

Repowering onshore wind farms: a technical and environmental exploration of foundation reuse.

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Executive Summary

With the need to increase energy generation from renewable sources and a desire to move towards subsidy-free wind energy generation, the industry is considering repowering existing wind farms to create systems which generate more energy per unit area and wind speed. This will likely involve an increase in turbine generation capacity and size. This report considers whether existing wind turbine generator (WTG) foundations can be re-used when the turbine is replaced. The considerations are broadly outlined in Fig. 1: Schematic of Logic Decisions for Repowering Consideration. The terminology used is defined in the Glossary after this summary.

The key understandings emerging from this research, and detailed further in the report, are:

- Repowering of wind farms in the UK on mineral soils has taken place, including one site in Orkney, Scotland. This repowered wind farm comprised only three wind turbine generators (WTG). Many wind farms in Scotland are on peat soils and consist of greater numbers of WTGs, and there is no precedent for repowering larger wind farms on peat soils in Scotland. However, there are some wind farms on peat soils currently being, or scheduled to be, repowered elsewhere in the UK. These could act as 'natural laboratories' for study of recovery of peatland after restoration.
- Outline engineering designs developed for this research demonstrate a foundation can be reused for a second generation of WTG. These designs use the existing foundation as a formation for a new foundation with increased width, suitable to support the increased loading.
- The reengineered foundations presented here are designed for a 30-year life, and due to onerous fatigue loading during use, their suitability for a subsequent repowering would have to be assessed. A design for an extended life foundation is feasible, but logistically difficult when future turbine designs are unknown.
- Industry consider that these reengineered foundations would add considerably to the cost of the wind farm construction due at least to the additional quantities of construction materials and this could counteract the effectiveness of repowering in supporting onshore wind power to be subsidy-free.
- Turbine manufactures consider repowering to be an important market but do not appear to be driving forward new designs for repowering sites with the same size of turbine.
- Many of the considerations associated with whether turbine repowering has an impact on the environment are pertinent to any wind farm development, and so may be mitigated, as new developments are, by best practice in construction and habitat management.
- Not all foundations would be used in a repowered windfarm with larger WTG as the spacing required between WTG would preclude this. Unused foundations would be restored.
- Given wind farms exist to generate electricity with minimal carbon (C) footprint, an assessment of repowering must consider key processes that affect this: the embedded C (as CO₂ emissions) used in the construction of the repowered wind farm, and disturbance to the environment that can reduce its capacity to sequester C, including the effectiveness of restoration at the end-of-life.
- The environmental footprint of a reengineered foundation can be compared to repowering with a new foundation. For this comparison the latter comprises two foundations: the old foundation restored as no longer required, and a new foundation constructed for the new WTG. The two most likely repowering scenarios of upscaling from 0.85 MW to 3.2 MW (scenario 1), and from 2.3 MW to 5.0 MW (scenario 2), are a focus of these comparisons.

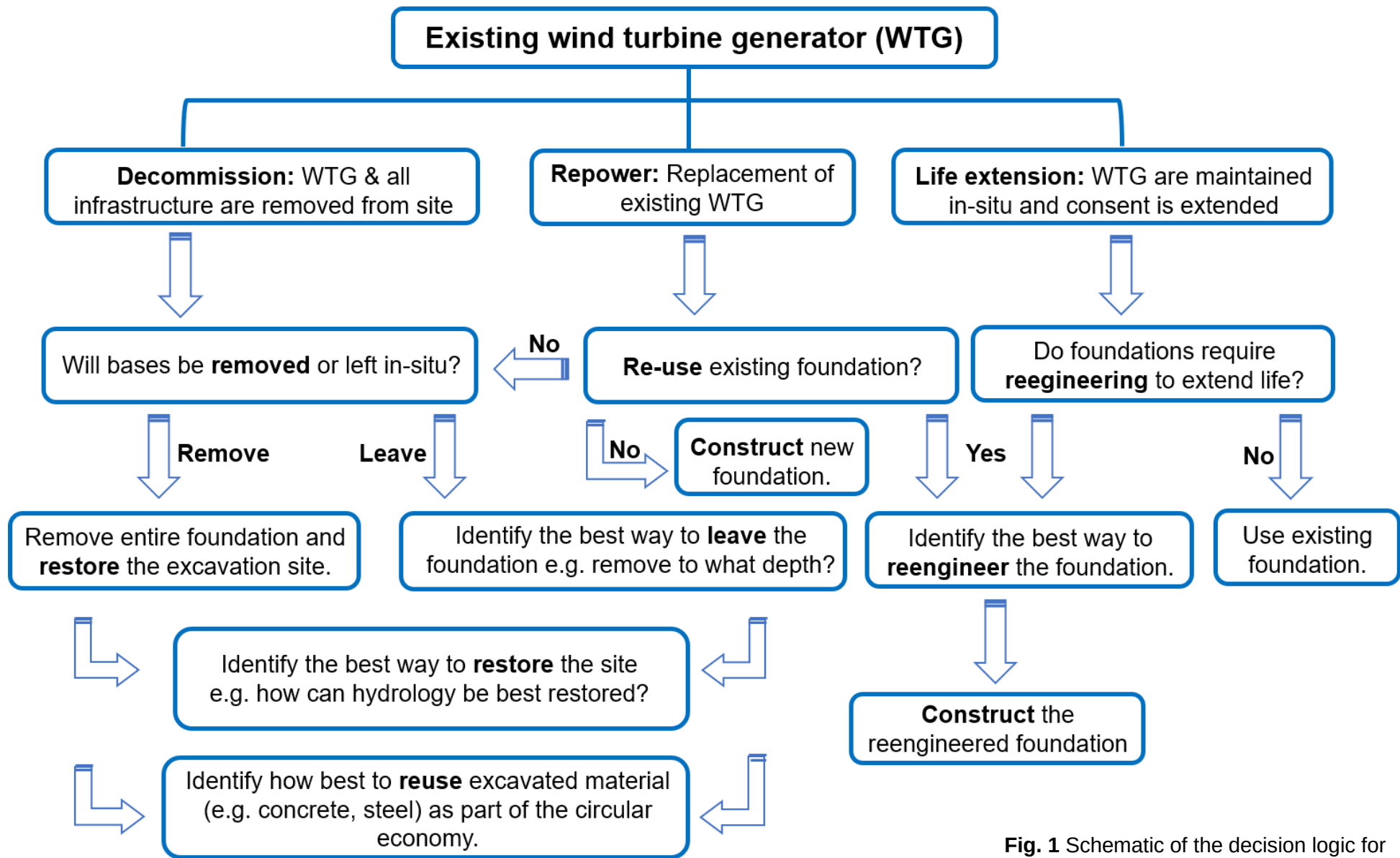


Fig. 1 Schematic of the decision logic for repowering considerations

Executive summary key understandings (cont.):

- Except for structural fill for one repowering scenario (considered unlikely to occur as repowering with the same capacity turbine), the quantity of materials required to construct a reengineered foundation are greater than repowering with a new foundation. For the two most likely repowering scenarios this represents 130 and 87 % more concrete, 52 and 23 % more steel, 185 and 106 % more aggregate, and 24 and 16% more structural fill. The impact of this extra resource requirement on wind farm payback time could be explored more fully with the Scottish Government Windfarm Carbon Assessment Tool (CAT).
- Soils represent an important C store, particularly peat soils, which are an important landscape in Scotland and host wind farms. Soil disturbance can cause loss of C, thus different approaches were used to estimate how much soil is disturbed when repowering with or without a reengineered foundation. Estimated volumes of soil excavation and reinstatement (representing respectively all soil disturbed, and that which must be sourced for restoration during the lifetime of a windfarm), were similar for all scenarios for the two foundation repowering approaches (-9 to +14 %). Only the end-of-life restoration of a foundation reengineered from 0.85 to 3.2 MW required more soil (+82 %). How these % differences affect soil C storage and translate to payback times could be estimated through developments to the CAT.
- Given this similarity in soil disturbance volume, an important consideration may be total surface area disturbance. This can impact on vegetation C sequestration and influence the area of a peatland drained. Approximately 30% more land surface area is disturbed for repowering using a new than reengineered foundation. The CAT considers C loss occurs until successful restoration, thus the payback time may be larger with a new foundation due to the larger excavation area and increased areal capacity for peat drainage. However, with two new foundations a larger area of land surface is reinstated after foundation construction leaving a smaller area for restoration at the end of the foundation lifetime. Thus, if there is recovery of the peatland functioning after reinstatement, this happens over a larger surface area when two foundations are used.
- There are key environmental unknowns associated with restoration in peatlands for reengineered foundations or new foundations at end-of-life. These are:
 - How quickly will peat infill acquire ecohydrological functioning and how is this influenced by the extent of recovery of the peatland hosting the windfarm (itself still an unknown)?
 - What is the optimum depth of foundation removal to allow ecohydrological functioning appropriate to the site being restored? Restoration plans outlined at the point of planning approval indicated a 1 m foundation removal before restoration, but this may be insufficient to support higher quality peatland vegetation.
 - If new foundations are used and old foundations left in place, albeit a reduced profile, will there be a habitat fragmentation?
 - How will residual turbine concrete foundations react with peat soil porewaters, and is the change in composition of these porewaters of concern?
- However, as minerogenic soils play less of a role in C-sequestration than peat soils, and land use appears unaffected in wind farms on minerogenic soils that have been disturbed, unless habitat disturbance is of concern, then the most environmentally-friendly approach appears to be to build a new foundation to accommodate the larger WTG than reengineering an existing foundation. This uses less resources that have an embedded CO₂ emission. This could suggest that repowering should first consider if wind farms on minerogenic soils can help meet the drive for more energy production from renewable sources.

- The Scottish Government Windfarm 'Carbon Assessment Tool' could be augmented to be suitable for application for repowered sites. Key points in this analysis are:
 - If a wind farm continues to be operational after the first approved lifetime, the loss of C due to not restoring the site must be passed on to the payback calculation for the repowered windfarm as a legacy debt. This is because C losses from the peatland continue in the repowered windfarm due to the site not being restored as originally planned, and the action of not restoring the site is attributable to the new development.
 - The influence of some processes associated with repowering on C payback time is unknown. Most are identified in the key environmental unknowns cited above but, additionally, there is a research need to assess if excavated C used in restoration should be considered a C loss (as excavated).
- In addition to the question of how to repower an existing site, this report briefly considers the alternative of new foundation design for an extended life (60-year), removing the need to undertake foundation works for repowering. It is considered that alternative materials to those typically used are unlikely to be effective, but, provided the necessary information relating to the second turbine was known at design stage, there is no technical barrier to the design of an extended life foundation. Thus, future research here could focus on environmental impact, cost and risk associated with a single extended life foundation, compared to two normal life foundations.

Whilst industry and regulators have contributed to and peer-reviewed the content of this report, their participation and co-authorship does not mean they endorse conclusions reached or recommendations made. The ownership of such statements rests with the academic authors.

Glossary of terms and supporting construction

The section provides a cross-section of the foundation components to help understand future discussion and defines terminology used in the text. The terms are in alphabetical order and thus the definition may contain a term defined later in the list.

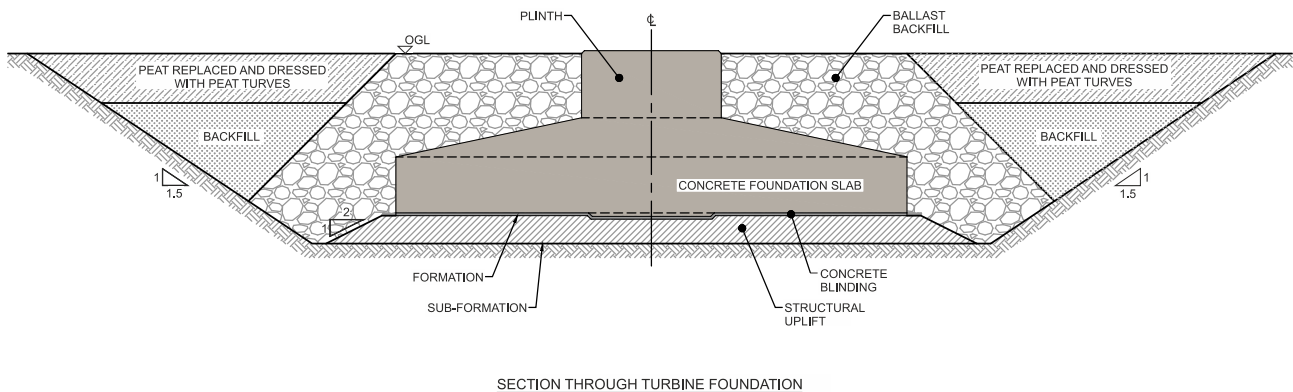


Fig. 2. A cross-section of a wind turbine generator foundation emplaced in peatland showing the different components involved in constructing the foundation and reinstating the land.

Anchor: A product (bolt) installed into existing concrete to transfer load.

Base slab: the main part of the foundation composed of reinforced concrete, overlying aggregate packing (the formation). This is the support structure (normally buried) used to transfer load from the turbine to the ground. In Fig. 2 this is annotated as the 'concrete foundation slab'.

Foundation: the foundation is the whole of the structure supporting the wind turbine generator, typically consisting of the base slab and the plinth (both constructed out of reinforced concrete), and it will contain granular backfill and aggregate packing to provide structure.

Foundation reengineering: the act of reengineering existing infrastructure to allow the erection of larger turbines. This report generally considers the removal of the plinth and building a new foundation on top of the old one.

Formation: the ground surface on which the foundation rests, typically at depth and created via excavation. Thereafter the land surface will be reinstated, usually to the previous level.

Overturning: To tip (a WTG) over onto its side. Forces and moments experienced by a WTG may cause overturning and the WTG foundation is designed to resist this.

Peak factored overturning moment: The maximum load a WTG foundation should be designed to resist which could result in overturning.

Plinth: the cylinder of reinforced concrete surrounding the connection to wind turbine generator and connected with the base slab. This is typically what would be removed as part of any restoration and would be replaced in repowering.

Life extension: maintaining the existing wind turbine generator beyond the approved planning consent without reengineering of foundations and thus with the same wind farm layout and turbine.

Reinstatement: the physical act of landscaping and profiling the land surface during the life of the wind farm. The profiling is targeted at returning the landscape to its original layout and thereafter the landscape would be allowed to recover naturally, although there may be element of active management more typical of restoration. For example:

- i) after the wind turbine generator (WTG) erection then soil excavated during the construction would be replaced around the foundation to return the landscape back to the original land surface height and allowed to revegetate;
- ii) after the removal of temporary tracks, different layers of soil are put back in their approximate order to achieve the pre-disturbance topography and the site allowed to revegetate naturally.

Restoration: the act of returning a landscape to its habitat during the life of the wind farm or after the wind farm and is likely to require active management to support efficient recovery e.g. reseeded, drain-blocking. There are multiple meanings associated with it and thus the term needs to be interpreted in context. For example:

- Immediate restoration following construction
- Habitat restoration / enhancement carried out during the operation of the wind farm
- The restoration of the site at the end of the wind farms life, with complete removal and decommissioning
- Restoration and repowering – whereby the site is ‘partially’ restored and repowered

Rotational stiffness: Rotational stiffness is the extent to which something resists rotation in response to a force. Wind turbine manufacturers specify a minimum rotational stiffness which the WTG foundation must provide to the base of the WTG tower.

Tower: The mast which holds the blades and generating equipment high above ground level

Void: the excavated area produced once a foundation has been wholly or partially removed.

Wind turbine generator (WTG): The engineered structure attached to the plinth that has blades which rotate with the wind and generate electricity. These typically increase in height with greater power output.

Wind farm repowering: the Scottish Government Onshore Wind Policy Statement (2017a) describes “repowering” as measures designed to extend the life of components and turbines at wind farm sites, or the replacing and replanting existing turbines. In the context of this report, repowering is a process which increases electricity generation capacity by either reengineering a foundation (thus reuse of a base already available) or by the construction of a new foundation (and the restoration of the redundant foundation), with both approaches supporting larger wind turbine.

1. Introduction

The key aims of this report are to consider how wind farm repowering may be supported by novel engineering approaches, how these approaches are considered by industry, and what would be the environmental considerations associated with wind farm repowering. The report also considers what adaptations would have to be made to the Scottish Government carbon (C) payback calculator (referred to below as the Windfarm C Assessment Tool) to calculate the CO₂ emissions expended in repowering that require to be offset by emissions saved through energy generated from wind power.

Repowering is an important issue given the drive towards a low carbon economy and the important role that onshore wind will play in this. For example, the amount of electricity generated from renewables in Scotland in 2015 equated to 59.4% of gross annual consumption, a fourfold increase from 12.2 % in 2000. Most of this growth can be attributed to onshore wind, complementing the post-war investment in large-scale hydro.

Since 2011, onshore wind in Scotland contributes nearly 60% of the UK's onshore wind capacity¹. The Scottish Government plans for future contributions from renewable energy are more ambitious, with 50% of all Scotland's energy consumption from renewable sources by 2030 and so onshore wind has an important role to play here. It is considered that proposals to repower existing wind farms, which are already in suitable sites, where environmental and other impacts have been shown to be capable of mitigation, can help to maintain or enhance installed capacity, underpinning renewable energy generation targets.

In Oct. 2017, Scotland had 3274 operational wind turbines, a further 1515 awaiting or under construction and 820 awaiting planning consent (Scottish Government Onshore Wind Policy Statement, 2017a). Thus, if repowering proceeds apace, many foundations could be reengineered or removed and the landscape subject to restoration. Over time, as wind farms are repowered, the number of foundations which could potentially be restored will increase. This is a legacy issue which the industry must consider now.

The Scottish Government Scottish Energy Strategy outlines a vision for the future energy system in Scotland to 2050 (Scottish Government Scottish Energy Strategy 2017b). The accompanying Onshore Wind Policy Statement (OWSP) (Scottish Government, 2017a) indicates industry should manage onshore wind energy production to have lower costs, and that new developments should be subsidy-free. This can be aided by onshore infrastructure that is as efficient as possible, with maximum re-use. Greater efficiency may take place through the process of repowering wind farms with new infrastructure (e.g. more efficient turbines), that allows greater electricity generation for a given wind resource i.e. maximum generation possible per unit spend on development and maintenance. The OSWP offers the following positions on repowering:

- many established onshore wind sites will be coming to the end of their consented life during the coming decade and beyond. As the need and demand for renewable power increases, they expect developers to review the potential for “repowering” at existing sites. This could be in the form of measures designed to extend the life of components and turbines at such sites, or replacing and replanting existing turbines with new turbines
- the Scottish Government position remains one of clear support in principle for repowering at existing sites. This is on the grounds of its potential to make the best use of existing sites, and – through the continued use of established infrastructure, grid connections and strong wind resource provide a cost-effective option to deliver renewable and decarbonisation targets.
- repowering is a term that can be used or applied to different scenarios, depending on the nature and scale of what is being contemplated or proposed at any given site.

- repowering applications will be subject to a clear and distinct assessment process and the Scottish Government propose to continue to discuss and to assess the right approach to such applications on a case by case basis, in accordance with established process and principles. Thus, the range of potential impacts and effects associated with any proposal can be properly assessed, and as such the level of environmental assessment, monitoring and information that may need to be undertaken and provided.

Additionally, SNH and SEPA are statutory consultees on Environmental Impact Assessments and can work with the energy industry to identify solutions in repowering that reduce the costs and impacts. The OWPS particularly identified the role of Scottish Natural Heritage (SNH) in repowering, given its responsibilities and wider role in considering and advising upon the impacts of onshore wind development on the natural heritage.

Thus, although the first tranche of onshore wind farms has not yet reached the end of their 25-year consent, as a new generation of more efficient turbines become available, it is likely that the repowering of onshore wind farms will become an important activity in the renewable onshore industry. To ensure that environmental impacts are minimized, the approach to repowering must be considered carefully.

SNH, SEPA and Construction Scotland Innovation Centre have commissioned this research to contribute to the development of practice and policy in Scotland in relation to wind farm repowering developments, supporting the development of “best practice” options for future wind turbine installations. This report focuses around comparison of options for existing wind foundations that could extend their lifecycle. It considers whether these create a more sustainable approach to repowering that offers advantages over the installation of completely new infrastructure. In this context, four areas have been considered:

1. are there new approaches to the design & construction of wind foundations that would allow reuse?
2. what is the industry consideration of the options and how do the costs compare to the existing model?
3. how are the turbine manufacturers responding to the repowering agenda?
4. what are the beneficial and detrimental effects that may arise if wind turbines foundations can be reused and are repowered, or cannot?

Planning is not being considered here as this is being delivered by the Planning System through Scottish Planning Policy, Scottish Government online advice, and Environmental Impact Assessment Regulations. However, this report may help inform the delivery of planning policy.

2. How this research was carried out

This report summarises understanding to inform the development of best practice. The report first provides an overview of existing repowering activity to outline the process to date and its associated engineering and environmental footprint (section 3). The engagement of turbine manufacturers with repowering (section 4), engineered solutions that may allow WTG foundation reuse are presented (section 5), and their viability (section 6) are presented. The environmental considerations are outlined (section 7) and how the Scottish Government Windfarm ‘Carbon Assessment Tool’ could be adapted to consider repowering is detailed (section 8).

Arup considered the technological and engineering solutions that would be required to reuse existing foundations. SSE and Scottish Power considered the validity and cost of the proposed engineered solution to reusing the foundations. Waldron (University of Glasgow) and Smith (University of Aberdeen) undertook the research associated with the consideration of the environmental responses to different approaches to repowering. Waldron collated all individual components to produce the report. As repowering is a new consideration there is little published research in this area, and even

less of direct relevance, and so some of the understanding has been reached by considering the processes relevant from the initial wind farm development. This report is considering the Scottish perspective only but has drawn on examples outwith Scotland where the information is relevant.

Websites referenced as information sources have been identified by a superscripted number, whilst document formatted publications are references are cited by the lead author name and year of publication, noting some may be on-line resources and so a website address is also provided.

3. Existing repowering activity

In the UK, at least ten sites have been repowered, or received permission to repower (Table 1, overleaf). Repowering has also taken place in Ireland, Spain² and Italy (Ferri et al, 2016). There has only been one site in Scotland repowered to date: the Spurness wind farm in Orkney, on the island of Sanday, 30 miles north of mainland Orkney. Repowering was undertaken as components for existing the Micon turbines were no longer available, and the wind resource here was considered excellent. Foundations were not reused and so works included construction of access tracks, hard-standings, foundations and a new welfare building. The larger wind farms that have been repowered in the UK are outwith Scotland.

The largest wind farm in Scotland to be in the repowering framework is the SSE Tangy wind farm on the Mull of Kintyre. This was granted planning approval for repowering in June 2015 to commence within the proceeding three years³. The consented approval was to replace the existing 22 turbines with 15 new turbines, almost doubling the wind farm installed generating capacity. This was termed Tangy III. However, in April 2017, SSE submitted a Scoping Report⁴ to the Scottish Government Energy Consents Unit (ECU) proposing an increase in tip height of the turbines proposed, from the consented 125 m up to 150 m. The Energy Consents Unit (ECU) have requested this is now called Tangy IV to avoid any confusion between the current proposal and the previously consented Tangy III repowering project. The Tangy IV modified proposals are largely unchanged since those submitted for the consented Tangy III project, except for the increase in tip height, and retention of forestry. All other elements of the site design (i.e. turbine locations, access track layout, etc.) remain unchanged. This project is currently on hold until further notice⁵.

Thus, repowering is occurring in the UK but is not commonplace. None of the repowered sites have used, or propose to use, the same foundations, as considered unsuitable for the new larger turbines. Instead where repowering has proceeded, original concrete foundations have been reduced to 1m below ground level and cabling left in place (see section 3.1). In some sites e.g. Carland Cross, the old turbine bases are now part of arable field systems and crops are grown over the top, so this depth of reinstatement is sufficient for ploughing and cultivation.

Repowered sites may provide an opportunity to assess if the restoration approaches where the foundation cannot be reused are successful. However, those completed to date have generally been on mineral soils and so their treatment and site recovery after disturbance do not offer immediate understanding of how to approach repowering on peat lands, which is an important consideration for Scotland. Peat soils exist in Ovenden Moor wind farm where repowering is almost complete, and at Llandinam Wind Farm, which is much larger than Ovenden. Thus, the repowering undertaken could offer insight into peat soils site recovery when turbine bases are partially removed and not reused. The Caton Moor site has a peaty surface, but not the depth of peat that may be present in wind farms in Scotland. Currently sheep graze the site.

