation types, areas of high risk based upon ground conditions, areas of high risk based upon access, and other constraints. Emphasis is to be placed on the risk mitigation measures, which are to be completed during the proceeding stages of the project delivery. This may include additional desk study assessment, ground investigation and construction installation trials.

Allowance in terms of cost and programme for phased-ground investigation within project proposal. [OUTPUT] An appreciation by the project team of the value of adequate ground investigation, allowance for phased ground investigations within the programme to assist with effective and efficient project delivery. Co-ordination of the phasing of the construction phase with the ground investigations to maximise the usefulness of the information obtained in management of ground risks.

5.2. DESIGN (SINGLE OPTION AND DETAILED DESIGN)

Development and enhancement of the preliminary desk study, reviewing available information as discussed within this paper. The stakeholders should provide any available relevant information available to the designers. [OUTPUT] All information available to the stakeholder is made available to the designers to ensure maximum value. This can help with better understanding of ground risks and avoid unnecessary costs in obtaining information already available elsewhere.

Existing services/buried utilities are a significant constraint on overhead line equipment placement. Any available information regarding the buried services/infrastructure within the rail corridor should be made available for OLE layout refinement as soon as possible in the design programme. [OUTPUT] Reduction in potential for OLE layout design and requirements for the re-design of OLE structures and foundations.

Phased Ground Investigation to be developed by designer/contractor and completed by competent ground investigation contractor experienced with ground investigation within the rail corridor. Supervision/monitoring should be provided by the foundation designer/contractor, who can then react to unforeseen ground conditions as the GI progresses and modify the investigation scope accordingly. [OUTPUT] Further assessment of any high-risk areas identified by the desk study. Confirmation of the anticipated ground conditions, assessment of particular ground hazards (e.g. mineworking's, voided ground, obstructions, soft ground, potential ground contamination, etc.), assessment of groundwater conditions, development of design ground models and obtaining information for assigning of parameters for design.

Additional phases of Ground Investigation to be developed by foundation designer/contractor. This is to focus on stratigraphy variability and areas anticipated to lead to problematic foundation construction. [OUTPUT] Refinement of the ground model within areas of greater uncertainty and risk. Reduce design and construction risks. Reduce costs and programme risks.

Early focus on foundation selection workshops with designer and installation contractor/ subcontractor attendance, following Phase 1 Ground Investigation and then Phase 2 Ground Investigation. [OUTPUT] Knowledgeable and competent parties working together to facilitate the most cost-effective foundation solutions to be developed through to detailed design.

The detailed design delivery should where possible allow modifications to be made by competent and authorised personnel (to approved methodology and limitations) as construction proceeds. This could include provision of dual foundation designs in advance of construction, provision of designs contingent on achieving defined minimum depths in conjunction with minimum penetration into defined strata. [OUTPUT] simplified design assurance process, giving maximum flexibility to the design and construction team where greater levels of uncertainty/ground risks have been identified.

5.3. DELIVERY (CONSTRUCTION, TEST & COMMISIONING)

As-built records can be very useful for verifying or refining ground modelling assumptions and designs. Careful consideration should be given to what records are required when specifying the works. Efforts should be made to ensure that the reasons why the records are required are clearly understood by the installation contractor and that these are obtained and provided to the designers. [OUTPUT] Allows competent person to review and amend foundation delivery or design if required. This may provide a very cost-effective foundation delivery and reduce cost and programme delay in the event of installation issues.

Staged foundation delivery, i.e. by use of as-built records, these are effective additional ground investigation. When ground investigation is sparse or lacking, this information is valuable. Design assumptions can be reviewed as works progress to allow efficiencies in design and construction. This may require additional geotechnical support during construction from a competent person knowledgeable in design and construction of these types of foundations. [OUTPUT] Use of all available information to refine ground models and designs as the works progress and realise potential design and construction efficiencies.

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