However, currently there is not a blueprint on how to approach repowering that has been extensively-used and has informed best practise at these sites and is relevant to wider Scottish needs and preponderance of organic soils.

Site name, location. Developer	Status	Proposed / implemented repowering	Soil type
Scotland			
Spurness, Orkney SSE	Completed 2013	Three turbines (2.75 MW) were replaced with 5 turbines (10 MW) ⁶	Agricultural and mineral soils
Tangy, Mull of Kintyre SSE	Consented 2015, not yet started	Replacing 22 existing turbines (18.7 MW) with 15 new turbines (36.8 MW)	Peat soils overlying glacial tills. Mean peat depth of 0.55 m, but up to 1.8 at new WTG locations
Rest of the UK			
Caton Moor, Cumbria, Thrive Energy	Completed 2006	Replaced 10 turbines with 8 (16 MW) ⁷	Acid upland soils with a peaty surface
Goonhilly, Lizard Peninsula, Cornwall REG Powr Management	Completed 2010 (replacing 1993 turbines)	14 turbines (5.6 MW) to 6 turbines (12 MW).	Mineral soils ⁸
Delabole, Cornwall, Good Energy	Completed 2011	10 turbines (4 MW) replaced with 4 (9.2MW) ⁹	Freely draining slightly acid soils
Carland Cross, Cornwall Scottish Power Renewables	Completed 2013	15 turbines (6 MW) replaced with 10 (20 MW) ¹⁰	Mineral soils.
Coal Clough, Burnley Yorkshire Scottish Power Renewables	Completed 2015	24 turbines (9.6 MW) replaced with 8 (16MW) ¹¹	Blanket bog present but repowering was on mineral soils (blanket bog present but avoided)
Ovenden Moor, Yorkshire, Yorkshire Wind Energy Ltd (owned by E.On and EPR Ltd)	Started summer 2015, Completion due early 2018	Replacing 23 turbines (9.2MW) with 9 turbines ¹² (22.5 MW)	Peat depth varies across the site; predominantly less than 1m in the south and southeast of the site; between 2m and 3m to the north; the occasional pocket of peat 3m to 4m deep
Llandinam, Wales, Scottish Power Renewables	Consented 2015; not started.	102 turbines (31 MW) to be replaced with 34 turbines (102 MW) ¹³	Peat soils overlying glacial tills, ranging in depth from 0.10 - 0.85 m, but up to 1.4 and 2.1 m locally ^{9B}
Rhyd-y-Groes, Anglesey, TPG Wind Ltd, (owned by E.On & Eurus Energy).	Consented 2016; not started.	24 turbines (7.2MW) replaced with 11 new turbines (9.9MW) ¹⁴	Mineral soils and no peat found on site

Table 1. Details of repowered wind farms, or those consenting for repowering, in the UK. Sites are listed in chronological order of completion. Soil category information was sourced from development EIA or the United Kingdom Soil Observatory (UKSO)¹⁵ soils map viewer.

3.1. The treatment of foundations and associated infrastructure during repowering

This section outlines the key processes that will take place during repowering, based on consideration of two sites, one repowered and the other planned to be repowered. Conditions within the outline restoration plans for end-of-life wind farms are also considered, as of relevance to restoration occurring during repowering.

3.1.1. Understanding from existing repowered sites

In the Spurness wind farm, the ‘cans’ (metal rings embedded in the concrete foundation to which the tower is attached) in the old foundation were cut free, and the concrete foundations left in-situ. The original planning condition required all ‘above ground level’ infrastructure to be removed and so this practice was consistent with this consent. The turbines were generally located in brown earth type soils, with a mixed land use of grazing and arable farming, and so the old foundations were covered with a layer of topsoil (0.5 to 1 m generally), the land re-profiled, and a seed mix applied. Cables were cut back and reused where appropriate.

This practice is broadly comparable to other repowering that has taken place in the UK. For, example at Ovenden Moor (Table 1) it appears that the following is taking place¹²:

- all above ground structures and equipment will be removed to at least 1 m below ground;
- connections to electricity generation cables will be dismantled
- the site will be landscaped using topsoil of similar composition to the surroundings to encourage the vegetation to recolonise and normal soil biogeochemical functioning to return.

Therefore, to date where the foundations were not reused, all above ground structures and equipment were removed, and the site was landscaped with appropriate soil covering to encourage habitat regeneration. This approach is consistent with the restoration proposed in the planning applications for site restoration at the end of the wind farm lifetime. Scottish Energy consents related to decommissioning can be found in examples available at <http://www.energyconsents.scot/>. Figs. 2 -4 help visualise the infrastructure that would have to be removed.



Fig. 3. A gravity foundation (there is no evidence of piling) during construction (2011) showing the infrastructure (left), that is subsequently infilled by concrete (right, but not the same foundation). This foundation has a can insert, which is now less common than a bolted connection, although still in use. Removal of the top 1-1.5 m would remove some of the vertical uprights (the plinth for the turbine), leaving the poured foundation and embedded steel largely intact. For scale, the person furthest to the left is 1.75 m (right). Soil depth on the LHS photo is ~ 1 m and below this is glacial till. Thus, removing the infrastructure here and replacing the soil with similar type (peat) and depth would generate a soil profile similar to before construction, and the concrete structure would map more closely to the underlying glacial till, but be less permeable. (Photos: ©Susan Waldron).



Fig. 4. Two different gravity foundations, constructed in 2016, that use bolted connections. The bolted connections will require a similar level of removal as the can connection. Note the difference in plinth thickness, with the left image foundation in a deeper soil having a thicker plinth than the right image plinth sited in bedrock. These images demonstrate the difference in infill volume that would be required if the foundations could not be reused for repowering and had to be removed completely or partially for restoration (Photos: ©SSE).

There can be different turbine plinth connections (can vs. bolted), and, depending on soil depth and depth to bedrock, different plinth designs for stability (gravity foundation vs. piled foundation) and plinth thickness. The type of foundation used can vary within a wind farm depending on site geotechnical conditions. However, the connection to the turbine shaft will not vary within a wind farm unless there have been new WTG erected in an extension to the original wind farm.

If permitted access tracks may be left for use by the landowner, or where appropriate material is available, may be covered with topsoil to encourage habitat regeneration. Repowering using new turbines in different locations will require the provision of new cabling, but repowering reusing the foundation may also require this. The cables that transport power from the WTG can be sited at different depths within the foundation but are typically at 1m depth. Cabling from WTG to the substation is typically laid adjacent to access tracks, either in a semi-insulating material such as sand, or using ducting for cables, but can be ploughed in with no additional surround. Thus, as disturbance is likely with both scenarios, this report focuses on foundation sustainability and cable trenches are only considered briefly in this report.

Whilst a similar process has occurred in Spurness⁶ and other wind farms, this approach to restoration exists as developers consider that the environmental impact is less than with the break-up of foundations and ancillary infrastructure and complete removal. However, each site needs to be considered on its own merits, so a common approach may not be appropriate, and the environmental analysis considers this further (section 7).

3.1.2. Understanding from planning consent related to decommissioning, restoration and aftercare

Considerable attention has been given to the scenario of decommissioning and restoration of a wind farm in the development of guidance to this process, including detail on the technical stages associated with the construction process (Welstead et al 2013, SNH 2016). Key here, are points of relevance to repowering where the foundations cannot be reused.

Firstly, planning authority permissions and Scottish Ministers Section 36 consents will typically contain a condition(s) relating to the decommissioning of a wind farm based on a decommissioning, restoration and aftercare statement. The condition often refers to wind turbines, ancillary equipment

and buildings being dismantled and removed from the site, and the land being restored and subject to aftercare, in accordance with the restoration and aftercare scheme (SNH 2016).

Secondly, the outline decommissioning plans submitted for discharge of pre-commencement conditions normally state that, based on current guidelines and regulations, foundations would be removed to 1 metre below ground level. However, the decommissioning approach is not detailed in the original planning application describing the restoration plan as it is expected that this will be developed more fully during the lifetime of the wind farm in a decommissioning-restoration plan (DRP) to accommodate changes that occur on site during this period e.g. the new residency of a protected species.

Whilst this guidance exists, no wind farms have been decommissioned and restored in a peatland environment, and so information on how the foundations and associated infrastructure are treated is lacking. As such it is likely that our best understanding of the repowering process will come from considering sites already repowered or through consideration of the wind farm construction process.

4. Assessment of the turbine manufacturer engagement with repowering

The following summarises the research undertaken by Scottish Enterprise to assess the role of turbine manufactures in repowering and the reuse of foundation, for sufficient industry demand present opportunities for Scotland's supply chain companies. The more detailed report response summary is given in Appendix 1.

Three wind turbine developers were approached to participate in a short survey to outline their plans for repowering and the use of concrete foundations. Gamesa and Vestas offered responses, Siemens did not.

Repowering was identified as their main area of business, especially overseas where repowering is currently taking place in the USA and Germany where turbines were installed in the 80s/90s.

Gamesa and Vestas emphasized, that for existing and future plans, there is a need for continued technology development and innovation in order to lower the costs of energy. One of the challenges for developers in the UK is the perceived preferred local planning authority landscape character fit for tip heights, which limits the use of larger turbines and so makes lowering the costs of energy more challenging.

If future wind turbine generators are larger i.e. rotors, then the wind turbine developers recognise that the foundations would have to increase in size to compensate for new technologies and concepts. The wind turbine developers identified that for some projects there was a request to modify foundations, but this has proven difficult at times due to the different component parts within the foundations such as concrete and steel.

In summary it appears that turbine manufacturers have been involved in repowering projects overseas and would be willing to work with developers and other stakeholders in the UK.

5. Design and construction approaches

Construction Scotland Innovation
Centre

**WTG foundation reuse working
group**

Engineering assessment of
foundation re-use

Issue 5 |

This report takes into account the particular instructions and requirements of our client.

It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

Job number 71854-01

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ARUP

5.1. Introduction

5.1.1. Brief

Arup were appointed by Construction Scotland Innovation Centre (CSIC) on 1st February 2017 to prepare a report on the engineering aspects of wind turbine foundation re-use. This scope was extended on 10th March 2017 with agreement of CSIC, and the extension funded by SSE.

The basis of the study was to be a typical foundation for a Siemens 2.3MW wind turbine generator (WTG). This WTG was a common turbine on wind farms in construction circa 2010-2012. Arup were asked to look at three re-use scenarios:

1. Re-powering with a similar turbine
2. Re-powering with a larger turbine, such as the Siemens 3.2MW
3. Re-powering with a larger turbine, such as a 5.0MW

Arup were also asked to consider re-use of a typical foundation for a 0.85MW WTG. This would be typical of wind farms which are about to become due for repowering. Arup were asked to look at one re-use scenario:

1. Re-powering with a larger turbine, such as the Siemens 3.2MW

In considering options for re-use in each scenario, Arup were asked to consider only technical adequacy, and not limit options by current planning requirements, commercial viability or Wind Turbine availability. The objective defined was to achieve a 30-year foundation design life for the new WTG, following 25 years of operation with the first WTG. Existing WTGs have a 20-year design life, and hence 25 years represents a period of sweating the asset beyond its design life. WTGs with 25- or 30-year design life are starting to become available.

This report does not consider the implication of designing new build foundations for a 60-year design life, something which has been identified by the group as a potential future study as outlined in section 5.5.

5.1.2. Approach

Detailed foundation analysis is a complex process. This report has drawn on experience of the design of new build foundations and the remediation of under designed foundations (foundations with a short design life, which require life extension). This experience was used to help identify the potential for re-use and the works required. Where applicable preliminary foundation stability and stiffness calculations have been undertaken to provide indicative sizing of the required works.

5.2. Engineering context

5.2.1. Foundation design

WTG Foundations are subjected to high overturning loads (predominantly from the wind pushing against the blades), applied a large number of times during the WTG's operational life. As a result, the design of significant areas of the foundation structure and connection to the tower, is governed by the requirements to meet the fatigue life (the ability to resist load applied a large number of times).

WTG foundations are typically designed for 20 or 25 years of fatigue loading.

5.2.2. Wind turbine generator development

WTG technology continues to develop, with both increasing size and improved technology improving generation output. Whilst WTG size and loading will vary between site, WTG manufacturer and model, the following graphs show variation between four WTGs:

- Gamesa 0.85MW: These WTGs are typically approaching the end of their design life.
- Siemens 2.3MW: Typically installed in 2010 to 2012, and no longer available
- Siemens 3.2 MW: Currently available model
- Confidential 6MW: indication of possible future direction.

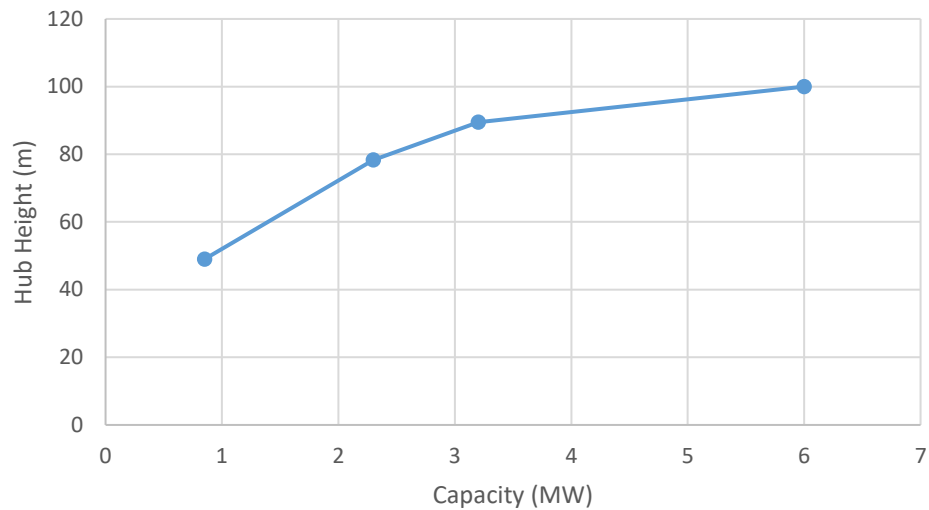


Fig. 5. Hub height vs. generation capacity.

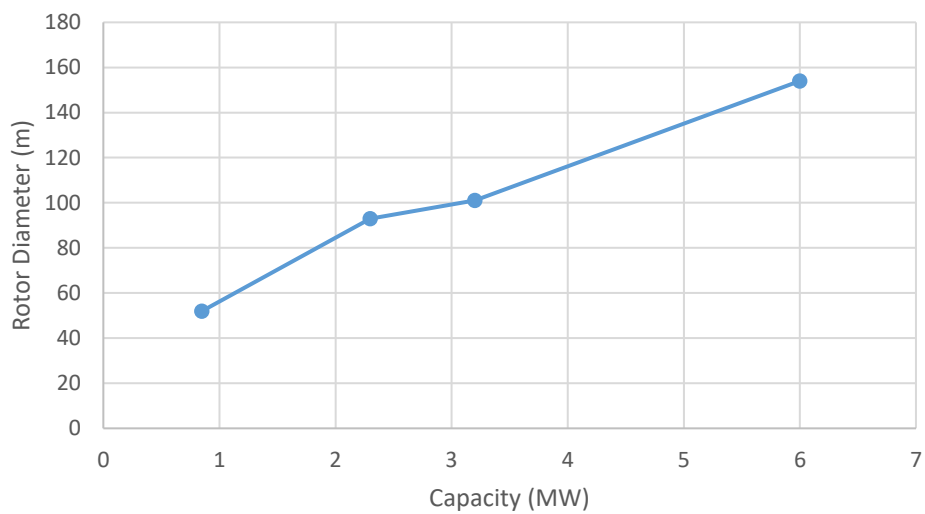


Fig. 6. Rotor diameter vs. generation capacity.

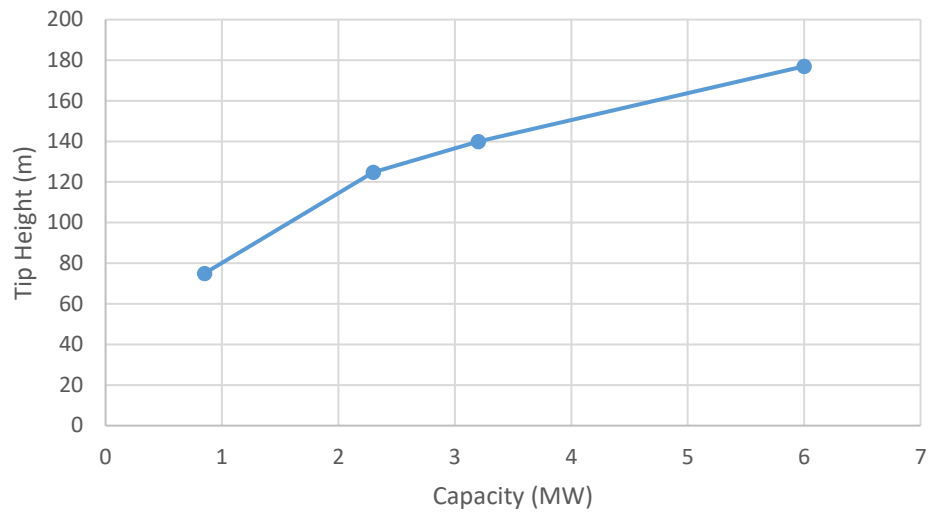


Fig. 7. Tip height vs. generation capacity.

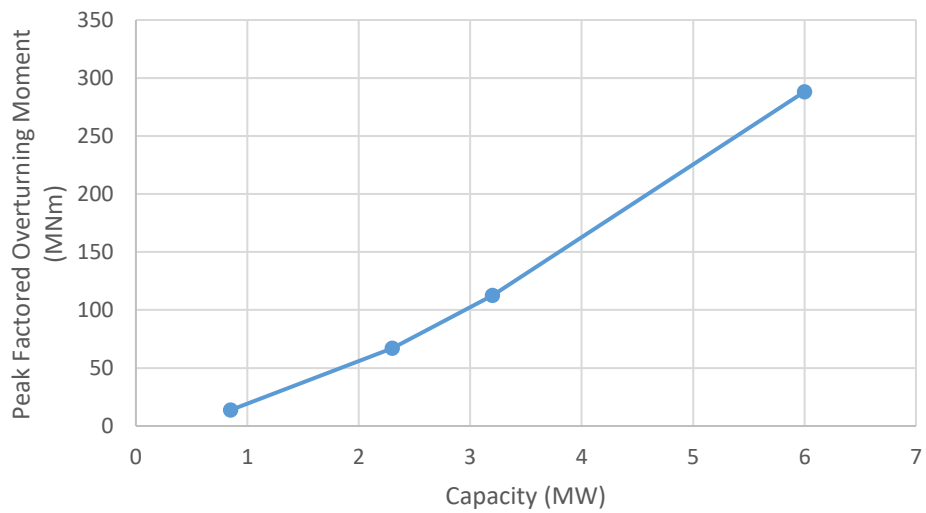


Fig. 8. Peak factored overturning moment vs. generation capacity.

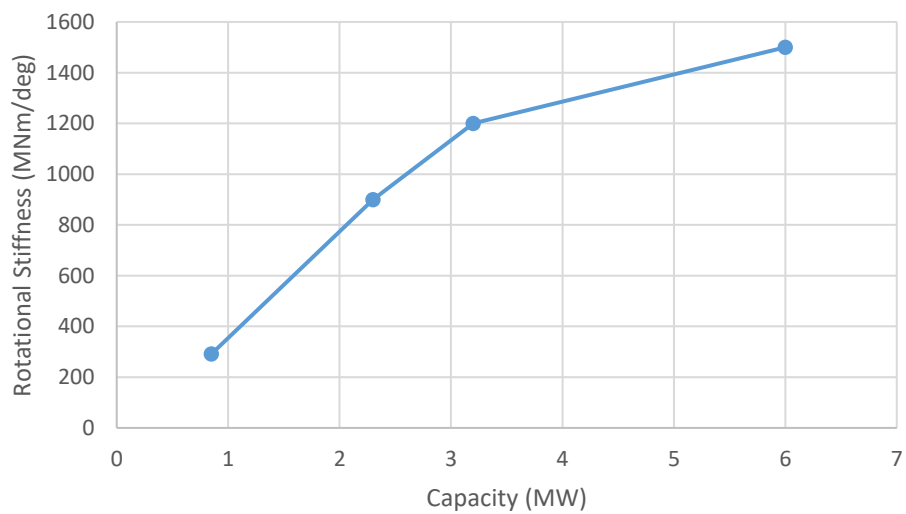


Fig. 9. Rotational stiffness vs. generation capacity.

While these comparisons include peak factored overturning moment vs generation capacity, as a simple basis of comparison, it is important to note that historically WTG development has resulted in increasingly significant fatigue and stiffness requirements. The effect of development is therefore not simply 'up scaling' with increasing peak load.

Transportation requirements also significantly constrain WTG design. For example, despite significantly increasing loads, tower base diameter has changed little due to practicalities in transportation.

5.3. Baseline – typical WTG foundations

Drawings of typical foundations for a 0.85MW WTG, a 2.3MW WTG and a 3.2MW WTG are included in Appendix 4A. These WTG foundations were designed by others, and while considered typical, have not been analysed by Arup.

A drawing of a foundation for a 5.0MW WTG is included in Appendix 4A. This foundation size has been derived by Arup as an indication of what is likely to be typical as a new-build foundation for WTGs of this size in future.

Quantities for these foundations are included in the following table.

Drawing Ref	Reinforced Concrete Volume (m ³)	Reinforcing Steel (tonnes)	Course Aggregate for Concrete (m ³)	Structural Fill Volume (m ³)	Total Excavation volume (m ³)
0850-1	130	19	65	203	1311
2300-1	423	60	212	373	3792
3200-1	656	92	328	381	4852
5000-1	1398	196	699	795	8343

Table 2. Baseline quantities for foundations

Drawing Ref	Excavated and reinstated during construction (m ³)	Excavated and removed during construction (m ³)	Required for end of life reinstatement (m ³)
0850-1	374	165	165
2300-1	750	323	323
3200-1	902	331	331
5000-1	1219	722	722

Table 3: Baseline peat quantities assuming 1m peat depth.

All these foundations include a significant depth of soil over the foundation (and a significant height of plinth). This is typical for these foundations however some foundations, particularly more recent foundations do not have a significant depth of soil over the foundations (plinth height is small), and this would be generally make re-use options more onerous.

Drawings showing anticipated end of life reinstatement works are included in Appendix 4C. These are based on removal of reinforced concrete and structural fill to 1m below ground level and backfill to ground level with soils/peat as applicable. This work would normally be undertaken from within the area of reinstatement shown.

5.4. Foundation re-use

5.4.1 Reusability of key components

5.4.1.1. Tower-slab connection

WTG towers are typically connected to the foundation using either a bolted arrangement or an Insert Can. In each case highly concentrated loads are transferred from the WTG tower to the foundation. These areas of very high stress concentration are always fatigue critical: that is design has been

driven by the original design life, and hence significant residual design life is very unusual. Methods of life extension are available in some instances for remediation of defective foundations, but the beneficial effect is small compared to a 25-30 year life extension. For life extension a new load path is therefore required at this connection.

5.4.1.2. Main slab

WTG foundations typically comprise a slab to spread load from the concentrated applied load at the tower base out to the soil below. This reaction from the soil below, together with the foundation self-weight and the weight of soil above is used to resist overturning.

Foundation slabs are fatigue critical, especially in the area near to the tower-slab connection, and near any piles. As original design in these areas is driven by the original design life, significant residual design life (relative to a 25-30 year life extension) is very unusual. Methods of life extension are available in some instances for remediation. While the methods are different to those for remediation of the tower-slab connection, the beneficial effect is also small compared to a 25-30 year life extension. For life extension a new load path is therefore required.

5.4.1.3. Mass

Structural mass is in general beneficial to resisting overturning. Connection of the existing WTG foundation mass to the new load paths (using anchors) could therefore reduce foundation size. This connection would have to withstand high fatigue loading and products suitable for this are extremely limited. From past experience, the use of such products requires significant drilling and cutting of the original concrete to enable installation, with associated environmental impact in addition to the embodied impacts which would need to be assessed. These connections are currently very expensive (the cost of these connections alone can be around 50% of the other foundation costs), and hence not normally used. However, they provide a technical option.

5.4.1.4. Formation

The ground surface on which a WTG foundation rests is called the formation. The works required to construct a formation vary significantly depending on the ground conditions. In some instances, the formation is in bedrock, or good soil, and excavation is the principle activity. In other instances, excavation to greater depth is required, and structural fill is then required to formation level.

While there is limited research into the formation degradation, current industry practise would allow the re-use of formations under WTG foundations.

5.4.2. Options for re-use

Based on the factors summarised in section 5.4.3, several foundation re-use options were identified. The options are outlined in the following sub-sections.

5.4.2.1. Removal of plinth and construction of new slab

Works comprise:

1. Removal of backfill over base.
2. Removal of existing plinth.
3. Excavation adjacent to base to extend formation.
4. Mass concrete backfill (required to prevent stiffness differential adjacent to existing foundation).
5. Construction of new foundation over the existing foundation.
6. Backfill around foundation.

Optionally works could also include installation of anchors into the original foundation to make use of its self-weight. This would be undertaken prior to construction of the new foundation.

Appendix 4B includes drawings for each foundation re-use scenario. Option 1 does not connect to the existing base, while Option 2 does. As can be seen the difference in foundation size is relatively small, particularly where re-use involves an increase in WTG size. As noted above anchor options suitable for the fatigue loading experienced in WTG foundations are very limited. Based on past experience, these anchors are likely to cost in the order of £5,300 each installed.

The available depth between the top of the existing WTG foundation slab and ground level is insufficient for the required slab stiffness for the following options:

- Reuse of 0.85MW foundation for 3.2MW WTG
- Reuse of 2.3MW foundation for 5.0MW WTG

The required slab thickness for these scenarios therefore projects above existing ground level.

In order to minimise the extent of excavation and associated peat disturbance, options 1 and 2 are both shown with constant thickness slabs. A sensitivity analysis on the use of a tapered slab is presented as option 3, for repowering a 2.3MW foundation with a 3.2 MW turbine. This illustrates that in this instance the introduction of the taper results in a small reduction of concrete volume while increasing the excavation adjacent to the base.

5.4.2.2. New slab entirely above ground level

This option would be as outlined in section 5.4.2.1, with the following differences:

1. The original plinth would be abandoned but only the top 100mm removed.
2. An increased volume of mass concrete would be required to the underside of the new foundation.

The difference in works required from the option outlined in section 5.4.2.1, would therefore be:

1. The volume of plinth removed is reduced.
2. The volume of mass concrete is increased.

An example of this is shown in Appendix 4B as Option 4 for the re-use of a foundation from a 2.3MW turbine for a 3.2MW turbine.

5.4.2.3. New slab around plinth: Complex transition piece

This option would be as outlined in section 5.4.2.1, with the following differences:

1. The original plinth would be abandoned but not removed.
2. An increase in slab depth would be required to compensate for decreased foundation stiffness arising from a loss of continuity through the centre of the foundation. As a result the slab would project above ground level in all cases. The additional depth would likely be in the order of 0.3-0.6m.
3. A complex steel transition piece would be required to connect from the standard diameter tower to the new connection piece.
4. Bespoke tower sections would be required as the bottom of the WTG tower would be at a higher level than normal.
5. An increased foundation footprint may be required, with associated increase in concrete volume and excavation.

A concept sketch of this option is provided in Appendix 4B as Option 5 for the re-use of a foundation from a 2.3MW turbine for a 3.2MW turbine.

The difference in works required from the option outlined in section 5.4.2.1, would therefore be:

1. The volume of plinth removed is reduced.
2. The volume of reinforced concrete is increased.
3. A complex steel transition piece is required.
4. The volume of mass concrete may increase.
5. The volume of excavation may increase.

No analysis of the transition piece has been undertaken, but an additional steel quantity of 35 tonnes is considered reasonable conceptual estimate.

5.4.2.4. Quantities

Quantities for each option are outlined in the following table. All quantities relate to that required for the re-use and do not include the quantities for construction of the original foundation.

Option	Drawing Ref	Reinforced Concrete (m ³)	Reinforcing Steel (tonnes)	Mass Concrete Volume (m ³)	Course Aggregate for Concrete (m ³)	Structural Fill Volume (m ³)	Excavation volume (m ³)
0.85MW to 3.2MW	0850-3200-01	1065	150	610	1057	524	3076
2.3MW to 2.3MW Option 1	2300-2300-01	708	100	390	530	127	3869
2.3MW to 2.3MW Option 2	2300-2300-02	631	89	309	451	81	3556
2.3MW to 3.2MW Option 1	2300-3200-01	1097	154	795	927	354	5356
2.3MW to 3.2MW Option 2	2300-3200-02	1056	148	753	885	331	5204
2.3MW to 3.2MW Option 3	2300-3200-03	969	136	834	882	376	5495
2.3MW to 3.2MW Option 4	2300-3200-04	1097	154	2047	1002	403	5666
2.3MW to 3.2MW Option 5	2300-3200-05	1057	149	795	907	354	5356
2.3MW to 5.0MW	2300-5000-01	1817	255	1165	1665	558	6642

Table 4: Re-use quantities.

Drawing Ref	Excavated and reinstated during construction (m ³)	Excavated and removed during construction (m ³)	Required for end of life reinstatement (m ³)
0.85MW to 3.2MW	373	738	903
2.3MW to 2.3MW Option 1	635	325	648
2.3MW to 2.3MW Option 2	613	272	595
2.3MW to 3.2MW Option 1	731	581	903
2.3MW to 3.2MW Option 2	721	554	877
2.3MW to 3.2MW Option 3	739	605	927
2.3MW to 3.2MW Option 4	803	581	903
2.3MW to 3.2MW Option 5	731	581	903
2.3MW to 5.0MW	804	806	1129

Table 5: Re-use peat quantities assuming 1m peat depth.

5.4.3. Re-used foundation decommissioning

Current foundation de-commissioning practice removes concrete typically to between 0.6m below ground level and 1.0m below ground level. On typical foundations this requires removal of part of the plinth only.

Each foundation re-use option results in a large slab within this depth, and hence if the same practice were to be applied the quantity of concrete and reinforcement to be removed at future decommissioning would be greatly increased.

Drawings showing anticipated end of life reinstatement works are included in Appendix 4C. These are based on removal of reinforced concrete and structural fill to 1m below ground level and backfill to ground level with soils/peat as applicable. This work would normally be undertaken from within the area of reinstatement shown.

5.5. New foundations with extended design life

During the course of this work Arup were asked to advise on what research would be needed to facilitate the design of WTG foundations with a 60-year operational design life.

There is no technical barrier to design of a WTG foundation for 60 years, provided:

1. The loading, and other criteria etc. for the 'second turbine' are known at foundation design stage.
2. Both turbines to be installed on the foundation over the design life have compatible connection details to the foundation.
3. The size of the tower bottom flange, the hold down bolts and anchor ring on both the first and the second turbines can be set to meet the requirements of the project and are not constrained to 'standard' products.

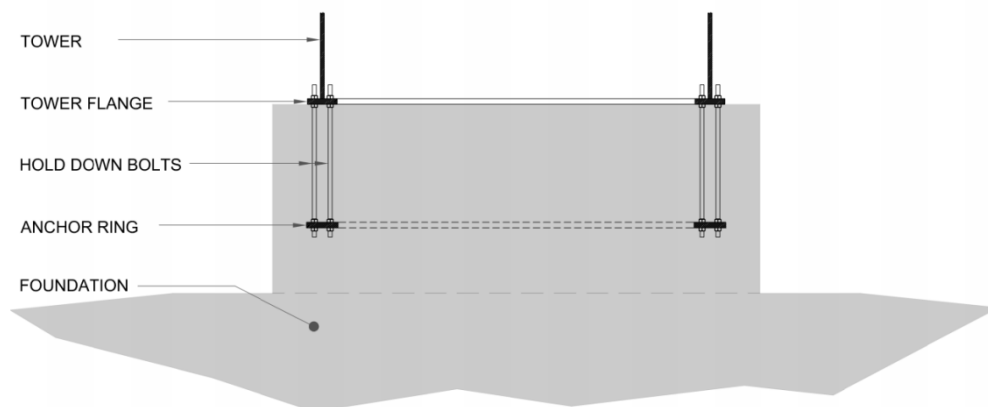


Fig. 10. Typical tower connection.

To expand on these three requirements:

- Item 1 cannot be known at present. It would be necessary to guess future requirements and add a margin to them to reduce (but not remove) the risk that the WTG foundation is unsuitable for turbines available when repowering is required.
- Item 2 constrains WTG tower geometry, as it is necessary for the second tower to have a connection which is geometrically compatible with the connection installed when the first WTG was installed. This therefore creates a risk that no (or only a small number) of suitable turbines are available at repowering.
- Item 3 may raise contractual, insurance and finance issues: Wind Turbine Suppliers are generally inflexible, and the flange is normally part of the certification process. Recertification could be a

lengthy and costly process, while use without certification could raise insurance and finance barriers.

From our experience it is clear that design for a 60-year life would require larger foundations with additional steel and concrete, and higher strength concrete. It is not clear whether (given the uncertainties identified above) design for a 60-year operating life would be the best environmental option or not. Further research on this could be valuable. This could compare following two options:

1. Current approach based on:
 - a. Foundation for current WTG, constructed and reinstated at end of life.
 - b. Foundation for a future generation WTG constructed in 30 years time and removed at end of life.
2. Alternative approach based on:
 - a. Foundation for current and possible future WTG, constructed for first WTG, reused under second WTG and removed at end of life of the third WTG.

This would compare environmental impact, material usage and cost for these two approaches. These could then be considered against the risks noted above. In order to undertake this comparison, a detailed technical assessment would be required looking at material grade and quantities required.

While a study considering alternative materials or repair options could be undertaken, these are issues Arup have considered already in other work. In the course of that work, no suitable alternative materials have been identified. With respect to repair, given the issues encountered, construction followed by repair options, where repair is technically possible (a significant limitation), have significantly greater cost and material use than construction of a new WTG foundation designed for the required life. While full assessment would be required, given that material use, additional peat disruption, additional construction activities etc. would be more onerous, it would appear unlikely the environmental impact of construction and repair (where technically possible) would be more favourable than a foundation designed for the intended life. In any case from our experience repair options would often not be available, and hence this would not be expected to be a common option. From our experience research would be better focused on new build for an extended life.

5.6 Conclusions

This report identifies the key parts of a WTG foundation which typically have potential for re-use. Due to the very onerous fatigue loading which WTG foundations are subjected to, the typical residual fatigue design life of the tower-slab connection and significant areas of the main slab is severely limited after operation of the original turbine.

Options for re-use are identified together with the works required for each option including key quantities. These options are not bound by potential constraints related to current planning requirements, commercial viability or Wind Turbine availability. Comparative new build options are also provided to allow holistic comparison to be undertaken.

WTG foundation load and stiffness requirements increase significantly with increased generation capacity and this factor has a significant bearing on the required works for re-use with larger WTGs.

The following sub-appendices for this section can be found in Appendix 4 at the end of the document:

Appendix A: Typical New Build Foundations.

Appendix B: Foundation Reuse Options.

Appendix C: Reinstatement works.

6. Industry perspective of new design approaches: cost-benefit analysis.

SSE and Scottish Power assessed the options detailed in the drawings within Arup's report. They concluded that the reengineering cost per foundation is between 2 and 3 times more than a new foundation for the target turbine type. This translates into hundreds of thousands of pounds per foundation and would therefore represent a multi-million pound increase in cost for a typical >50MW wind farm.

Typically, the increase in cost is driven by the addition of mass concrete to form a suitable formation and the fact the reengineered foundation is significantly larger than a new foundation. The use of anchors for the Option 2 scenarios does reduce the volume of the foundation, however this is not a significant enough reduction to justify the additional cost of the anchors.

As the level of excavation required for both a new and reengineered foundation is broadly similar (Tables 2,4) the excavation costs were not included in the comparison. Neither were future costs; these depends on the outcome of the environmental assessment for decommissioning/repowering of the wind farm. If the end-of-life recommendation is to remove the whole of the foundation, or a proportion to a given depth below ground, then there will be additional costs associated with the reengineered foundation as it is at surface and has a larger volume. Section 7 considers the volumes of material that must be reinstated at end-of-life as part of the restoration process, and this is mostly greater for the reengineered foundation than repowering using a new turbine base. Thus, this likely also represents an increased cost.

7. Environmental considerations

7.1 Introduction

A key consideration for renewable energy development is that the payback time for C expended in the development process is significantly smaller than the carbon saving associated with the power generated from the wind farm. This section focusses mostly on C balance of wind farm repowering, both C expenditure associated with construction, and the ecological, hydrological, and biogeochemical Earth surface processes that influence soil C gain or loss. Other environmental considerations less-directly related to C expended in repowering or restoration may be considered here, but with a lesser focus. Some aspects considered here are discussed in more detail in section 8 which explores how the mechanistic control on C storage or losses are accommodated in the Scottish Government Windfarm 'Carbon Assessment Tool', which could be developed for repowering considerations

With a focus on the energy policy and thus C balance, the following environmental considerations associated with wind farm construction or repowering are not considered here: visual effects; noise; traffic access, socio-economic and recreational land-use change; communication interference; cultural heritage, organism level ecology (e.g. birds).

How this section has been researched is described in Appendix 2.

7.1.1. Approach to this section

The effects that may arise if wind turbine generator foundations are removed, or conversely are reused, are considered for the following scenarios: the response to repowering where the same foundations can be used and the response to repowering where the foundations cannot be reused. Some foundations may be re-engineered to receive a new WTG, but some foundations may be unable to receive a new WTG due to the layout being constrained by different distance requirements between larger turbines. Thus, the fate of foundations that cannot be reused is of interest.

Repowering using new turbine locations within the same wind farm is not discussed in detail, but this consideration may be referred to when making a comparison of the environmental trade-offs that may take place when using a new site rather than the existing foundation. Such repowering would constitute new construction activity and is covered by other approaches elsewhere – for example the 'Good Practise during Wind Farm Construction' (Scottish Renewables et al., 2010), the Scottish Government C Assessment Tool (Scottish Government¹⁶) and in a recent analysis of how the assessment tool may be developed (Chapter 3 Waldron et al, 2015). The EIA approach for new developments is well-established, as is the use of the Scottish Government C Assessment Tool, so the impacts can be considered within these frameworks.

An agreed position has not yet been reached by the regulatory bodies, Scottish Government and planners on whether the environmental benefits and impact of repowering should be considered relative to the non-repowered, decommissioned and restored windfarm, or relative to the existing windfarm. Thus, this is not considered further here other than to note that whichever practice occurs, when accounting for C emissions, the losses associated with not restoring the site are attributable to the new, repowered, development. Therefore, the calculations of C payback should start from the position of the (hypothetical) restored site, even if the restoration does not actually occur. Otherwise the payback time submitted for the planning approval consideration was incorrect.

This section will use the Arup-designed foundation as the model for the re-engineered foundation. The key considerations emerging from the reengineering that inform this consideration are:

- the reengineered foundations will be wider than the foundation needed for a new foundation for the same power of turbine (Arup Appendices 2 vs. 1)
- slab thickness will have to be increased (section 5.4.2.1)
- a different above-ground configuration may result (section 5.4.2.3)
- the reengineered foundation in these designs will not support use for more than one additional lifetime.

7.2 The environmental context of wind farm deployment in Scotland

Different soils have different water tables and soil chemistry. In turn this influences plant functional group (e.g., Potvin et al, 2014), and, as the food web is influenced by the vegetation, higher ecological functioning. Further the payback time for a wind farm constructed in peatland is usually greater due to loss of this C-rich soil, and this vulnerability may be expected to be extended to aspects of repowering. For these reasons, it is important to consider first the soil environment in which turbines are positioned, particularly peatland as this is an important Scottish landscape. Scotland now has a National Peatland Plan¹⁷ that provides a framework for recognising, communicating and, where appropriate, quantifying the benefits of healthy peatlands and improving the condition of those which are damaged or degraded.

In September 2014, turbine locations and underlying soil type and depth were mapped and analysed using a GIS (Yeluripati et al, in Waldron et al, 2014). This exercise identified 4394 turbines operational or consented (Yeluripati et al, 2014). This is less than recent figures from the Scottish Government of 5472 operational or consented at October 2017¹. The Yeluripati analysis will therefore not fully reflect current distribution but will provide an indicative understanding.

48 $\geq$ 50 MW wind farms were mapped as consented in Scotland, offering a generation capacity of 5445.3 MW from 2019 turbines (Yeluripati et al, 2014). There were 524 <50 MW wind farms offering a generation capacity of 3896 MW from 224 single turbine developments, 87 two-turbine, 63 three-turbine, and 87 above-10 turbine installations, totaling 2415 turbines. A large proportion of the operational installation is comprised of small wind farms with fewer than five turbines, which are often community or private landowner proposals (Yeluripati et al, 2014).

The soil depth data analysis was quite coarse as the authors did not have access to the soil depth data that the developers use to guide turbine micro-siting, and so it relied on average peat depth within the GIS polygon, generated from data sourced predominantly from soil surveys (Yeluripati et al, 2014). The GIS analysis accords reasonably well with a similar internal analysis carried out by SNH. However, given the scale at which soil depth data was available, the conclusions about peat depth, should be considered indicative than absolute.

For $\geq$ 50 MW generating capacity wind farms in Sept. 2014, it was estimated that approximately 26 % of wind turbines are on mineral soils, 44 % of wind turbines are estimated to be on peats up to 1 m depth, and 30% are estimated to be on peat deeper than 1 m. For sub-50 MW wind farms, approximately 54% wind farm turbines are on mineral soils, 31% are on shallow-to-medium depth peats and 14% of sub 50 MW wind farm turbines are on deep peat areas (Table 3 in Yeluripati et al, 2014, provides more detail of these groupings).

Although the peat depth interpretation is indicative, this analysis shows that by September 2014, an estimated 58% of turbines (n = 2581) are on areas of peat land. Unless a decision is made to prioritise repowering on mineral soils, this C-rich soil will be likely be disturbed by the process of repowering, either through foundation reengineering, or through the need to use new sites to install the new foundations.

Climatic, hydrological, soil and biological processes, and their interactions are the key environmental drivers of our present-day landscape. Where possible the response of each of these areas to repowering will be considered separately here, but this may not always be possible. We also consider resource use under different repowering scenarios.

7.3 Carbon security impacts associated with foundation reengineering versus new foundations

The C-expenditure payback time in wind farm construction is affected by multiple processes, but two key processes are the volume of concrete used in construction, and the volume of soil disturbance as this may represent loss of soil C. The latter will be considered in section 7.4. This section considers the volume of natural resources required to reengineer a foundation to accommodate a larger WTG, and the alternative of repowering through abandoning the old foundation and creating a new foundation. Producing and transporting this natural resource has a C footprint (in addition to a financial cost). The following two scenarios, considered most probable in a repowering landscape, are used to illustrate the difference in quantities needed in foundation construction.

1. 0.85 MW foundation that has been reengineered to a 3.2 MW turbine vs. the quantities if there are two separate foundation to provide energy over the same period
2. 2.3 MW foundation that has been reengineered to a 5 MW turbine vs. the quantities if there are two separate foundation to provide energy over the same period.

The quantities for the abandoned foundation must be added to the estimates for new foundation to represent the same period of power generation. More detail about how these calculations were undertaken and the results for all repowering scenarios considered can be found in Appendix 3.

Foundations considered & drawing ref. (ARUP Appendix 4C)	Concrete	Reinforced Steel (tonnes)	Aggregate	Structural fill
Scenario 1				
0.85 MW (850-1-R) & 3.2 MW (3200-1-R) <i>or</i> 0.85MW reengineered to 3.2 MW (0850-3200-01-R)	786 m ³ 1805 m ³	111 169	393 m ³ 1122 m ³	584 m ³ 727 m ³
required for reengineering foundation	+130 %	+52 %	+185 %	+24 %
Scenario 2				
2.3 MW (2300-1-R) & 5 MW (5000-1-R) <i>or</i> 2.3MW reengineered to 5.0MW (2300-5000-01-R)	1821 m ³ 3405 m ³	256 315	911 m ³ 1877 m ³	1168 m ³ 1353 m ³
required for reengineering foundation	+87 %	+23 %	+106 %	+16 %

Table 6: A comparison of the volume of materials required in reengineering a foundation, to using two separate foundations (from Arup section 5 tables 2 and 4).

For the above scenarios (Table 6), and for all materials required for foundation construction, the reengineered foundation requires more than the construction of two separate foundations. With concrete for example this is due to the need for reinforced and mass concrete in the reengineered foundation (Table 4, Arup section 5.4.2.4); the single use foundation requires only reinforced concrete (Table 2, Arup section 5.3). For any comparative scenario the reengineered foundation requires a larger volume of concrete than two separate turbines foundations (Table 4 and Appendix 3, Table A3-4). This can be more than twice as much (reengineering a 2.3 MW foundation to a 3.2

MW foundation requires + 231%; Table A3-4). The least difference in concrete required is when reengineering a foundation for a WTG of similar MW (+61 to 80 %). The other postulated common repowering approaches uses at least 64% more concrete.

Steel is another material that has a high embedded-C cost. The reengineered foundations require more steel for all scenarios considered (Table 4, Table A3-4) than if repowering with two foundations. Most steel proportionally is required in the likely repowering scenario of 0.85 to 3.2 MW (+ 52%).

Only the structural fill requirements are less with a reengineered foundation when repowering with a similar capacity WTG (-33 to -39 %, Table A3-4), and this is considered not likely to happen as will not increase power generation.

This comparison (and Table A3-4) demonstrate that the additional quantities of material required for construction volumes can vary when repowering using an engineered foundation, influenced by the change in size of foundation. Calculating this impact on C expended in the construction process could be undertaken using the Scottish Government Windfarm 'Carbon Assessment Tool' (Section 8). The technical guidance to this tool explains in detail the process-based understanding behind this tool¹⁶ and so different processes that influence C expended in development will not be explained here. However, there are practises that could confer benefits (or represent challenges) to C-expended that can be considered in this section. For example:

- If foundations cannot be reengineered and void infill is required, the timing between old foundation restoration and new foundation construction is crucial to minimise the C footprint of the repowering. A land surface with vegetation fixing C is a restoration requirement to meet the assumptions the payback period generated for submission of the original wind farm planning approval. Soil infill material could be maintained to retain its vegetative cover and allow a plant community to form on the infill as soon as possible, although this will likely prove challenging.
- This becomes more difficult if the material is to be stored, and/or transported, with increased likelihood of losing soil structure and storage time and distance increase. Similarly sourcing sufficient quantities of void peat infill and retaining a soil structure upon emplacement may become more challenging with increasing depth of infill. The long-term storage of material on site has waste management implications and if aggregate, soil infill, or cover, are to be removed from site and disposed of, or repurposed as cannot be stored, a shortage of local material could be expected. If material is to be sourced from elsewhere the C footprint of the development could increase. Translocated peat blocks are unlikely to be bigger than 1 m³. Stacking blocks may create surfaces along which there could be preferential flow. Thus, there needs to be consideration prior to repowering of the C footprint of soil acquisition associated with restoration where the foundations cannot be reengineered.
- Recycling of material could reduce the C footprint of the new and reengineered foundations, compared to that of foundations installed when the wind farm was first commissioned. For example, blast furnace slag is a waste by-product that could have good acid resistance (e.g., Dyer, 2017). The aggregate required for the concrete (and access tracks and new hard-standing) could partially be sourced from recycled material from the decommissioning of the existing turbine hard-standing and surplus tracks. It is unlikely the recycled concrete could be used in the foundations. However, it is now routine for developments to include recycled material where possible, so this strategy may offer limited benefits. Ensuring understanding of new resource availability in a circular economy may offer would help the repowering agenda to produce the most sustainable foundation design.

7.4. System functioning: soil.

The over-arching considerations here are that: i) repowering will cause additional soil and so C loss; ii) the restored area may not develop a stable vegetation cover which could result in soil C loss and erosion; iii) there may be an interaction between the soil and the remnant foundation that changes the biogeochemical soil functioning.

The effectiveness of restoration to promote a viable soil-based ecosystem and biogeochemical functioning is considered in the discussion of vegetation and hydrology. This section focuses on soil C loss. This can occur during excavation for a new or re-engineered foundation, or later from the soil that is introduced to restore the void created as part of the end-of-life turbine restoration - unless the turbine infrastructure is removed only to ground level, there would have to be infill.

The extent of soil C loss will likely be related to the volume of material that will be excavated and to perimeter length of disturbance as the perimeter impacts on the soil that is not excavated. The perimeter length relates to the volume of soil drained by the void through the depth of the hole, and the extent of drainage of the peat at the specific site. Thus, a key consideration for sustainable repowering is whether using a reengineered foundation would lead to less soil disturbance than repowering through abandoning the existing foundation and constructing a new foundation. For completeness this consideration must be taken to end-of-life analysis for the different approaches to repowering, particularly as a second lifetime cannot be supported by the reengineered foundation designs outlined here. The scenario analysis for soil C loss considers three different approaches to understanding soil C loss:

- A. end-of-life requirements where restoration of foundations occurs. This is the simplest parameter to use as it is a measure of soil volume that has been removed for the lifetime of the foundation;
- B. in addition to the volume of soil required for the end-of life restoration, some of the soil excavated will be reinstated. This reinstated soil may lose, for a period of time or permanently, the C-sequestration properties present prior to excavation;
- C. in addition to the volume of soil required for the end-of life restoration, and the volume of soil reinstated after excavation, there is a mass of soil which is excavated and removed during construction and thus it no longer offers the C-sequestration properties previously. This volume may be part of the volume that has to be reinstated at end of life, but for effective restoration new soil may have to be found and thus this total volume of disturbance should be considered.

7.4.1. Changes in excavation and reinstatement volumes for repowering with or without a reengineered foundation:

This analysis of the difference in excavation and reinstatement volumes also focuses on the two most probable repowering scenarios considered earlier: repowering from 0.85 to 3.2 MW, and from 2.3 to 5.0 MW (Table 7). The analysis considers a restoration depth of 1 m. As the foundation structure slopes (Fig. 2), an increased depth would increase volume estimates, but not proportionally i.e. 2 m depth will not result in twice the volumes. A different depth than 1 m has not been considered in these illustrations and thus this exercise should be repeated if a different restoration depth is preferred (development to the windfarm payback calculator could accommodate this).

Soil consideration approach A: With scenario 1 (0.85 to 3.2 MW), reinstatement at end-of-life for restoration would require 82% more soil for the reengineered WTG foundation than if two separate foundations were being restored (Table 7). With Scenario 2 (2.3 to 5.0 MW) the reengineered foundation also requires more soil for restoration but much less, only 8% (Table 7). Only reengineering the foundation of a 2.3 MW WTG to accommodate a new 2.3 MW WTG, uses the same (option 1) or less (-8%, option 2) soil reinstatement for restoration at end of life than two separate foundations (Table A3-1). For all other scenarios a greater volume of reinstated soil is

needed at end-of-life of the reengineered foundation than two separate ones (ranging from 34 to 42% more).

Soil consideration approach B: When all soil that will be reinstated is considered the volume calculated for the two scenarios become more similar. For scenario 1 the reengineered foundation requires a smaller volume of soil reinstatement (-7 %) and for scenario 2 the reengineered foundation requires a larger volume of soil reinstatement (+ 5 %). The volume of material reinstated is also less with a reengineered foundation when repowering with a similar capacity WTG (-9 to -5 %, Table A3-2), and more with all other scenarios (8 to 13 %) - but these scenarios are considered not likely to happen as they will not increase power generation significantly.

Soil consideration approach C: When all soil that will be removed or reinstated is considered, the volume calculated for the two approaches is similar. For scenario 1 reengineering the foundation increases soil volume (+13 %) but for scenario 2 the reengineered foundation decreases soil volume (-6 %). Again, the total volume of material is less with a reengineered foundation when repowering with a similar capacity WTG (-4 to -3 %, Table A3-3), and more with all other scenarios (9 to 14 %).

Unlike the results from the consideration of construction materials, where the reengineered foundation consistently required more materials, only the 0.85 to 3.2 MW repowering requires reinstatement of considerably greater volumes of soil for end-of-life restoration. All considerations that include soil excavation and reinstatement volumes (representing all soil disturbed and that which must be sourced for restoration), result in similar volumes (-9 to +14 %) and there is not a consistent pattern between scenario 1 and 2 in the three approaches to assessing how soil C is affected. How these % differences translate to payback times could be estimated through developments to the windfarm payback calculator.

Given this similarity in volumes of soil disturbed, an important consideration to support decisions of whether to reengineer a foundation for repowering or build a new foundation and restore the old foundation, may be how much total surface area is disturbed, and the potential extent of drainage of the surrounding peatland. These influence the capacity for the land surface to sequester C and for the loss of C from peatland soil respectively. The approach to this consideration is described in Appendix 3.

For both scenarios, using a reengineered foundation results in less surface area disturbance during foundation construction and a smaller total edge disturbance (as represented by the excavation perimeters) (Table 7). However, less of the land surface is reinstated at commissioning with the reengineered foundation than with two foundations, both as an absolute area and as a proportion of the area disturbed. Thus, the reengineered foundation requires a larger surface area to be restored at end-of-life than two foundations. If the soil reinstated develops a vegetation community that fixes C and stops soil C loss, this could happen more effectively with two turbines and so over the lifetime of the repowered site (including the first operational life) there may be more C sequestered by vegetation. However, the reengineered foundation disturbs an area already reinstated and so the new disturbance may be of a land surface less efficiently or not sequestering C. Using two foundations always disturbs a 'new' surface. The relative balance of these processes to C losses could be modelled by adjustments to the 'Carbon Assessment Tool'.

	Soil considerations scenarios A, B and C, where end-of-life reinstatement assumes 1 m depth			
Foundations considered & drawing ref. (Appendix 4: ARUP appendix C)	A. Reinstatement end-of-life only	B. Reinstatement during construction & at end-of life	C. Reinstatement during construction, at end-of life, & excavated and removed during construction	
<u>Scenario 1</u>				
0.85 MW (850-1-R) & 3.2 MW (3200-1-R)	496 m ³	1772 m ³	2553 m ³	
or				
0.85MW reengineered to 3.2 MW (0850-3200-01-R)	903 m ³	1650 m ³	2268 m ³	
required for reengineering foundation	+82 %	-7 %	+13 %	
<u>Scenario 2</u>				
2.3 MW (2300-1-R) & 5 MW (5000-1-R)	1045 m ³	3014 m ³	3812 m ³	
or				
2.3MW reengineered to 5.0MW (2300-5000-01-R)	1129 m ³	3152 m ³	4059 m ³	
required for reengineering foundation	+8 %	5 %	-6 %	
	Surface area considerations: potential area disturbed and perimeter drainage and			
<u>Scenario 1& 2 as above</u>	Total surface area disturbance	Excavation perimeter	Reinstated at commissioning (% of surface area disturbed)	Restored at end of life
0.85 MW & 3.2 MW	1899.26 m ²	213.94 m	1327.99 m ² (69.9 %)	571.27 m ²
or				
0.85MW reengineered to 3.2 MW	1372.61 m ²	131.33 m	388.38 m ² (28.3%)	984.23 m ²
required for reengineering foundation	-27.7 %	-38.6 %	-70.8 %	+72.3 %
2.3 MW (2300-1-R) & 5 MW (5000-1-R)	3220.01 m ²	281.64 m	2054.24 m ² (63.7%)	1165.77 m ²
or				
2.3MW reengineered to 5.0MW	2050.84 m ²	160.54 m	831.62 m ² (40.6%)	1219.22 m ²
required for reengineering foundation	-36.6 %	-43.0 %	-59.5 %	+4.6 %

Table 7: A comparison of i) the volume of material required for reinstatement of new turbine foundations, or of reengineered foundations, at WTG end-of-life (from section 5, Arup tables 3 and 5), and ii) potential length of perimeter disturbance and surface area disturbed and restored. The difference between the two latter represents the surface area reinstated at commissioning,

7.4.2. Disturbance adjacent to the foundation:

For both scenarios using a reengineered foundation results in less surface area disturbance during foundation construction and a smaller total edge disturbance (as represented by the excavation perimeters) (Table 7). However, it seems unlikely that any foundations could be reused without some further disturbance around the existing foundation (and associated infrastructure). This could be compaction, which will affect hydrological and biogeochemical functioning. There may be less overall compaction if a foundation is reused, than from the combined activity undertaken in construction of a new foundation and restoration of the existing foundation area given the smaller perimeter, but both scenarios will potentially compact new ground. It is usual that the works would be done from the excavation of the original foundation, therefore the surrounding area would remain unaffected albeit that the excavation will be wider. Further, if the foundation cannot be reused, removal of the foundation infrastructure (in full or part) should be accompanied by removal of the hard-standing – unless serving a new foundation. If the area of hard-standing is insufficient to erect the new WTG, then expansion of this area could also disturb soil that currently does not comprise part of the wind farm infrastructure.

Further, although the disturbed area for new foundation reconstruction and associated connections (tracks and cabling) may be localised, with existing foundations in place and new ones being built (occurring if reengineered foundations are not used), the density of foundations increases within the wind farm, and whether habitat fragmentation (e.g. Fischer and Lindenmayer 2007) and hydrological disconnectivity and more drainage result may have to be considered.

7.4.3. Considerations associated with the nature of the infill after foundation extraction:

This infill material for restoration could come from the excavation of material should new foundations be constructed, and an advantage here is that a similar soil type, seed bank, microbial community is likely to be introduced, although this would have to be assessed before transfer if a comparable soil and vegetation community was important.

Soil loss associated with reengineering or removing the foundations, and the translocation of soil from elsewhere for infill, can be estimated, and this impact on the ecosystem service of C storage considered in a repowering C payback estimation. It cannot be assumed that removed soil can be reinstated without C loss and there is not published research that shows otherwise, thus the most conservative position should continue to be assumed in this calculation: that is the loss of all C stored in the soil, either by oxidation (respiration by bacteria) or removal from the site by catchment drainage through run-off processes, or if dry, by wind.

It is also necessary to consider whether the introduced material will have, or will develop sufficiently quickly, a structure that supports soil microbial and vegetation community functioning, allows comparable C storage to pre-development and offers geotechnical stability. This is considered further under the hydrology and vegetation sections.

7.5. System functioning: hydrology

The primary considerations associated with hydrological impacts are: i) will foundation reengineering or removal cause damage to hydrological functioning of the site?; ii) will any key ecosystems be affected downstream of the repowering due to changes in hydrological functioning? The latter is covered in section 7.6 on vegetation

Whether repowering or restoration processes causes contamination of water bodies that are important ecologically or used for private and public water supplies is not considered here as a) it does not have a C expenditure focus and b) this is a standard consideration during the EIA process and addressed in every construction environmental management plan prepared for civil engineering works, thus would extend to reengineering of foundations. Further, reengineered foundations will

use materials of similar composition to that used in a new foundation installation i.e. similar to wind farms currently under construction, and so reengineering of a foundation is not likely to present a new chemical contaminant. Removal of foundation during restoration would be a mechanical process, so chemical contamination is not a concern and effective traps as part of the EIA should avoid downstream silting.

7.5.1. Hydrological functioning of the wind farm landscape

To consider how hydrological functions will be affected by reengineering or removal of foundations for repowering, it is necessary to first consider the hydrological functioning of a landscape to hosting a wind farm, which also controls soil functioning and surface vegetation. Foundations are unlikely to be sited in upwelling areas as this could result in foundation instability and so this consideration focuses on a hydrological setting where the water table follows the surface topography and shows a climatically-controlled seasonal variation. The hydrological impacts on ground-water dependent vegetation which may be influenced by wind farms are addressed in the vegetation section.

The habitat requirement of the water table is crucial hydrological consideration. In peatland sites it must be present close to the surface, or typically vary from the surface to a depth of approximately 40 cm (e.g. Lindsay and Clough, 2015) in response to reduced rainfall and increased evapotranspiration during warmer weather. This is needed to ensure that the peatland maintains the crucial ecosystem service role of C fixation. In minerogenic soils water table depth is less critical as long as the soil moisture gradient present supports plant growth and thus C fixation. Thus, the considerations in this section of the water table are a) as an effectively functioning water table is needed for C fixation, and b) there can be hydrologically-induced soil loss, which is in effect C loss.

An ongoing consideration in wind farm developments is whether disturbance of the system enhances drainage of the site and so the water table is affected. Such effects have been postulated (e.g. Parry et al, 2014) associated with roads that cross peatland, where the down slope site is drained more heavily due to lack of hydrological connectivity with the upslope site due to the truncation by this linear feature (e.g. Grace et al, 2013). Most foundations are adjacent to the access track, although a proportion will be at the end of the access track, so there may be this potential impact, but it is primarily associated with the access track rather than the foundation per se (noting that wind farms are engineered to avoid infrastructure causing hydrological barriers e.g. floating roads).

Placing a turbine within a landscape does not always cause a reduction in water table; this is dependent on the position of the turbine in the landscape. If the turbine is in a sloping site and has interrupted surface flow pathways, then it is more likely that the area downslope of the turbine may have a change in water delivery and so may be drier and the water table will be lower than if there had not been the disturbance. However, emplacement of a foundation into the land largely represents emplacement of an impermeable body through which water will not pass (to be otherwise would imply a fractured foundation and this would be structurally unstable) and so water will flow around it. High water tables around the foundation can be observed in the field (Fig. 11).

An indication that the habitat water table has reached or is approaching equilibrium with the foundation would be the establishment of vegetation around the foundation, possibly even in the hard-standing. If the water table was too high or too low there would be flooding or soil moisture deficit and such conditions would not be stable enough for vegetation. However, if the electricity transmission cabling from the foundation is embedded in a more porous medium, such as sand, the hydraulic conductivity will be significantly higher than in the peat and so this could act as a preferential pathway to flow from the turbine. If there is evidence that this is the case it should be part of restoration considerations, for which the considerations are similar and so this is not detailed.

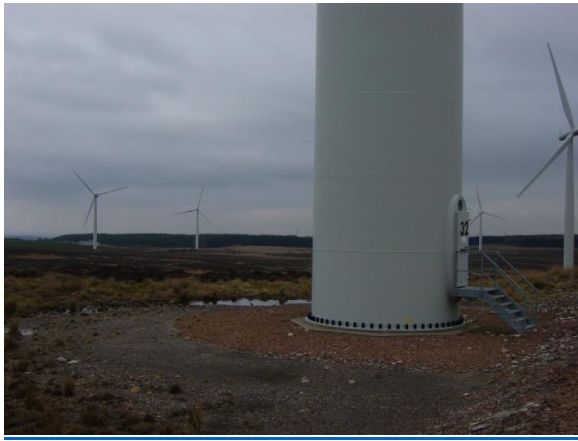


Fig. 11. Photograph showing the water table is present at the edge of the foundation and hard-standing (March 2011). The peatland may be slightly higher and so drainage is towards the foundation and as such the water is pooling at the contact with the less permeable infrastructure. This turbine has been in place since ~ 2004. Note some vegetation recolonisation on the hard-standing, but not significantly so. Photo ©Susan Waldron

With this understanding of landscape hydrological behaviour, it is likely that the following hydrological responses may occur during construction or restoration processes associated with repowering. Important here is that restoration and infill after decommissioning occurs over an area larger than just the concrete component of the foundation. Backfill (Fig. 2) will also be removed and thus infill will be on existing soils if present at the restoration depth.

- If there has been perimeter disturbance of the soils, then there may be a change in hydraulic conductivity between these and the infill. If the perimeter soils have been compacted, they may have a lower hydraulic conductivity. However, if they have lost water to the foundation excavation during the reengineering or restoration (e.g., due to gravity inflow into the topographically lower area; edge-drying naturally due to the climate) the soils may have higher conductivity through structurally-induced preferential flow pathways. This process may occur during foundation reengineering or restoration, or in the construction of a new foundation, so this response will not be specific to whether a foundation is reengineered or restored. It can also be mitigated for by carrying out the restoration works from within the perimeter of the foundation and adjacent track.
- If the foundation was removed and the site restored by infill, there should be no disparity in surface height of the foundation infill and the surroundings, and so gravity inflow would cease. However, even if filled with the same material, it is unlikely that the infill material will have the same structure as the surroundings when first emplaced. Although the surroundings have been disturbed previously, they will have had ~18 years to recover and so will have developed a hydrological functioning more similar to the pre-construction conditions. Further, the infill may not have retained its source structure, and this would affect hydrological functioning. The hydraulic conductivity of the infill could be greater if there was preferential flow between layers of infill, or between peat blocks. Conversely, if compression of the infill has taken place hydrological conductivity may be reduced. Thus, there would be a disparity in hydrological behaviour until equilibrium between the infill and surrounding soils has been created. Any hydrological difference could affect water table position. If the reengineered foundation cannot be reused at end-of-life, then this consideration is also relevant for its restoration.
- If the restoration infill remains underlain by some foundation or bedrock, and neither have been fractured by the removal process (considered unlikely), the foundation or bedrock is still much more impermeable and so water will not drain rapidly vertically. Thus, the presence of an underlying foundation will not undermine the development of a water table in the over-lying infill.
- However, if the infill undergoes settling and so is topographically lower, or is more permeable than its surroundings, water could inflow, even if slowly. With minimal flow vertically over the concrete component of the foundation, or laterally if the surrounding soils have lower hydraulic

conductivity (as may be found with compressed peats), it could be that the infill volume becomes over-saturated and the soil (peat) becomes unconsolidated. Further inflow of water, through direct receipt or from surface run-off during heavy and prolonged rainfall could cause movement of this unconsolidated infill, possibly out of or within the restored area.

- Loss of the void infill would be undesirable as it represents loss of C, undermines the surface vegetation recolonisation, could result in the delivery of sediment to water courses (depending on the volume of material moved, the closeness to the water course and the retention properties - roughness - of the surface over which the material flows), and could lead to instability that could result in drainage of, or collapse of up-slope material.
- Mobilisation of void infill would be a separate process from any slippage of peat upslope of the excavation. Both processes although highly unlikely to occur, can be mitigated through the consideration given slope stability in wind farm developments (e.g. Peat Landslide Hazard and Risk Assessments: Best Practice Guide for Proposed Electricity Generation Developments¹⁸). Thus, a peat risk assessment for each location identifying mitigations could be put in place to decide if routine application of control measures is needed, regardless of whether the foundation was reengineered for a larger WTG or whether a new foundation was needed. That such consideration includes restored foundations needs confirmed.
- To ensure the restored foundation site is hydrologically similar to its surroundings, thus helping avoid instabilities, a sufficient depth of infill is required to promote hydrological connectivity to support soil development and vegetation recovery. However, this should be as shallow as possible to stop the infill acting as a sump whilst the soil infill structure develops. Water table depths around the foundation will be site-specific and so the developer may need to survey this when restoring foundations to identify the appropriate depth needed for hydrological connectivity in the restored foundation.
- Any changes to the surface dimension of a foundation reengineered for repowering, and the associated hard-standing, could affect the volume of run-off generated from this surface. This will be design dependent, with some options showing more concrete at the surface (Arup appendices). It is necessary to ensure that run-off changes do not directly impact perimeter soil stability and could be a consideration in the Civil Engineering design of the foundation and hardstand.
- During foundation reengineering or restoration there will be disruption to the hydrological functioning of the landscape directly in the locale of the foundations, and this will result in water table dynamics in the surrounding soils that are less favourable for soil functioning than if the foundation was not disturbed. Further, water table position and flow pathways are controlled by climate, as well as topography and soil hydraulic properties. Not all turbines will be restored or reengineered contemporaneously, thus the hydrological impact may differ between turbine locations. Climate-induced differences could be minimised by completing restoration or reengineering in as short a time as possible, facilitated for example by having all materials for reengineered or restoration ready before the existing foundation is excavated. Developer practise is to minimise the time an excavation is open, but this is still likely to be many weeks. This effect will occur with both reengineered and restored foundations and the only difference that may occur that is approach related is whether at end-of-life restoration the larger area to be restored makes doing this quickly more challenging.
- There will be disturbance to hydrological functioning with foundation reengineering or restoration. Recovery may be expected on the same timescale as has occurred during the original turbine emplacement, but there is little understanding of what this is as it has not been a research focus.

The only restoration scenario that would minimise disruption to the hydrological functioning of the site as is, would be to remove the foundations to the ground surface only. There are several reasons why this is not desirable (e.g. the C payback calculation considered by planners assumed that restoration would occur and with that C fixation; discussed later) and so this has not been explored further.

These considerations demonstrate there is some uncertainty in the environmental response, which could be alleviated by study of some of the peatland sites that are undergoing or will shortly undergo restoration (Table 1).

7.6. System functioning: vegetation

A vegetated land surface offers multiple ecosystem services: offering habitat and food for higher trophic levels, stopping soil erosion, reducing the speed of overland flow, influencing soil water balance and for this consideration, playing an important role in C sequestration in soils. Thus, it is important in a landscape to encourage the colonisation of vegetation, and this is most sustainable if appropriate to the hydroecological and climatic conditions.

Section 7.4. end-of-life restoration scenario analysis showed that, for a reengineered foundation, the total surface area disturbed will be smaller than repowering where new foundations are used (Table A3-5). A remaining unknown for vegetation recovery is whether it is better to disturb two smaller areas that together constitute a larger surface area than would occur with the reengineered foundation, but the latter has less soil reinstatement. The importance of vegetative cover to soil C security has been considered in section 7.4. Similarly, to the construction of a new wind farm, the impact of less soil reinstatement on vegetation would be assessed by the EIA undertaken for repowering (as feeding into the restoration plan) and would consider habitat fragmentation. Thus, here the impact of changes to the extent of vegetated surface area for different repowering scenarios is not discussed further.

In this section the key considerations are i) if the foundation is not being reengineered and is being restored, what needs to be considered to allow successful vegetation restoration and ii) for a reengineered foundation, could there be an impact on vegetation remote to the turbine e.g., Ground Water Dependant Terrestrial Ecosystems (GWDTE). The former consideration focuses on peatlands as mineral soils can be revegetated with success (as evidenced by sites that have been repowered, Table 1).

7.6.1. Successful vegetation restoration, if a foundation is being restored

Key to successful revegetation in peatland restoration is the position of the water table. Effective restoration that has occurred on peatland sites previously has usually involved drain-blocking (e.g. Armstrong et al, 2009) to raise water tables and encourage higher water tables to allow only peat-forming plants to form. This is considered likely to be effective when the slope is shallow, as it would be with a wind turbine as such siting is needed to avoid issues of peat instability. However, the drainage channel that is blocked will be generally less than 1 m wide (e.g. Armstrong et al 2009), whilst the void that would be infilled after foundation removal could have a drainage edge of up to 160.54 m (the 2.3 MW to 5.0 MW reengineered foundation, Table A3-5), and there may be hydrological disconnection with the surrounding soils as discussed earlier. Ensuring a functioning water table is more challenging in foundation restoration than in drain-blocking.

Published literature was reviewed to assess if there is an effective peat depth for the successful restoration of ombrotrophic bog vegetation (Lindsay and Clough, 2016). This relied on understanding generated from cutover peat bogs generally, as there are only a handful of studies where peat has been emplaced into an excavated area (e.g. Nwaishi et al 2015). Here as part of fen restoration in Canadian oil sands, a void was backfilled with peat extracted from a donor fen and re-compacted to create a flat surface level with the foundation of the slope. In the latter a depth of 2 m infill was used,

but this was chosen partially to be thick enough to attenuate the upwelling of solutes from the contaminated land below.

From the summarised research findings (Lindsay and Clough, 2016), it was postulated that water table should not go below -40 cm or bog vegetation recovery will be impacted. Further, for ombrotrophic bog vegetation to grow it seems that a minimum peat depth of 0.5 m is needed when the peat is strongly-humified (at least H7 on the von Post scale). If the peat is less-humified, then a residual peat depth of 1 m is recommended. For both scenarios, to stop cracking and drying and so loss of peat depth, the surface has a 20-30 cm of 'top-spit' (living plant) material.

This '1m depth' is consistent with the depth to which foundations have been removed previously when restored in repowered sites. It is also the depth to which existing restoration plans for end-of-life decommissioning propose to remove the foundation and infill. However, if depth to bedrock was shallower than 1 m, an additional volume would not be excavated to reach 1 m as this would be restoration atypical of the natural environment. The depth of excavation would likely be the depth to bedrock.

If the infill area is hydrologically connected with the surrounding peatland, a 1 m infill depth of peat may feasibly support vegetation recolonisation. Ecohydrological regulatory function is needed to replenish water lost during evapotranspiration and to allow water movement out of the infill to stop over-saturation and an open pool. There may be situations where open pools are desired, but the pool emerging from a void infill may be quite different in plant cover to the naturally-patterned hollow and pool surface found in many peatlands (e.g. Mazerolle et al, 2006). Further the C payback calculation, which may have informed the initial development consent, assumes that when the foundation is restored a vegetated surface is realised and thus net C loss is halted. The development of an open water pool is inconsistent with this restoration assumption.

Ecohydrological functioning can be disrupted by loss of peat structure in the translocation and void infilling (Nwaishi et al 2015), or where the peat has been thought to be translocated well, by climatic conditions after emplacement. For example, translocation of fresh large turves, 1 m deep, of blanket bog into carefully-prepared receptor cells, during restoration of Tow Law, an open cast coal mine in Durham, preserved most of the vegetation intact (Standen and Owen 1999). However, seven years later there had been a severe decline in the frequency of *Sphagnum* (20 % of its initial frequency) considered to be caused by drying of the underlying peat, with three unusually dry summers following the translocation. It was concluded if this loss continues the blanket bog would be more like a wet heath.

The SNH literature review (Lindsay and Clough, 2016) also found that it seems very challenging to create the conditions that support development of an ombrotrophic peat vegetation if the peat depth is less than 2 m. Instead poor-fen bog vegetation, which can persist for 200-300 years, colonised restored sites (UK, northern Germany, Estonia and Canadian studies were considered). Thus, a 1m infill may not support a high-quality peatland vegetation and if this is required then a deeper peat infill may be needed.

However, infilling a void, of 27 to 51.5 m diameter (Table A3-5), with 2 m of peat presents resource (where to source this volume of peat) and geotechnical (peat stability) challenges, both important considerations, particularly as wind farms tracks facilitates public access for recreation, and sometimes animals for grazing, to landscapes previously less accessible. Yet establishing what depth a peat infill must be to maximise the restoration undertaken seems of crucial importance. Thus, if foundations cannot be reused in repowering, it seems a requirement before restoration starts is to establish more conclusively the requisite depth of peat infill, and whether this will vary between sites,

or even foundations. As WTG are microsituated in developments to avoid deep peat, similarly this could be a factor in choosing which foundation to restore or reuse in a repowering scenario.

Unfortunately, there are no previous studies of turbine removal and void infill in peat for comparison. However, it may be possible to return to sites such as Tow Law, restored in 1991 (Standen and Owen, 1999), and assess how the translocated peat vegetation has developed. Alternatively, peat-filled borrow pits could be resurveyed to understand ecohydrological and vegetation dynamics. Detail of such 'research resources' are listed in a report commissioned for SEPA on using peat spoil for construction works (Lantschner et al, 2011, Table 5), thus they will not be repeated here, other than to note that within this list there are borrow pits with 1-3 metres of peat infill. These could be good models to revisit and inform a better understanding of what depth of peat infill meets restoration requirement for vegetation recovery.

Vegetation colonisation stabilises the soil surface. Some restoration projects have reseeded with a fast-growing grass, although not a local vegetation. For example, this approach has been used to minimise erosion in the gullied Pennine peatlands by the NGO Moors for the Future, although they are now reseeded with *Sphagnum* plugs grown off site especially for this purpose¹³. The research describing the Pennine restoration is beginning to be published (e.g. Evans et al, 2017), but the detail is not yet available. However, its outputs could be explored further to inform best practise.

7.6.2. Impacts on vegetation remote to the turbine:

Habitats classified as Ground Water Dependant Terrestrial Ecosystems (GWDTE) may be impacted directly or indirectly from foundation restoration due to changes in sub-surface hydrology as described earlier affecting groundwater flow pathways. The analysis in Table 7 shows that the disturbed area for reengineering will depend on the turbine upsizing reconfiguration and will be larger than the excavation for restoration. There are current guidelines for exclusion radii for wind farm developments near GWDTE: 100m exclusion radius for 1m excavation; 250 m for greater than 1 m excavation depth (SEPA 2014), and these could influence decisions on where to repower. Thus, for both reengineering and restoration, an analysis of the impact of the activity on the surrounding vegetation would be required.

Independent of the soil type, it is possible that the wind farm habitat may have changed during the lifetime of the windfarm, for example in response to changes in hydrology due to drainage, restoration work undertaken during this time, a microclimatic effect from the wind farm (Armstrong et al, 2015) or to external drivers such as a changing climate. Thus, in support of the repowering consent application, a vegetation survey incorporating comparison to a similar survey prior to the original wind farm development, should identify if there are areas that need special consideration for protection or further restoration.

In such cases, there are existing directions to support the repowering design. For example, where activities are either within, or may affect a Natura site, consideration of the Habitats Regulations requirements will be necessary. The Habitats Regulations Appraisal (HRA) should consider all aspects of the repowering that causes disturbance (e.g. dismantling of the turbine, excavation around the foundation, mechanical adjustments to the foundation, addition of new concrete and steel, erection of the new turbine), and decide whether this is likely to have a significant effect on any Natura site. This appraisal should build on the thinking and assessment undertaking for the original development, and as part of the monitoring for the Decommissioning and Restoration Plan. It should rely on the conservation objectives for the site, to ascertain that there will be 'no adverse effect on site integrity' as defined by the Regulations (SNH, 2016).

7.7. System functioning: biogeochemical impacts on system functioning.

This section considers the interaction of soil and water to produce a soil profile that functions similarly to the surrounding habitat, fulfilling the role of C storage and thus restoration could be considered a success. The importance of peat depth to ecohydrological functioning has been considered. Other aspects of soil or ecosystem functioning that would be indicators of a restored site could be the rates of gas (CO₂, CH₄ and N-gas species) exchange, uptake and emissions (e.g. Wilson et al, 2016), and microbial and fungal community profile (e.g., (Andersen et al, 2006). Whilst this data exists for some wind farm sites (e.g., Armstrong et al, 2015a, b; Richardson et al, 2015) these parameters are not measured routinely, nor in assessing the environmental impacts of wind farm developments (of which repowering is a component). Thus, gas emission balances and soil biota composition are not considered further here.

Rather, this section focuses on: i) whether the foundation could impact soil biogeochemical processes through chemical interaction with the soil; ii) the practises of repowering soil management that would support the most effective biogeochemical recovery. The former consideration is less relevant to repowering where the foundation is reengineered, as the new structure would envelope the old foundation (see section 5) and the new design would specify the integrity of the concrete for the duration of the repowering planning extension to be non-reactive. Thus, this section focuses more on where foundations cannot be reused, and restoration is required, and this is also relevant to restoration of a reengineered foundation. Further the following consideration is most relevant to where only part of the foundation would be removed, as if fully removed the residual foundation remains would be very small in comparison to the volume of surrounding soil.

Firstly, there are unlikely to be any chemicals used in restoration that could impact biogeochemical functioning. Foundation removal would be a mechanical process. This consideration focuses on whether there could be an interaction with peat soils and the foundation that could result in a change in pore water chemistry (and thus peat land biogeochemistry).

The cured concrete mineral composition will largely comprise compounds of calcium with silicate, aluminium and iron oxides (e.g., Mindess and Young, 1981). Although this is probably different to most host lithology mineral composition in Scotland, which tends to be less calcium-rich, these minerals may be found in smaller quantities naturally. Further, the mineral composition will be somewhat dependent on the aggregates available and some wind farms used on-site borrow pits for concrete aggregate. Thus, the foundation minerogenic composition is not completely 'alien' to the subsurface and, in some wind farms, may share greater similarity.

However, the cured cement is a relatively alkaline material: when properly cured the pH initially is 12.5 (e.g., Mindess and Young, 1981). For turbines in peatland, the foundation is exposed to pH of porewater ranging from 3.5 to 7, where higher pH values usually indicate reaction with the underlying substrate and mixing with groundwaters, (e.g. Shotyk and Steinmann, 1994; Armstrong, et al, 2015b; Griffiths and Sebestyen, 2016). Thus, there could be acid attack of the concrete in the lower pH systems.

This is counteracted in foundation construction by using a foundation designed in accordance with the site conditions, which should be resistant to degradation by reaction with the surrounding soil pore water for the time duration specified in the construction brief. The concrete specification is based on the geotechnical analysis of the site to determine the 'Design Sulfate' class for the site. This along with the pH values, taken from the ground investigation data, generates an Aggressive Chemical Environment for Concrete (ACEC) classification. As such different concrete specifications may be used in different wind farms or within the wind farm, and where acid conditions are expected, will have a composition that minimises reaction fronts penetrating the foundation and reducing its mechanical properties.

Supporting research that considers if such chemical degradation can occur with current or restored foundations could not be found. There are some publications that show acidic waters, including organic acids such as found in peats, will react with and can cause deterioration of concrete (e.g. Regmi et al, 2011; Haferkorn et al, 2012; Dyer 2017; Olivia et al, 2017). These are not specific to WTG foundations, but similarly it would be incorrect to assume such an interaction will not occur.

Further, the process of partial foundation removal is likely to create an uneven surface, and some concrete rubble, which, for complete removal, would require hand-picking to capture the small fragments. If surface fractures were present, even at the microscale, this would create a new surface area for reaction with soil pore water. Whether this would occur at a greater rate, as the residual foundation is now older than the resistance duration guaranteed in the construction brief, is unknown. Thus, there may be a research need to explore whether reaction of residual foundation with peat pore water occurs. However, design guidance for durability is 50 years, so covers repowering and restoration lifetime.

For context, where this is most likely to be of a concern is where the compositionally different porewater becomes hydrologically connected with surface vegetation that prefer acidic conditions. Depending on the site slope, lateral transport of porewater could reach, and so influence, surface vegetation downhill of the foundation. Whilst upward flow of water from the foundation is unlikely, there may still be an ionic gradient from the foundation to the surface, with more nutrient rich waters resulting in poor-fen vegetation communities. Thus, infill depth is an important consideration as has a role to play in suppressing connectivity of the surface with the underlying substrate (e.g. Nwaishi et al., 2015).

The other process that could expose the residual foundation to new weathering is freeze-thaw action by creating smaller fragments and fresh faces for reaction. However prolonged atmospheric temperatures of 0°C or below would be required to propagate this temperature through the soil profile and to the new surface of the excavated foundation. Such weather conditions do not occur in the Scottish climate.

Soil management during repowering to support the most effective biogeochemical recovery: Most crucial for effective biogeochemical functioning is that the infill soil has the maximum structural integrity possible and a similar composition to the surroundings, and that there is minimum damage to the surroundings. The advice in the '[Good Practice During Windfarm Construction](#)' guidelines (Scottish Renewables et al, 2010) for onshore windfarms is of value and relevant to augmentation of the existing foundations where excavation is required, or in restoration. SEPA's guidance on reusing peat¹⁴ may also be useful. Particularly important is to:

- excavate of large, intact blocks of peat which are less prone to drying out.
- minimising the movement of extracted peat and spray material to keep it moist and prevent desiccation.
- if peat is stockpiled for restoration of the removed foundation soil infill, undertake this in large amounts where the sides of the piles are bladed to minimise the drying surface area.
- minimise the time between extraction and restoration where possible.

7.8. Summary appraisal of the considerations of foundation reengineering or restoration

The key consideration is how to treat the foundation. If the foundation cannot be reused, the choice is whether to remove part of the foundation or to remove all of it. From the consideration above of the environmental response, the following key points emerge:

- To assess whether reengineering an existing foundation or constructing a new foundation is more environmentally sustainable, the implications for restoration at the end of the next life of either option also need to be considered. If the engineered foundation cannot be used a second time, restoration of a land surface to provide ecosystem services is likely to be required - as it would be now with foundations that are not reengineered. However, for reengineering designs considered here, for the two most likely repowering scenarios (and many others), key resource quantities required are greater for the reengineered foundation than if repowering proceeded with a new turbine foundation and the existing foundation was abandoned. The extent of soil disturbance during construction and required at end-of-life for restoration is more similar for both repowering approaches, but which has greater impact on these quantities is not consistent. Surface area disturbance is greater with two new foundations than one reengineered foundation, but more of that disturbed land is reinstated at foundation commissioning and so offers most chance of recovery. The impact of these C payback time needs to be further explored through formal calculations of C expenditure in construction using a tool such as an adapted Scottish Government Windfarm 'Carbon Assessment Tool'.
- For effective restoration the infill must be of sufficient depth to allow self-regulating ecohydrological functioning. Where the soil is shallow, and not peat, the foundation may be removed only to a depth below the soil to support land use (e.g. safe ploughing of fields) and the soil infill profiled and reinstated with a seed mix appropriate to the area. There are existing examples of this, and the turbine removal depth here was 1 m.
- Where the soil is peat and not shallow, there is no model yet to understand what depth of infill is required. Assuming bedrock is not shallower, at least 1 m of peat depth seems required, but if ombrotrophic peatland vegetation is important, this may need to be 2 m. This depth may present peat stability issues and be a safety hazard to the public.
- Regardless of the depth of infill there are greater environmental benefits if the new surface is vegetated as soon as possible. Understanding how to acquire, move and position infill material in sufficient volumes, with the best structure to support ecohydrological functioning and the growth of appropriate surface vegetation, is a key consideration in repowering planning.
- The extent to which the foundation has been and will continue to be subject to reaction with acidic peat waters is unknown. Such reactions may continue to happen with the component of the concrete foundation that is not removed, particularly if new concrete is exposed. The impact of this on peatland functioning is not known, as is the extent to which this could be a concern. A hydrological assessment of flow pathways may be required to assess if changed porewaters are returned to areas of sensitive vegetation.
- The effectiveness of the processes above in restoring peatland functioning will influence the payback time and net carbon savings associated with the power generated from the wind farm. The Scottish Government Windfarm 'Carbon Assessment Tool' could be adapted to allow these calculations to be made and inform repowering decisions.

8. The application of the Scottish Government Windfarm ‘Carbon Assessment Tool’

To provide a complete assessment of C payback time, the Scottish Government Windfarm CAT should be developed to include C emissions associated with repowering. Modification of the tool will be required to allow the different processes associated with repowering to be accounted for. This section identifies the developments needed and briefly outlines any research activity that would be necessary to support these developments. This builds on a recent short report for SEPA on how to capture the *physical* aspects of repowering (Smith & Perks, 2016). That report considered C savings due to changes in capacity factor with age of turbines, increased size or relocation of foundations, and reuse or early decommissioning of infrastructure. It recommended including:

- a reduction in capacity factor with age of turbines (e.g. Staffell and Green, 2014),
- the option to describe felling of forestry and a “donut” extension of existing foundations (e.g. as with the Arup design of more concrete over and around the existing concrete in the foundation),
- a function to pass the C cost of not restoring hydrology to the repowered windfarm,
- a “legacy debt” to account for losses of payback time and gains due to earlier decommissioning.

It did not consider the methodology used to restore an area occupied by a foundation if it is no longer to be used, and how this will impact C payback. It also did not consider the C implications of the different engineering options used to recommission the turbine, or to remove the foundation (either fully or partially) and restore the area that the foundation occupied. This analysis focuses on how to incorporate these further processes associated with repowering into the Windfarm CAT to inform decision-making.

The additional practises associated with repowering that should be included in the Windfarm CAT include:

1. Foundation removal;
 - a. Complete removal of the foundation,
 - b. Removal of the foundation only to a specified depth (e.g. surface or 1 m), or
 - c. Reuse of foundation.
2. Backfilling of foundation;
 - a. Backfilling with impermeable medium (e.g. clay subsoil) and shallow surface layer of peat,
 - b. Backfilling with a deep layer of relatively undisturbed peat,
 - c. Not backfilling and leaving a visible concrete foundation at the surface.
3. Removal / replacement of cable;
 - a. Replacement in ducting,
 - b. Ploughing over and replacing cable in same area,
 - c. Ploughing over to remove old cable and putting new cable in a different area/

Note, it has been assumed that cables from the previous installation must be removed.

The potential C impacts of the different choices associated with these practises include

1. Peat and hydrology
 - a. Failure to restore hydrology as planned in the original consent due to foundations being reused
 - b. Disturbance / compaction around the foundation / cable trenches
 - c. Temporary infrastructure / hard-standing required for extraction

- d. Drainage of surrounding area due to fully or partially removing the foundation and leaving a void or backfilled volume with higher hydraulic conductivity than the surrounding area
 - e. Relocation of peat / subsoil for backfilling
 - f. Potential decomposition of backfilled peat
 - g. Potential for instability (peat-slides or ponding) of backfilled peat
 - h. Changes in pH and other chemical composition of peat due to slow degradation of an abandoned foundation
2. Energy use
- a. for extraction of concrete foundations
 - b. for backfilling the redundant foundation bowl
 - c. in transporting replacement and redundant turbines, and soil for infill
 - d. for mechanical blocking of drainage channels
 - e. for manufacture of new turbines (already included in the Windfarm CAT under "Carbon dioxide emissions from turbine life")
3. Plant communities
- a. Failure to restore habitat as planned in the original consent due to the foundation being reused
 - b. Permanent loss or regeneration of ombrotrophic vegetation over foundations
 - c. Impact of degrading foundations on plant communities through changes in pH

Possible methodologies for description of the potential impacts of repowering are summarised below, highlighting areas where further research is needed.

8.1. Peat and Hydrology

8.1.1. *Failure to restore hydrology due to foundations being reused* – If the initial estimate of C payback time was based on the developer identifying that the site would be restored, the Windfarm CAT assumes that, after restoration, the hydrology of the system will function in the pre-disturbance state and C losses from the peat will be stopped, so saving potential C losses from the peat. If the site is now repowered, independently of whether the foundation is reused or not, the C saving associated with restoring the hydrology is not activated. Although the original development was responsible for putting in the drains, the C cost of not restoring, after the original planned time of restoration, occurs due to the repowering of the site. Therefore, in agreement with Smith & Perks (2016), this C cost should be transferred to the redevelopment. If turbine bases are reengineered and reused, it is likely the turbine spacing will likely change with a new layout and some foundations will become redundant and would be restored and so variable restoration would also have to be considered.

8.1.2. *Disturbance or compaction around the foundation or cable trenches* – Although this should be minimal as the foundation would be worked within the confines of the original excavation and the adjacent hardstand, further research is needed to determine the extent and impacts of any additional disturbance or compaction that is likely to occur around the foundation on decommissioning (or indeed installation). If the disturbed or compacted area around the foundation is found to have a significant extent, the impacts on hydrology and peat decomposition should be included in the Windfarm CAT using the best available evidence and, if possible, evidence from further research. Including this term would also encourage best practise of reengineering / restoration from existing hard-standing to minimise disturbance. There are currently no detailed measurements of the impacts

of compaction on C losses from the peats due to construction, decommissioning or recommissioning of wind turbines. In forested peat soils, compaction due to harvesting machinery ranged from 594 to 640 kPa (Nugent et al., 2003). Drainage and compaction of pristine peats can cause a significant decrease in hydraulic conductivity (Mustamo et al., 2016). Increased emissions of methane, even in well aerated soils, have been observed following such compaction (Frey et al., 2011). This was due to decreased soil macropore space and lowered hydraulic conductivity that persisted even after a year after compaction.

8.1.3. *Temporary infrastructure or hard-standing required for extraction* – Provision is already made in the Windfarm CAT to describe temporary infrastructure and hard-standing. However, it currently only allows one time of restoration to be specified for the whole site. If temporary infrastructure and hard-standing could be used in construction and repowering, the tool should be updated to allow different times of restoration to be specified for different areas, allowing some structures to be retained throughout the lifetime of the windfarm, while others are restored immediately following construction / repowering.

8.1.4. *Drainage of surrounding area due to fully or partially removing the foundation* – No description is included in the Windfarm CAT of the impacts on drainage of fully or partially removing foundations. The tool should be updated to allow specification of the different options: depth of extraction, nature of any backfilling giving depth of impermeable layer and peat, slope of surrounding area and presence of any water outlets from the created void. This will allow the volume of water held in the extracted and backfilled void and the volume of water removed from the area to be estimated. A continuously-draining void will have a much larger impact on the surrounding peats than an isolated void, which will quickly come to steady state with the surrounding area and form either a stagnant pond or a boggy area of land, depending on the backfilling practice used. Further research is needed to determine the hydraulic conductivity of backfilled materials and to provide recommendations for the best ways to minimise impacts on the surrounding peats.

8.1.5. *Relocation of peat or subsoil for backfilling* – Peat and subsoil used for backfilling following removal of the old foundations may come from areas excavated for new foundations or borrow-pits. Excavation of areas for foundations and hardstanding and the use of borrow-pits are already described in the Windfarm CAT. Therefore, no change in the structure of the tool is needed to accommodate this. Some rewording of the inputs may be needed to clarify the meaning of terms used here. However, there is a need to revisit the question of how much of the translocated peat C is decomposed.

8.1.6. *Potential decomposition of backfilled peat* – The decomposition of peat following backfilling depends on the hydrological conditions of the peat, and the extent of disturbance and drying of the peat during relocation. Estimates of the rate of decomposition following backfilling need to be included in the Windfarm CAT. However, there is currently no research evidence available that directly determines the impacts of relocating peats on the rate of decomposition. Working in tropical Andean peatlands, Urbina and Benavides (2015), observed increased decomposition rates in response to small scale disturbance of peats. Similarly, Berglund & Berglund (2011) found enhanced decomposition in response to cultivation of northern peat soils, dependent on the lability of the organic matter. However, the soils in both these sites are subject to other factors that enhance the rate of decomposition, such as fertiliser application, trampling by cattle and cultivation of arable crops. Further research is needed to determine the impact of backfilling peat with different extents of disturbance on the rate of decomposition of the peat.

8.1.7. *Potential for instability (peat-slides or ponding) of backfilled peat* – The risk of peat-slides is not included in the Windfarm CAT as catastrophic events such as this are very difficult to predict. Instead, the tool takes the approach of recommending avoidance of practices that are likely to result

in peatland instability. Peat slide is considered unlikely, but this is unknown, and so further research to determine the practices associated with backfilling peat that should be avoided may be useful. Windfarm developers generally complete peat stability assessments, geotechnical risk assessment and peat management plans to avoid peat slides. Guidance on handling and storing peats are given by McCulloch (2006), SEPA (2010), SNH & FCS (2010), SR et al. (2010), SNH et al. (2011) and SR & SEPA (2012).

8.1.8. *Changes in pH due to slow degradation of an abandoned foundation* – Although pH of peat impacts the rate of peat decomposition (Yavitt et al., 2015), pH was not found to be a key controlling factor in the limited pH range used to derive equations for changes in CO₂ and CH₄ emissions (Nayak et al., 2010). Therefore, pH is not currently an input to the Windfarm CAT. If pH changes significantly due to dissolution of foundation cations from the degrading concrete foundation, it will become a controlling factor, so it will be necessary to derive new equations to describe the change in decomposition associated with the changes in pH observed. Research is needed to determine the extent of pH change around degrading concrete foundations and the impact this has on soil organic matter decomposition and emissions from the peat.

8.2. Energy Use

End of life reinstatement work usually involves removal of reinforced concrete, structural fill to 1m below ground level and backfill to ground level with soil / peat (ARUP, 2017). This would be replaced by the work needed to re-use the foundation. Currently the reinstatement work is included in the Windfarm CAT as a single input figure under “Turbine life”. In order to estimate the change in C payback time due to repowering, this would need to be explicitly included in the model so that it can be subtracted from the new work required for foundation re-use.

8.2.1. *Replacement of concrete foundations* - Arup (2017) estimated that in moving from 0.85 to 3.2 MW turbines, the amount of reinforced concrete used increases from 130 to 1065 m³, and an additional 610 m³ of mass concrete is needed; the structural fill increases from 203 to 524 m³ and the excavation volume increases from 1311 to 3076 m³. According to Arup (2017), because the concrete foundation is an area of very high cyclic loading and stress concentration (transferred from the wind turbine tower to the plinth that it sits on), the design is usually dictated by the expected life of the turbine. The existing foundation will not support the larger WTG without re-engineering. Therefore, the concrete plinth will usually need to be removed, even when repowering over the same foundation. If it is abandoned, the top 1000 mm will be removed. Additional energy requirements are therefore for plinth removal, to excavate the foundation for extension, and to produce and position more concrete and fill material. The energy requirements of these activities and the C emissions associated with the increased volume of concrete use would need to be explicitly described in the Windfarm CAT in order to describe the change in emissions.

8.2.2. *Backfilling the redundant turbine bowl* – If repowering involved removing of the foundations, the redundant bowl would need to be backfilled. The energy required for this depends on the source of the soil / peat used for backfilling. If it is likely that backfill will be obtained from a very distant source, transportation of the materials should be accounted for in the Windfarm CAT. This is currently accounted for in the “Turbine life” value, but a more explicit calculation within the Windfarm CAT would be useful as it would encourage more consideration of the energy associated with sourcing material for backfilling.

8.2.3. *Transporting replacement and redundant turbines* – The C costs of transporting turbines is currently accounted for in the “Turbine life” value, so no change is necessary to describe the transport

of replacement and redundant turbines. However, more explicit calculation of the energy required for transportation within the Windfarm CAT would be beneficial as it would encourage consideration of the impact of turbine source and destination on energy use.

8.2.4. *Mechanical blocking of drainage channels* – This energy costs of this process are not currently described in the Windfarm CAT. If found to be significant, they should be explicitly included in the model.

8.3. Plant Communities

8.3.1. *Failure to restore due to the foundation being reused* - If the initial estimate of C payback time was based on the developer identifying that the habitat at the site would be restored, the Windfarm CAT assumes that, after restoration, the plant communities will function in the pre-disturbance state and C losses from reduced C capture by plants will be stopped. If the site is repowered, the restoration of habitat, as identified in the original estimate, is not achieved. The impacts of this are changes to the quality and quantity of organic matter input to the soil and changes in the hydrological properties of the peat (Taylor and Price, 2015). Although the original development was responsible for the loss of habitat, the C cost following the original planned time of restoration occurs due to the repowering of the site. Therefore, in agreement with Smith & Perks (2016), this C cost should be transferred to the redevelopment.

8.3.2. *Permanent loss or regeneration of ombrotrophic vegetation over foundations* – Taylor and Price (2015) observed that regenerating Sphagnum moss layers directly overlying cutover peat significantly increased in bulk density and water holding capacity with age. This suggests that the loss of ombrotrophic vegetation will have a significant impact on the hydrological properties of the peat. If the hydrology of the peat is not restored to its pre-installation state, then the peat will continue to decompose more rapidly, resulting in net carbon dioxide emissions. This additional loss would be attributable to the repowered windfarm, although it would be relatively small, as it would only impact backfilled peat under the footprint of the redundant foundation. Further research is needed to develop methods to avoid permanent loss of ombrotrophic vegetation over foundations.

8.3.3. *Impact of degrading foundations on plant communities through changes in pH* – The impact of pH on the plant communities is not included in the Windfarm CAT. It is currently unclear whether this will be an important factor, but the extent of the impact on carbon dioxide emissions is not likely to be large and it will be limited to the area immediately around the foundations. Further research is needed to determine the impact of degrading foundations on pH, and the effect this has on plant communities.

Table 8. Summary of changes to the Windfarm Carbon Assessment Tool needed to describe the impacts of repowering

Impact of repowering	Change needed in the Windfarm Carbon Assessment Tool	Further research needed
1. PEAT AND HYDROLOGY		
a. Failure to restore hydrology due to foundations being reused	C cost of not restoring hydrology should be transferred to repowered windfarm	Extent and impacts of disturbance or compaction
b. Disturbance or compaction around the foundation or cable trenches	If extent significant, include impacts on hydrology and peat decomposition	
c. Temporary infrastructure or hard-standing required for extraction	Allow different times of restoration to be specified for different areas of hard-standing or infrastructure	
d. Drainage of surrounding area due to fully or partially removed foundation	Estimate the impacts of the different options for removing foundations (inputs depth of extraction, nature of any backfilling giving depth of impermeable layer and peat, slope of surrounding area and presence of any water outlets from the extracted bowl)	Changes in hydraulic conductivity of backfilled materials and methods to minimize impacts on surrounding peats
e. Relocation of peat or subsoil for backfilling	No structural change needed; some rewording of inputs may be required to clarify inputs	Impact of relocation of peats on decomposition
f. Potential decomposition of backfilled peat	Estimates rate of decomposition of peat following backfilling with different extents of disturbance, differently restored hydrological conditions and peats of different lability	
g. Potential for instability (peat-slides or ponding) of backfilled peat	No change required	Practices associated with backfilling peat that result in structural instability
h. Changes in pH due to slow degradation of an abandoned foundation	Adapt decomposition equations to include changes in soil pH associated with degrading foundations. Incorporate equations for changes in pH associated with degrading foundations	Changes in soil pH associated with degrading foundations. Impact of pH changes on peat decomposition.

Impact of repowering	Change needed in the Windfarm Carbon Assessment Tool	Further research needed
2. ENERGY USE FOR:		
a. replacement of concrete foundations	Explicitly describe end of life reinstatement work so that it can be subtracted from new work for re-use (currently given as part of "Turbine life" value). Describe C costs associated with plinth removal, excavation around the foundation of the existing foundations to extend formation, and backfilling with mass concrete.	
b. backfilling redundant bowl	Explicitly calculate the energy costs associated with transportation of material used for backfilling to encourage use of local materials (currently given as part of "Turbine life" value)	
c. transporting replacement and redundant turbines	Explicitly calculate of the energy costs associated with transportation of the replacement and redundant turbines to encourage use of more local developers and breakers (currently given as part of "Turbine life" value)	
d. mechanical blocking of drainage channels	Explicitly include energy costs of mechanical blocking of drains (if significant)	The energy cost of mechanically blocking drains
3. PLANT COMMUNITIES		
a. Failure to restore habitat	C cost of not restoring habitat should be transferred to repowered windfarm	
b. Permanent loss or regeneration of ombrotrophic vegetation over foundations	Unknown	Methods to avoid permanent loss of ombrotrophic vegetation over foundations.
c. Impact of degrading foundations on plant communities through changes in pH	Unknown	Extent of release of ions from degrading foundations and cables, and impact of released ions on plant communities

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References:

- Andersen R, Francez AJ, and Rochefort L (2006) The physicochemical and microbiological status of a restored bog in Quebec: Identification of relevant criteria to monitor success. *Soil Biology and Biochemistry*, 38, 6, 1375-1387, doi: 10.1016/j.soilbio.2005.10.01
- Armstrong A, Holden J, Kay P, Foulger M, Gledhill S, McDonald AT and Walker A. (2009) Drain-blocking techniques on blanket peat: A framework for best practice. *Journal of Environmental Management*. 90, 11, 3512-9. doi: 10.1016/j.jenvman.2009.06.003.
- Armstrong A, Burton RR, Lee SE, Mobbs S, Ostle NJ, Smith V, Waldron S and Whitaker J (2016) Ground-level climate at a peatland wind farm in Scotland is affected by wind turbine operation. *Environmental Research Letters* 11, 11 044024
- Armstrong A, Richardson H, Waldron S., Ostle NJ and Whitaker J (2015a). Field measurements of peatland carbon cycling at a wind farm hosting peatland in Scotland, UK. NERC Environmental Information Data Centre. 10.5285/99416ba1-b670-4a82-8225-9644293fb4de
- Armstrong A, Waldron S, Ostle NJ, Richardson H and Whitaker J (2015b) Biotic and abiotic factors interact to regulate northern peatland carbon cycling. *Ecosystems*, 1-15
- Barnes KK, Carleton WM, Taylor, HM, Throckmorton RI and Vanden Berg GE (Eds.) (1971) Compaction of Agricultural Soils. An ASAE Monograph. American Society of Agricultural Engineers, St Joseph, Michigan (471 pp.).
- Berglund Ö and Berglund K 2011. Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biology & Biochemistry*, 43, 923-931.
- Dyer T (2017) Influence of cement type on resistance to organic acids *Magazine of Concrete Research*, 69, 4, 175–200, <http://dx.doi.org/10.1680/jmacr.16.00271>
- Evans ME, Shuttleworth E, Pilkington M, Allott T, Walker J and Spencer T (2017) Trajectories of ecosystem service change in restored peatlands. *Geophysical Research Abstracts* 19, <http://meetingorganizer.copernicus.org/EGU2017/EGU2017-17993.pdf>
- Everaert J (2014) Collision risk and micro-avoidance rates of birds with wind turbines in Flanders *Bird Study*, 61, 2, 220-230
- Ferri VI, Battisti C and Soccini C (2016) Bats in a Mediterranean mountainous landscape: Does wind farm repowering induce changes at assemblage and species level? *Environmental Management* 57, 6,1240-1246 doi 10.1007/s00267-016-0686-2
- Fischer J and Lindenmayer DB (2007) Landscape modification and habitat fragmentation: a synthesis *Global Ecology and Biogeography* 16, 265–280
- Frey B, Niklaus PA, Kremer J, Lüscher P and Zimmermann S (2011) Heavy-machinery traffic impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. *Applied and Environmental Microbiology* 77, 17, 6060-6068 doi: 10.1128/AEM.05206-11

- Grace, M, Dykes AP, Thorp SPR, and Crowle AJW. (2013). *Natural England review of upland evidence - The impacts of tracks on the integrity and hydrological function of blanket peat. Natural England Evidence Review, Number 002.*
- Griffiths NA and Sebestyen SD (2016) Dynamic vertical profiles of peat porewater chemistry in a northern peatland. *Wetlands*, 36, 3, 1119-1130, doi:10.1007/s13157-016-0829-5
- Haferkorn I, Kloess G, and Franz A (2012) Organic acid attack of hydrated cement *European Mineralogical Conference* Vol. 1, EMC2012-658-1. Last accessed 19/7/17 <http://meetingorganizer.copernicus.org/EMC2012/EMC2012-658-1.pdf>
- Lantschner L, McMullen A and MacDougall K (2011) Restoration techniques using peat soil from construction works. *An EnviroCentre Report for SEPA: 4468* Last accessed 18/7/17 <https://www.sepa.org.uk/media/163263/restoration-techniques-using-peat-spoil-from-construction-works.pdf>
- Lindsay RA & Clough J (2016). A review of the influence of ombrotrophic peat depth on the successful restoration of bog habitat. *Scottish Natural Heritage Commissioned Report No. 925.* www.snh.org.uk/pdfs/publications/commissioned_reports/925.pdf
- Mazerolle MJ, Poulin M, Lavoie C, Richefort L, Desrochers A and Drolet B (2006) Animal and vegetation patterns in natural and man-made bog pools: implications for restoration. *Freshwater Biology*, 51, 333-350
- McCulloch F (2006). Guidance for the risk management of peat slips on the construction of low volume / low cost roads over peat. *Forestry Civil Engineering* <http://www.roadex.org/wp-content/uploads/2014/01/Guidelines-for-the-Risk-Management-of-Peat-Slips.pdf>
- Mindess S & Young JF (1981): Concrete, Prentice-Hall, Inc., Englewood Cliffs, NJ, pp. 671.
- Mustamo P, Hyvärinen M, Ronkanen A. and Kløve B. (2016) Physical properties of peat soils under different land use options. *Soil Use & Management* 32, 400-410.
- Nayak DR, Miller D, Nolan A, Smith P and Smith JU 2010. Calculating carbon budgets of wind farms on Scottish peatlands. *Mires & Peat* 4, Article 09, <http://www.mires-and-peat.net/>, ISSN 1819-754X.
- Nugent C, Kanali C, Owende PMO, Nieuwenhuis M and Ward S (2003) Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. *Forest Ecology and Management* 180, 1-3, 85-98 doi 10.1016/S0378-1127(02)00628-X
- Nwaishi F, Petrone RM, Price JS, Ketcheson SJ, Slawson R and Andersen R (2015) Impacts of donor-peat management practices on the functional characteristics of a constructed fen. *Ecological Engineering* 81, 471–480
- Olivia M, Pradana T and Sitompul IR (2017) Properties of plain and blended cement concrete immersed in acidic peat water canal, *Procedia Engineering*, 171, 557-563
- Parry LE, Holden J and Chapman PJ (2014) Restoration of blanket peatlands *Journal of Environmental Management* 133,193-205
- Potvin LR, Kane ES, Rodney AC, Chimner A, Kolka RK and Lilleskov EAE (2014) Effects of water table position and plant functional group on plant community, aboveground production, and peat properties in a peatland mesocosm experiment (PEATcosm) *Plant and Soil* DOI: 10.1007/s11104-014-2301-8
- Regmi G, Indraratna B, Nghiêm LD, Golab A and Guru Prasad B (2011) Treatment of acidic groundwater in acid sulfate soil terrain using recycled concrete: column experiments. *Journal of Environmental Engineering*, 137,6, 433-443.

- Richardson H, Waldron S, Whitaker J. and Ostle N. (2015). Measures of peatland carbon cycling from peat mesocosm incubation experiments. NERC Environmental Information Data Centre. 10.5285/e15fbbab-1cdd-4509-81a3-aa050e927dd0.
- Scottish Government Onshore Wind Policy Statement 2017a ISBN: 9781788515283 <http://www.gov.scot/Publications/2017/01/7344>
- Scottish Government Scottish Energy Strategy 2017b: The future of energy in Scotland ISBN: 9781788515276 <http://www.gov.scot/Resource/0051/00513466.pdf>
- Scottish Renewables, Scottish Natural Heritage (SNH), Scottish Environment Protection Agency (SEPA) and Forestry Commission Scotland (2010). Good practice during windfarm construction. <http://www.snh.org.uk/pdfs/strategy/renewables/Good%20practice%20during%20windfarm%20construction.pdf>
- Scottish Renewables and SEPA (2012). Developments on peatland: guidance on the assessment of peat volumes, reuse of excavated peat and the minimisation of waste.
- SEPA (2010). SEPA Regulatory Position Statement – Developments on Peat.
- SEPA (2014) Guidance note 31. Land Use Planning System https://www.sepa.org.uk/media/143868/lupsgu31_planning_guidance_on_groundwater_abstr_actions.pdf
- Shotyk W and Steinmann P (1994) Pore-water indicators of rainwater-dominated versus groundwater-dominated peat bog profiles (Jura Mountains, Switzerland). *Chemical Geology*, 116, 1-2, 137-146 doi: 10.1016/0009-2541(94)90162-7
- Smith JU & Perks M 2016. The Scottish Government Windfarm Carbon Assessment Tool Development – Technical guidance, lite version and repowering. Contract: A12929. Final Report to SEPA. Part D – Scoping study for repowering.
- SNH and Forestry Commission Scotland (FCS) (2010). Floating Roads on Peat.
- SNH, SEPA, Scottish Government and James Hutton Institute (2011). Guidance – Developments on Peatland: Site Surveys.
- SNH (2016) Decommissioning and Restoration Plans for wind farms Guidance Version 2 <http://www.snh.gov.uk/docs/A1434319.pdf>
- Staffell I and Green R (2014) How does wind farm performance decline with age? *Renewable Energy*, 66, 775-786
- Standen V and Owen MJ (1999) An evaluation of the use of translocated blanket bog vegetation for heathland restoration. *Applied Vegetation Science*, 2, 2, 181-188
- Taylor N and Price J (2015) Soil water dynamics and hydrophysical properties of regenerating *Sphagnum* layers in a cutover peatland. *Hydrological Processes*, 29, 3878-3892.
- Urbina JC and Benavides JC (2015) Simulated small scale disturbances increase decomposition rates and facilitates invasive species encroachment in a high elevation tropical Andean peatland. *Biotropica*, 27, 143-151.
- Waldron S, Yeluripati J, Saunders M, Conniff A, Chapman S, Miller D, Matthews R, Smith J, and Govan S (2014) The Peatland C Calculator, Its Use and Future Potential. http://www.climateexchange.org.uk/files/1614/5030/6656/Carbon_Calculator_-_FINAL_Report_14_Dec_15.pdf
- Welstead J, Hirst R, Keogh D, Robb G and Bainsfair R (2013) Research and guidance on restoration and decommissioning of onshore wind farms. *Scottish Natural Heritage Commissioned Report No. 591*.

http://www.snh.org.uk/pdfs/publications/commissioned_reports/591.pdf

Wilson D, Blain D, Couwenberg J, Evans CD, Murdiyarso D, Page SE, Renou-Wilson F, Rieley JO, Sirin A, Strack M and Tuittila E-S (2016) Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 17, DOI: 10.19189/MaP.2016.OMB.222

Yavitt JB, Williams CJ, Wieder RK (2005). Soil chemistry versus environmental controls on production of CH₄ and CO₂ in northern peatlands. *European J. of Soil Science*, 56, 169-178.

Websites

¹ Calculated using data in Table ET6.1 9th August 2018 update, available at <https://www.gov.uk/government/statistics/energy-trends-section-6-renewables> Last accessed 26/9/18

² Presentation 2 - Repowering Onshore Wind Projects - William Black, Scottish Power Renewables <https://www.nature.scot/onshore-renewables-repowering-natural-heritage-considerations-7-december-2016> Last accessed 26/9/18

³ <http://sse.com/whatwedo/ourprojectsandassets/renewables/tangy/> Last accessed 26/9/18

⁴ <http://sse.com/media/465183/Modified-Tangy-III-Scoping-Report-April-2017-Low-Res.pdf> Last accessed 26/9/18

⁵ <http://sse.com/whatwedo/ourprojectsandassets/renewables/tangy-repower/> Last accessed 26/9/18

⁶ <https://www.rjmcleod.co.uk/services/energy/energy-2013/spurness-wind-farm-sanday/> Last accessed 26/9/18

⁷ <https://www.thriverenewables.co.uk/projects/caton-moor-wind-farm/>; Last accessed 26/9/18

⁸ <http://planning.cornwall.gov.uk/online-applications/applicationDetails.do?activeTab=documents&keyVal=MWXG7KFG06Q00> Last accessed 26/9/18

⁹ <https://www.goodenergy.co.uk/our-energy/our-energy-farms/our-wind-farms/delabole-wind-farm/> Last accessed 26/9/18

¹⁰ https://www.scottishpowerrenewables.com/pages/carland_cross_repowering.aspx Last accessed 26/9/18

¹¹ https://www.scottishpowerrenewables.com/pages/coal_clough.aspx Last accessed 26/9/18

¹² https://www.eonenergy.com/About-eon/our-company/generation/planning-for-the-future/wind/onshore/ovenden-moor-repower/~media/PDFs/Generation/wind/onshore/ovenden-moor-repower/Vol_1_Environmental_Statement.pdf. Last access 28/5/18 Link appears broken on 26/9/18. Reference to this document in the following, accessed 26/9/18

https://www.iema.net/assets/nts/Aecom/Ovenden_Moor_Wind_Farm_NTS_August_2012.pdf

¹³ https://www.scottishpowerrenewables.com/pages/llandinam_repowering.aspx Last accessed 28/5/18

¹⁴ <https://www.eonenergy.com/About-eon/our-company/generation/planning-for-the-future/wind/onshore/rhyd-y-groes-repower/project-information> Last accessed 26/9/18

¹⁵ <http://mapapps2.bgs.ac.uk/ukso/home.html?layer=NSRISoilscapes> Last accessed 26/9/18

¹⁶ <http://www.gov.scot/WindFarmsAndCarbon> Last accessed 26/9/18

¹⁷ <https://www.nature.scot/climate-change/taking-action/carbon-management/restoring-scotlands-peatlands/scotlands-national-peatland-plan> Last accessed 26/9/18

¹⁸ <http://www.gov.scot/Publications/2006/12/21162303/0> Last accessed 28/5/18

Appendix 1: Re-Usable Onshore Wind Turbine Foundations Project – Scottish Enterprise Work Package

SSE & ScottishPower Renewables supplied contact details for developers Siemens, Gamesa & Vestas in order to set up calls to discuss their future plans for onshore repowering. It was agreed that due to time constraints and locations to set up online calls rather than face-to-face meetings. Scottish Enterprise, SSE & SPR discussed and agreed the questions to be asked. Scottish Enterprise after initial introductions from SSE and SPR contacted the developers and both Gamesa & Vestas responded agreeing to participate. The call with Gamesa took place on 15/2/17 and the call with Vestas took place on 20/2/17. All findings from the calls were collated by Scottish Enterprise and sent out to the call participants for verification. There has been no response from Siemens to date.

What is your strategy for remaining turbines, repowering, existing or future plan?

- Lower costs of energy by continued technology development.
- Due to restriction on height (max 125) in the UK it is not easy to offer larger turbines compared to overseas markets where height restrictions are less restricted thus making lowering the cost of energy a challenge and restricts competitiveness.

As a turbine manufacturer how do you plan to service the market where volumes are lower, smaller production areas?

- There is no differentiation.

What happens if the wind turbine to be replaced / repowered is discontinued? Would you remake the discontinued turbine?

- The developer would recommend using their latest product as it would be the most efficient; however, some older models are still available in their product portfolios and are proven in the market. Problems can occur if the volumes are too low for an older turbine or replacement parts are difficult to obtain.

Have you had discussions regarding foundations?

- With third party designers and external consultants

Have you been asked to reuse foundations?

- In specific cases the developer has been asked to maintain or modify foundations. It is difficult to analysis an entire foundation for reuse due to the different component parts i.e. concrete, steel etc.

For repowering are bigger foundations required?

- For larger rotors, new technologies and concepts then foundations may have to increase in size.

As a turbine manufacture what have you done in other markets regarding repowering? Is there a demand overseas?

Repowering is a main area of business.

Repowering is currently taking place in the USA and Germany where turbines were installed in the 80s/90s.

A life extension programme is offered to extend the life of a turbine from 20-30 years thus reducing the investment for the wind farms.

Looking forward 20 years what do you think will be the size and rating for a turbine?

Depends on the trend and what the wind industry will be like.

Appendix 2: How section 7 was researched.

The search for material to inform this environmental analysis was undertaken using the search engine 'Web of Science Service for UK Education' (<http://wok.mimas.ac.uk/>). This provides access to multiple data foundations of research publications going back to 1970, and additionally books and patents. For ease of reading established and accepted environmental understanding is not referenced (e.g. the ecosystem services a vegetated soil provides) but references are introduced to support less common or unusual considerations. Where possible open access publications have been referenced.

There is very little published on the environmental consideration of turbine repowering, and only two publications (as of Jan. 2017) that document field studies in repowered sites. One focussed on whether fewer larger turbines could impact bird mortality (it is possible it could reduce mortality; Everaert, 2014) or affect the diversity in flying assemblages of bats (some bats species may be sensitive to repowering; Ferri et al, 2016) and so did not contain material directly relevant to turbine foundation reuse.

Thus, additionally commissioned research and internet search engines were used to consider the 'grey' literature, with commissioned agency research considered reliable (e.g. Lindsay and Clough, 2015) as this would have had internal and possibly external review, and subsequent versions may have been revised in response to stakeholder feedback and observations of inaccuracy. Developers were also contacted to ask for information about repowered sites or restored sites undertaken as part of wind farm habitat management plans that may offer further insight.

Finally, in lieu of explicitly relevant research, the authors' understanding of the environmental response to initial wind farm construction has been used to inform consideration of environmental response to repowering, drawing particularly on peer-reviewed review journal articles that seek to assess how cohesive the environmental response given there can be site-specific variation.

Appendix 3: Calculations behind the summary tables in section 7

The calculations in section 7 compare the construction of a reengineered foundations to the use of two separate foundations to repower to provide an estimate of the difference in quantities (for example, of soil required for restoration or concrete required in construction) in the two approaches or the surface area disturbance during excavation. As the alternative being considered is the reengineered foundation, the difference in the two approaches is expressed as a % of the quantities for the two-foundation repowering scenario:

$$\text{difference} = \frac{\text{quantities/area for reengineered foundations} - \text{quantities/area for two foundations}}{\text{quantities/area for two foundations}} \%$$

A +ve value means that that more material is removed / needed for restoration / required in construction / a larger surface area disturbed if a reengineered foundation is implemented, than constructing two foundations. A -ve value means quantities are larger or a smaller surface area is disturbed if two foundations were adopted to repower.

Three different scenarios of soil disturbance are considered and are calculated for only 1m depth of foundation restoration:

1. The volume of soil required for end of life reinstatement only (Table A3-1);
 2. The amount of soil required for end of life reinstatement only *and* the amount of soil that was excavated and reinstated (Table A3-2);
 3. The volume of soil required for end of life reinstatement only, *and* the amount of soil that was excavated and reinstated, *and* the volume of soil that was excavated and removed (Table A3-3).
- Additionally, the quantities of materials required for a reengineered turbine base or for two foundations have been calculated (Table A3-4) and surface area disturbed and the perimeter drainage for repowering with a new foundation versus reengineering the existing foundation are considered (Table A3-5). This does not draw on values in the ARUP report, but uses the drawings in Appendix 4 and thus the logic behind this is as follows.

All calculations use the estimates in the Arup analysis (section 5 of this report) except for Table A3-5 which uses dimensions in Appendix 4. Thus, the logic behind these estimates is as following:

Foundation not reused: area reinstated & area restored at end-of-life

1. The first excavation creates a surface area disturbance equal to the area of excavation. These are the ARUP diagrams that are coded -1 (Appendix 4 Arup appendix A)
2. However, not all this area has foundation at the surface so after excavation there is an area which is reinstated, and an area that represents the foundation and eventually would be restored should the foundation not be reengineered. The area that will need to be restored at end of life is depicted in diagram labelled -1-R (Appendix 4 Arup appendix C).
3. Thus, the area immediately restored can be calculated by subtracting the end of life restoration (-1-R) from the total excavation surface area (-1).

Foundation reused: area reinstated & area restored at end-of-life

1. Following on from above, if a foundation was to be reengineered a new excavation would be made, and given the larger dimensions of the new foundation, the surface area

disturbance would be greater and encompass the original excavation. The reengineered foundation is shown in Arup diagrams that link the change in size e.g. 0.85MW to 2.3 MW is labelled 0850-2300-1 (Appendix 4 Arup appendix B)

2. This too would involve some restoration before end of life.
3. To assess if this was more problematic than two new foundations, the dimensions of disturbance here would have to be compared to two new foundation (diagrams -1, Appendix 4 Arup Appendix A).

Thus, we calculate the area of two foundations (and associated reinstatement, restoration; - the appropriate -1 drawings) and compare that to the reengineered foundation (e.g. 0850-2300-1).

In all the following tables the cells in **blue** are those referred to in example calculations.

If the excel file behind these calculations are not on the [project web-site](#), they can be requested from Susan Waldron or Kenny Taylor. However sufficient information exists in these tables for the calculations to be reproduced without these.

Table A3-1: Comparison of soil required for reinstatement only. The column entitled 'Repowering with a new foundation' represents the volume for two separate foundations e.g. 0.85MW (165 m³) and 3.2MW (331 m³) = 496 m³.

From Section 5 Table 3:

Drawing Ref: new foundations	Required for end of life reinstatement (m ³)
Construct 0.85MW 0850-1	165
Construct 2.3MW 2300-1	323
Construct 3.2MW 3200-1	331
Construct 5.0MW 5000-1	722

From Section 5 Table 5

Option	Drawing Ref	Required for end of life reinstatement (m ³)	Repowering with a new foundation (m ³)	% difference for reengineered than new foundation
0.85MW to 3.2MW	0850-3200-01	903	496	82
2.3MW to 2.3MW Option 1	2300-2300-01	648	646	0
2.3MW to 2.3MW Option 2	2300-2300-02	595	646	-8
2.3MW to 3.2MW Option 1	2300-3200-01	903	654	38
2.3MW to 3.2MW Option 2	2300-3200-02	877	654	34
2.3MW to 3.2MW Option 3	2300-3200-03	927	654	42
2.3MW to 3.2MW Option 4	2300-3200-04	903	654	38
2.3MW to 3.2MW Option 5	2300-3200-05	903	654	38
2.3MW to 5.0MW	2300-5000-01	1129	1045	8

Table A3-2: Comparison of soil required for reinstatement *and* the volumes of soil that was excavated and reinstated. Thus, the columns entitled 'Total volume of soil disturbed with R-foundation' and 'Repowering with a new foundation' compare scenarios as in Table A3-1, but uses the sum of quantities in 'Excavated and reinstated' and in 'Required for end of life reinstatement'. Further, Table 4 does not include the original foundation quantities and so these must be added in. For example, the 0.85 to 3.2 MW repowering has 373 m³ excavated and reinstated and 903 m³ required to be found for reinstatement (which would mean possible disturbance of another resource), but additionally 374 m³ had also been excavated and reinstated in construction the 0.85 MW foundation and so this must be included totalling 1650 m³. The brighter blue cells show the quantities for two foundations.

Option & Drawing Ref (from Section 5 Table 3)	Excavated and reinstated during construction (m ³)	Required for end of life reinstatement (m ³)			
Construct 0.85MW 0850-1	374	165			
Construct 2.3MW 2300-1	750	323			
Construct 3.2MW 3200-1	902	331			
Construct 5.0MW 5000-1	1219	722			
Reengineered option (from Section 5 Table 5)	Excavated and reinstated during construction (m ³)	Required for end of life reinstatement (m ³)	Total volume of soil disturbed with R-foundation	Repowering with a new foundation (m ³)	% difference for reengineered than new foundation
0.85MW to 3.2MW	373	903	1650	1772	-7
2.3MW to 2.3MW Option 1	635	648	2033	2146	-5
2.3MW to 2.3MW Option 2	613	595	1958	2146	-9
2.3MW to 3.2MW Option 1	731	903	2536	2306	10
2.3MW to 3.2MW Option 2	721	877	2500	2306	8
2.3MW to 3.2MW Option 3	739	927	2568	2306	11
2.3MW to 3.2MW Option 4	803	903	2608	2306	13
2.3MW to 3.2MW Option 5	731	903	2536	2306	10
2.3MW to 5.0MW	804	1129	3152	3014	5

Table A3-3: Comparison of soil required for reinstatement *and* the volumes of soil that was excavated and reinstated *and* the volume of soil that was excavated and removed. Thus, the columns entitled 'Total volume of soil disturbed with R-foundation' and 'Repowering with a new foundation' compare scenarios as in Table A3-1 but use the sum of all for a given foundation. As before section 5 Arup Table 5 does not include the original foundation quantities and so these must be added in. For example, the 0.85 to 3.2 MW repowering has 373 m³ excavated and reinstated, 738 m³ excavated and removed and 903 m³ required to be found for reinstatement, but additionally in construction the existing 0.85 MW foundation 374 m³ and 165 m³ had also been respectively excavated and reinstated, or removed, and so this must be included, totalling 2553 m³. The brighter blue cells show the quantities for two foundations.

Option & Drawing Ref (from section 5 Table 3)	Excavated and reinstated during construction (m ³)	Excavated and removed during construction (m ³)	Required for end of life reinstatement (m ³)			
Construct 0.85MW 0850-1	374	165	165			
Construct 2.3MW 2300-1	750	323	323			
Construct 3.2MW 3200-1	902	331	331			
Construct 5.0MW 5000-1	1219	722	722			
Reengineered option (from section 5 Table 5)	Excavated and reinstated during construction (m ³)	Excavated and removed during construction (m ³)	Required for end of life reinstatement (m ³)	Total volume of soil disturbed with R-foundation	Repowering with a new foundation	% difference for reengineered than new foundation
0.85MW to 3.2MW	373	738	903	2553	2268	13
2.3MW to 2.3MW Option 1	635	325	648	2681	2792	-4
2.3MW to 2.3MW Option 2	613	272	595	2713	2792	-3
2.3MW to 3.2MW Option 1	731	581	903	3288	2960	11
2.3MW to 3.2MW Option 2	721	554	877	3225	2960	9
2.3MW to 3.2MW Option 3	739	605	927	3344	2960	13
2.3MW to 3.2MW Option 4	803	581	903	3360	2960	14
2.3MW to 3.2MW Option 5	731	581	903	3288	2960	11
2.3MW to 5.0MW	804	806	1129	3812	4059	-6

Table A3-4: Comparison of quantities required for repowering with a new foundation versus reengineering the existing foundation. The first page here are the quantities, and the calculated differences are overleaf. Examples are given in shades of blue. For example, the total concrete volume for a reengineered foundation includes the volume concrete that is reinforced (1065 m³) and the mass concrete (610 m³) of the new design but also contains the reinforced concrete from the original foundation (130 m³) = 1805 m³. The new foundation does not require mass concrete so only the reinforced volumes are considered. For example, repowering from 2.3 MW (423 m³) to 5.0 MW (1398 m³) uses 1821 m³ of reinforced concrete. Similar logic follows for other quantities.

Option & Drawing Ref (from section 5 Arup Table 2)	Reinforced Concrete (m ³)	Reinforcing Steel (tonnes)	Course Aggregate for Concrete (m ³)		Structural Fill Volume (m ³)	Total Excavation volume (m ³)
Construct 0.85MW 0850-1	130	19	65		203	1311
Construct 2.3MW 2300-1	423	60	212		373	3792
Construct 3.2MW 3200-1	656	92	328		381	4852
Construct 5.0MW 5000-1	1398	196	699		795	8343
Option (from section 5 Arup Table 4)	Reinforced Concrete (m ³)	Reinforcing Steel (tonnes)	Mass Concrete Volume (m ³)	Course Aggregate for Concrete (m ³)	Structural Fill Volume (m ³)	Excavation volume (m ³)
0.85MW to 3.2MW	1065	150	610	1057	524	3076
2.3MW to 2.3MW Option 1	708	100	390	530	127	3869
2.3MW to 2.3MW Option 2	631	89	309	451	81	3556
2.3MW to 3.2MW Option 1	1097	154	795	927	354	5356
2.3MW to 3.2MW Option 2	1056	148	753	885	331	5204
2.3MW to 3.2MW Option 3	969	136	834	882	376	5495
2.3MW to 3.2MW Option 4	1097	154	2047	1002	403	5666
2.3MW to 3.2MW Option 5	1057	149	795	907	354	5356
2.3MW to 5.0MW	1817	255	1165	1665	558	6642

	Concrete			Steel		
Option	Repowering with a new foundation	Total concrete volume reengineered foundation	% difference for reengineered than new foundation	Repowering with a new foundation	Total steel mass reengineered foundation	% difference for reengineered than new foundation
0.85MW to 3.2MW	786	1805	130	111	169	52
2.3MW to 2.3MW Option 1	846	1521	80	120	160	33
2.3MW to 2.3MW Option 2	846	1363	61	120	149	24
2.3MW to 3.2MW Option 1	1079	2315	115	152	214	41
2.3MW to 3.2MW Option 2	1079	2232	107	152	208	37
2.3MW to 3.2MW Option 3	1079	2226	106	152	196	29
2.3MW to 3.2MW Option 4	1079	3567	231	152	214	41
2.3MW to 3.2MW Option 5	1079	2275	111	152	209	38
2.3MW to 5.0MW	1821	3405	87	256	315	23
	Aggregate			Structural fill		
Option	Repowering with a new foundation	Total aggregate mass reengineered foundation	% difference for reengineered than new foundation	Repowering with a new foundation	Total structural fill mass reengineered foundation	% difference for reengineered than new foundation
0.85MW to 3.2MW	393	1122	185	584	727	24
2.3MW to 2.3MW Option 1	424	742	75	746	500	-33
2.3MW to 2.3MW Option 2	424	663	56	746	454	-39
2.3MW to 3.2MW Option 1	540	1139	111	754	727	-4
2.3MW to 3.2MW Option 2	540	1097	103	754	704	-7
2.3MW to 3.2MW Option 3	540	1094	103	754	749	-1
2.3MW to 3.2MW Option 4	540	1214	125	754	776	3
2.3MW to 3.2MW Option 5	540	1119	107	754	727	-4
2.3MW to 5.0MW	911	1877	106	1168	1353	16

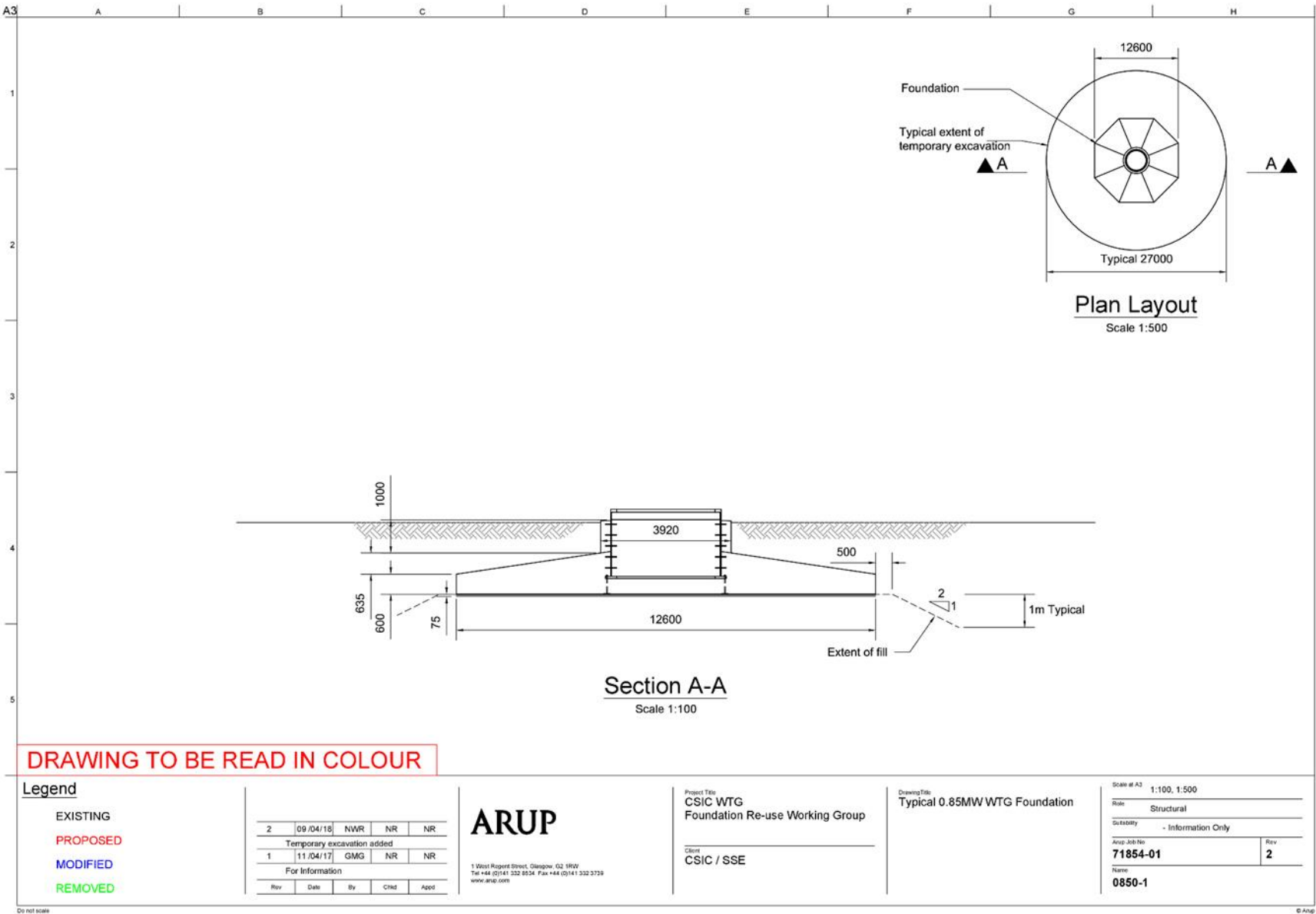
Table A3-5: Comparison of surface area disturbed and perimeter drainage for repowering with a new foundation versus reengineering the existing foundation. The first column is the diameter of the total area excavated (from which part will be reinstated when operational and the remainder restored when no longer operational). This can be compared to two equivalent foundations. For example (blue), the reengineered foundation results in less surface area disturbance and consequently drainage perimeter is smaller than constructing two new foundations. However, the reengineered foundation has less total restoration than two new foundations and for most scenarios more surface must be restored at the decommissioning stage. Thus, whilst the area disturbed on the surface is smaller, less soil is reinstated after construction during the operational period, so more surface needs to be restored at the end of the foundation lifetime.

Drawing Ref Single foundation	Excavated outer diameter (m)	Surface area (m ²)	Perimeter (m)	Reinstated at commissioning (m ²)	Restored at end of life (m ²)	
0.85MW 0850-1	27.00	572.56	84.82	381.42	191.13	
2.3MW 2300-1	38.45	1161.13	120.79	789.59	371.54	
3.2MW 3200-1	41.10	1326.70	129.12	946.57	380.13	
5.0MW 5000-1	51.20	2058.87	160.85	1264.65	794.23	
Reengineered (from Arup Appendix 4)	Excavated outer diameter (m)	Surface area (m ²)	Perimeter (m)	Reinstated at commissioning (m ²)	Restored at end of life (m ²)	Excavation area for 2 foundations (m ²)
0.85MW to 3.2MW	41.8	1372.61	131.33	388.38	984.23	1899.26
2.3MW to 2.3MW Option 1	41.9	1378.85	131.63	662.54	716.31	2322.27
2.3MW to 2.3MW Option 2	40.7	1301.00	127.86	640.48	660.52	2322.27
2.3MW to 3.2MW Option 1	47.1	1742.34	147.97	758.11	984.23	2487.84
2.3MW to 3.2MW Option 2	46.6	1705.54	146.40	748.92	956.62	2487.84
2.3MW to 3.2MW Option 3	47.6	1775.79	149.38	766.38	1009.41	2487.84
2.3MW to 3.2MW Option 4	48.1	1817.11	151.11	718.52	1098.58	2487.84
2.3MW to 3.2MW Option 5	47.1	1742.34	147.97	758.11	984.23	2487.84
2.3MW to 5.0MW	51.1	2050.84	160.54	831.62	1219.22	3220.01

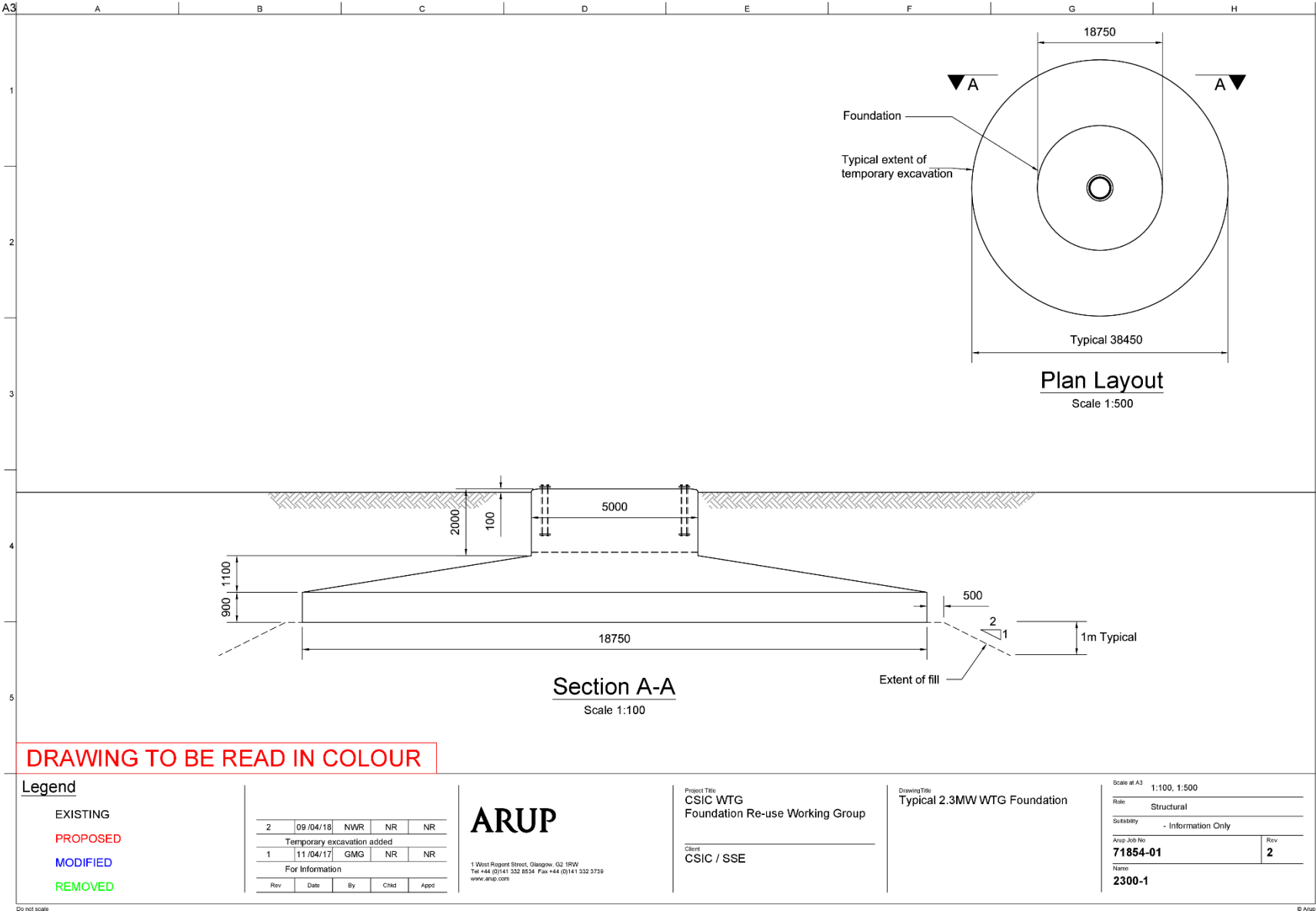
Reengineered vs. two foundations (denominator)	% diff surface area	Perimeter for two foundations (m)	% diff perimeter	% diff surface area for reinstated	% diff surface area for restored
0.85MW to 3.2MW	-27.7	213.94	-38.6	-70.8	72.3
2.3MW to 2.3MW Option 1	-40.6	241.59	-45.5	-58.0	-3.6
2.3MW to 2.3MW Option 2	-44.0	241.59	-47.1	-59.4	-11.1
2.3MW to 3.2MW Option 1	-30.0	249.91	-40.8	-56.3	30.9
2.3MW to 3.2MW Option 2	-31.4	249.91	-41.4	-56.9	27.3
2.3MW to 3.2MW Option 3	-28.6	249.91	-40.2	-55.9	34.3
2.3MW to 3.2MW Option 4	-27.0	249.91	-39.5	-58.6	46.2
2.3MW to 3.2MW Option 5	-30.0	249.91	-40.8	-56.3	30.9
2.3MW to 5.0MW	-36.3	281.64	-43.0	-59.5	4.6

Appendix 4: ARUP foundation designs and report verification
(overleaf)

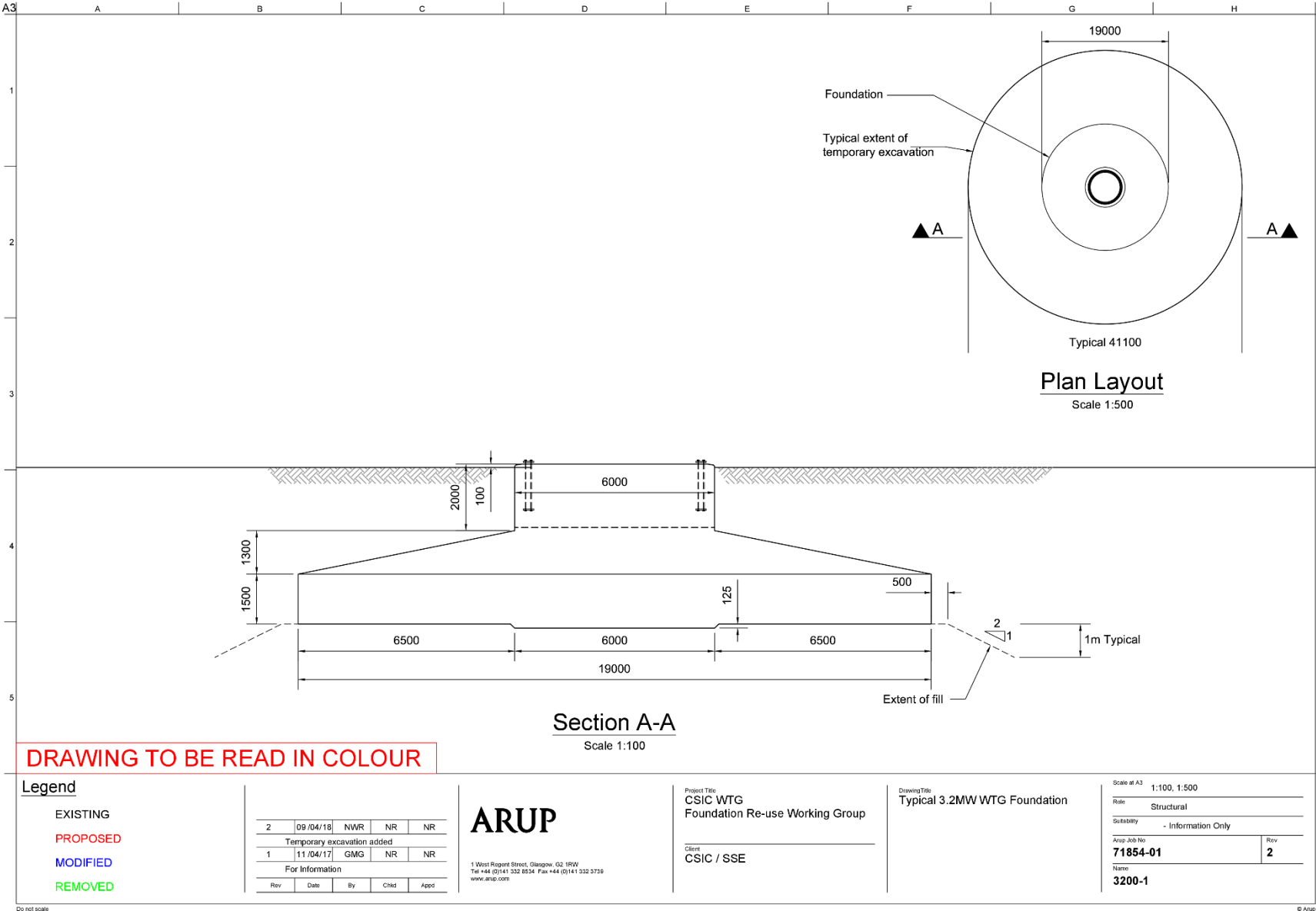
Appendix 4: Arup Appendix A Typical New Build Foundations



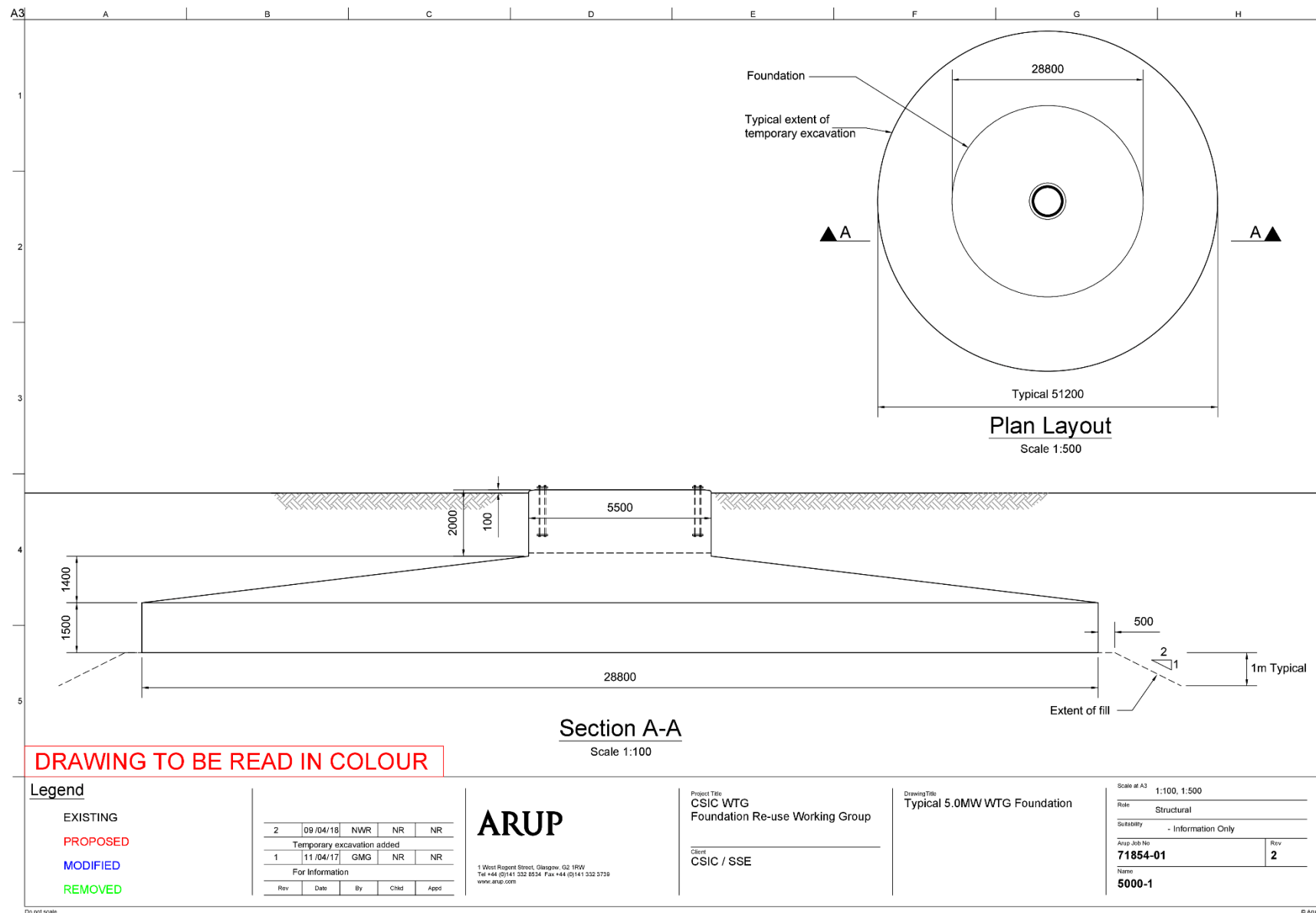
Appendix 4: Arup Appendix A Typical New Build Foundations



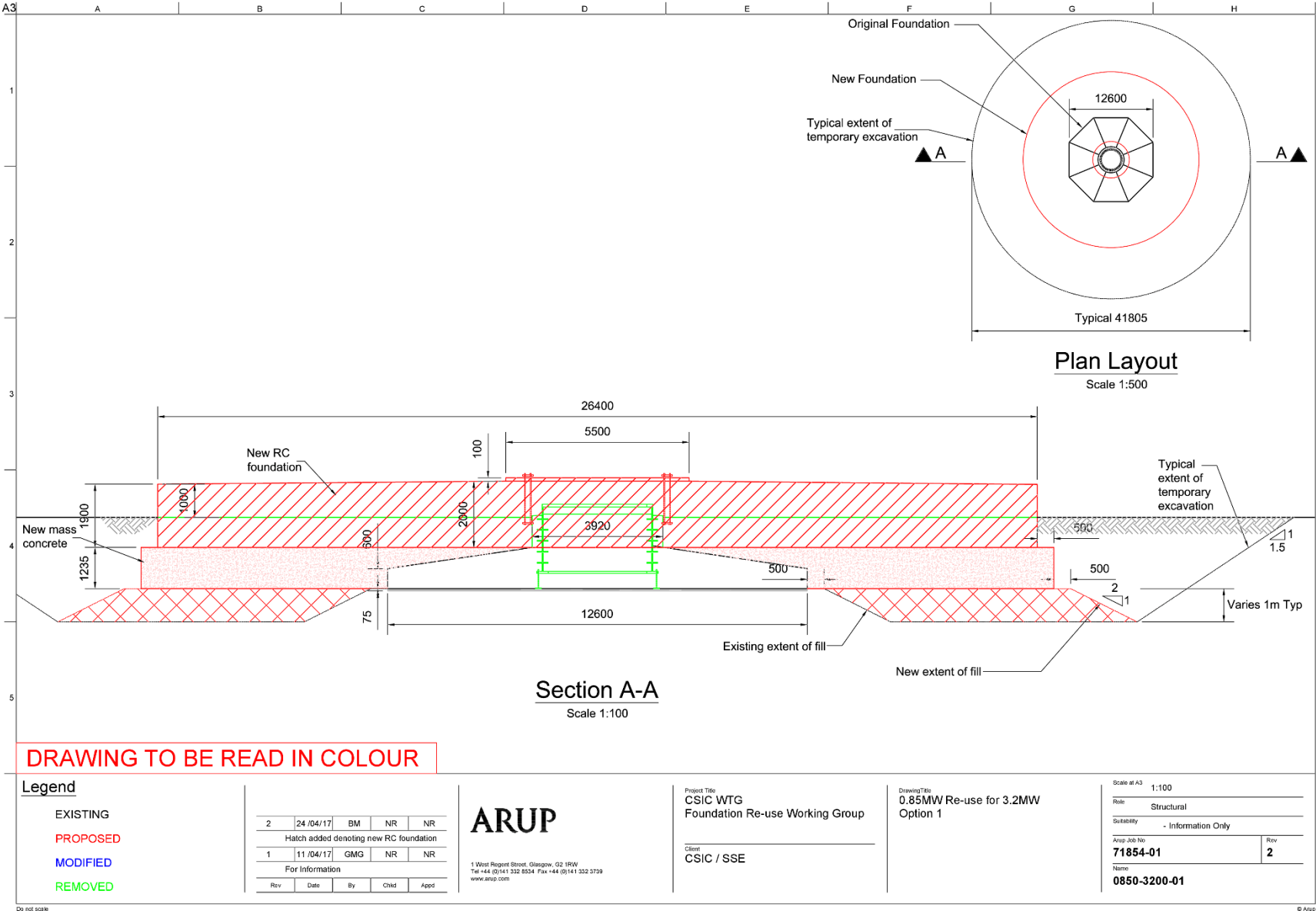
Appendix 4: Arup Appendix A Typical New Build Foundations



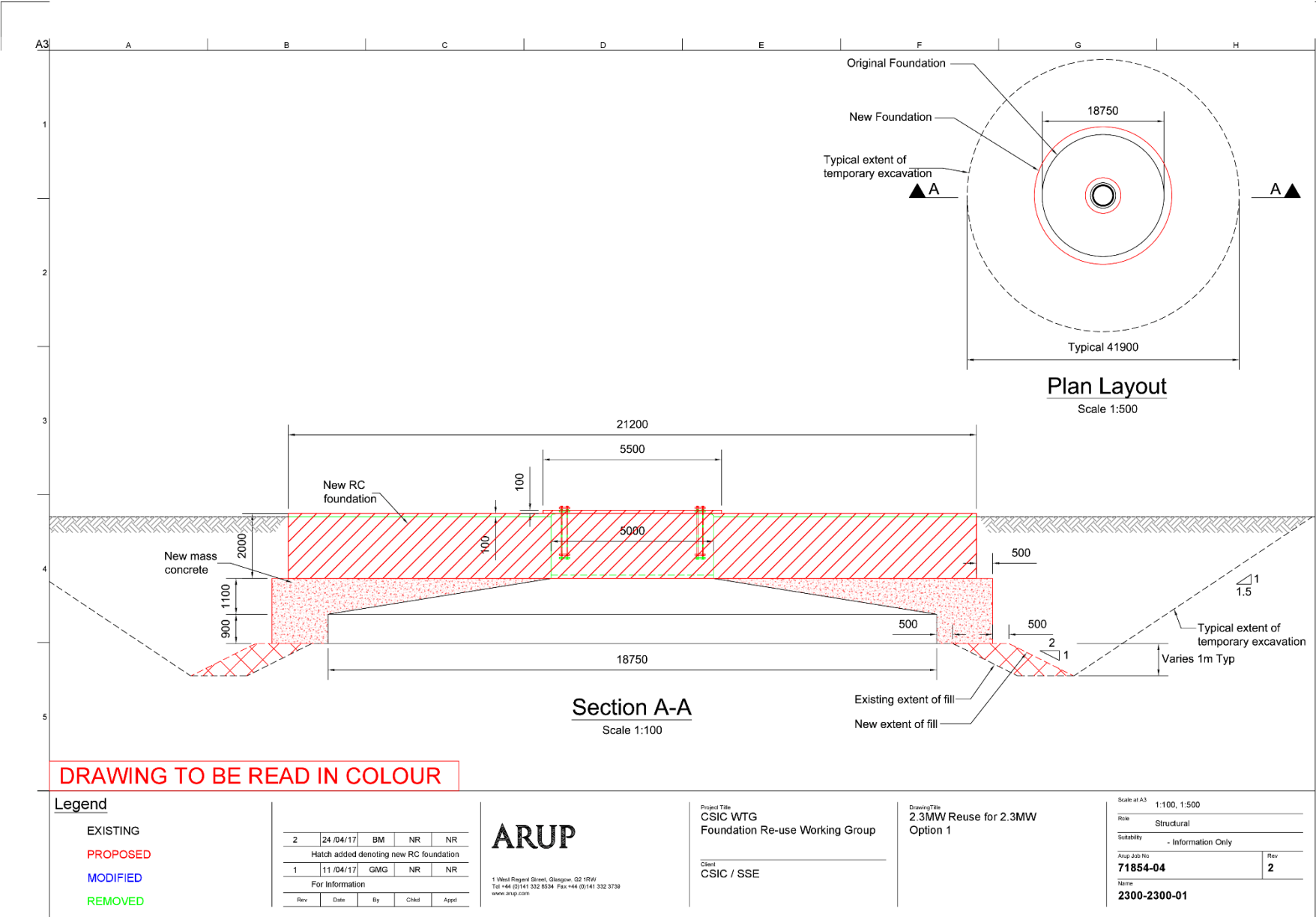
Appendix 4: Arup Appendix A Typical New Build Foundations



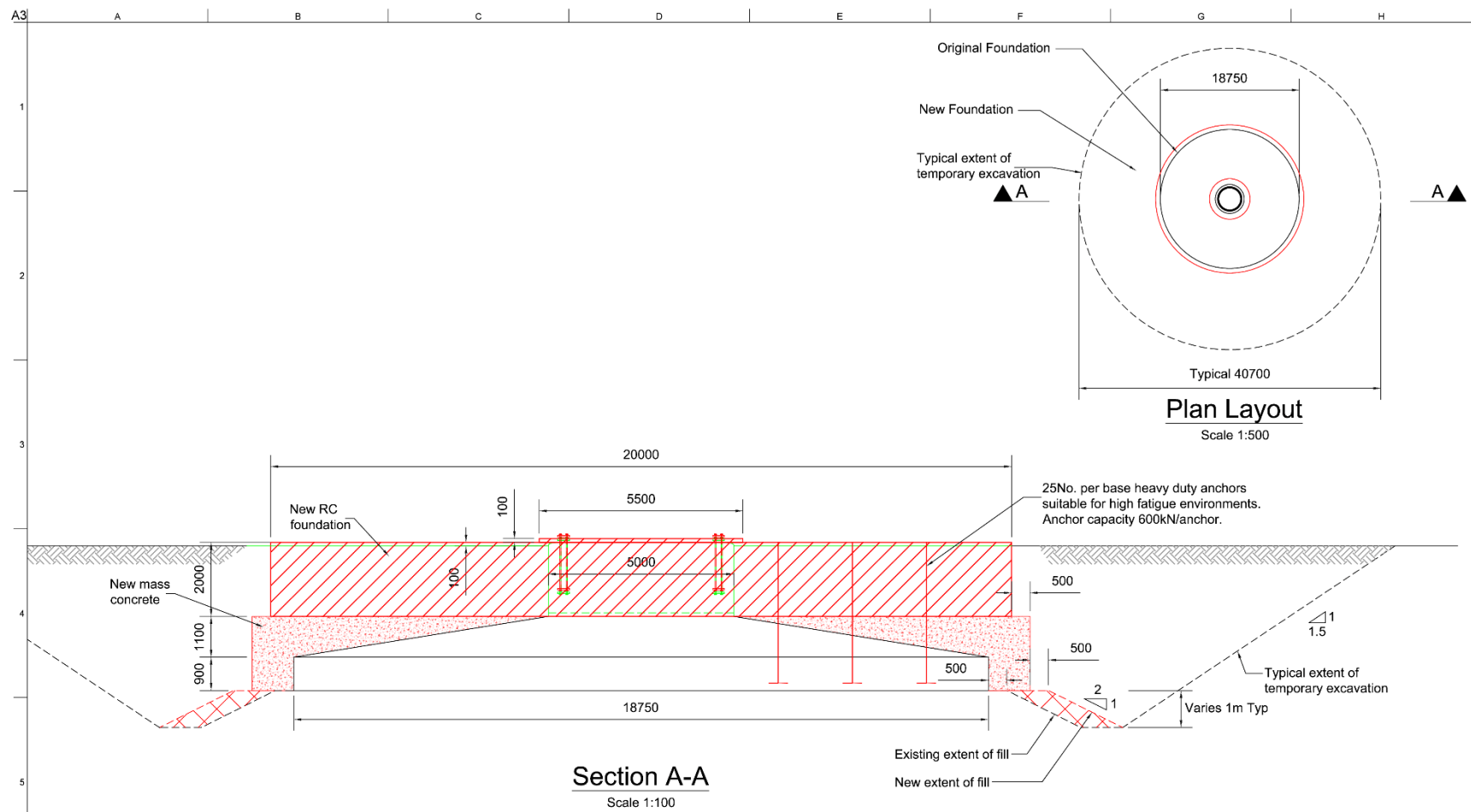
Appendix 4: Arup Appendix B Foundation Reuse Options



Appendix 4: Arup Appendix B Foundation Reuse Options



Appendix 4: Arup Appendix B Foundation Reuse Options



DRAWING TO BE READ IN COLOUR

Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

2	24 /04/17	BM	NR	NR
Hatch added denoting new RC foundation				
1	11 /04/17	GMG	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

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Client
CSIC / SSE

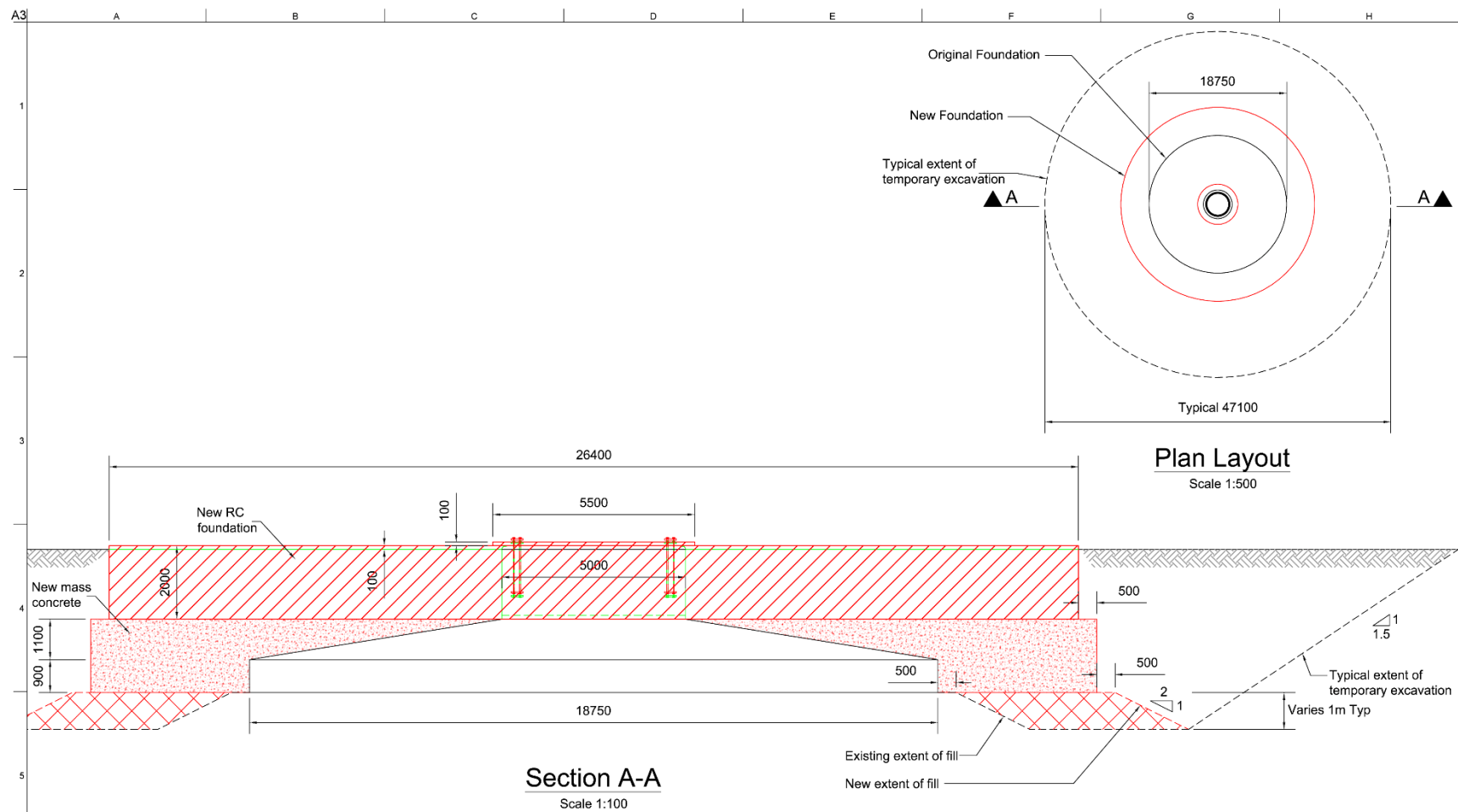
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Option 2

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Suitability	- Information Only
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Name	2300-2300-02
Rev	2

Do not scale

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Appendix 4: Arup Appendix B Foundation Reuse Options



DRAWING TO BE READ IN COLOUR

Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

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Hatch added denoting new RC foundation				
1	11 /04/17	GMG	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

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Drawing Title
2.3MW Reuse for 3.2MW
Option 1

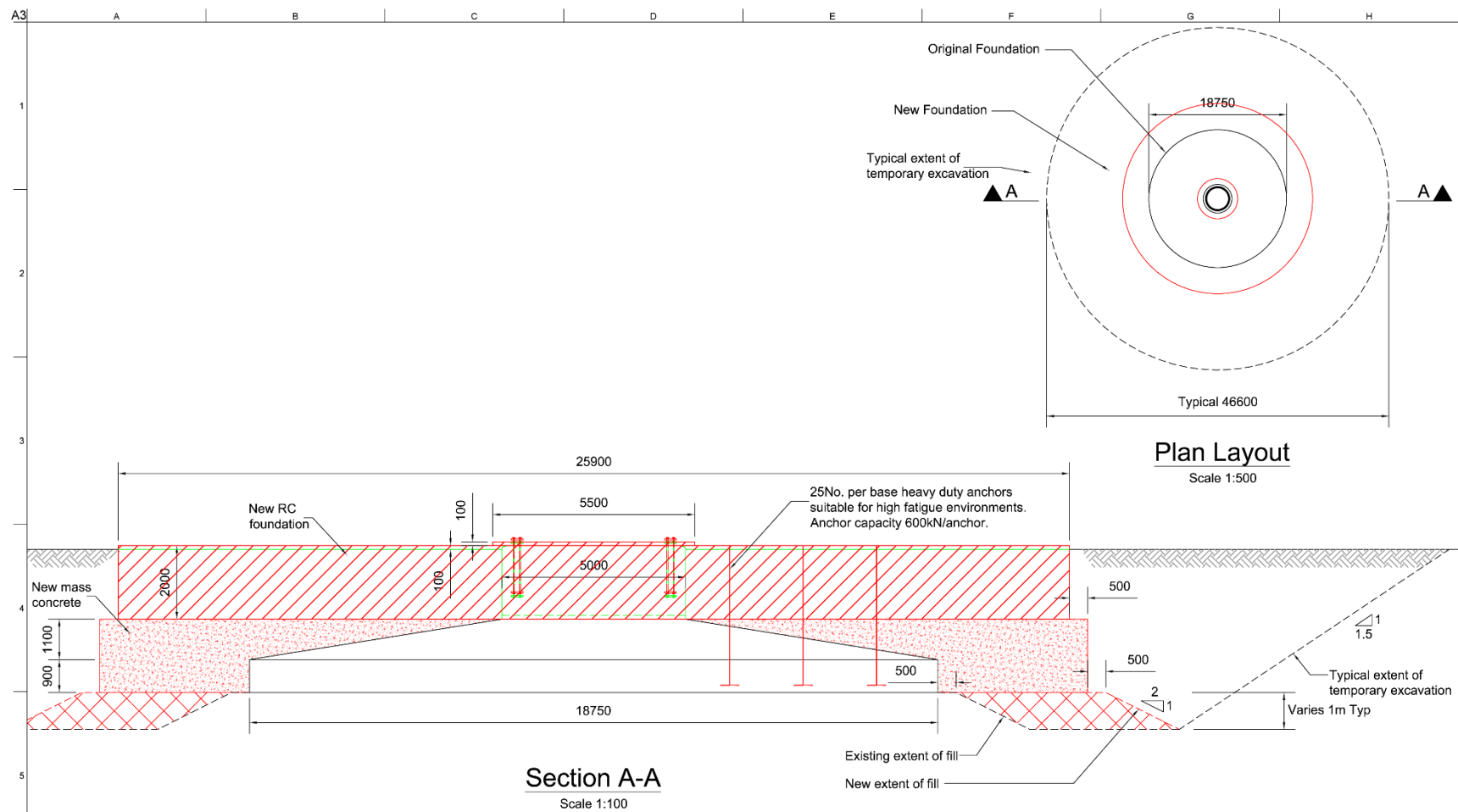
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Role
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Suitability
- Information Only
Arup Job No
71854-01
Name
2300-3200-01
Rev
2

Do not scale

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Appendix 4: Arup Appendix B Foundation Reuse Options



DRAWING TO BE READ IN COLOUR

Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

2	24 /04/17	BM	NR	NR
Hatch added denoting new RC foundation				
1	11 /04/17	GMG	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

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Drawing Title
2.3MW Reuse for 3.2MW
Option 2

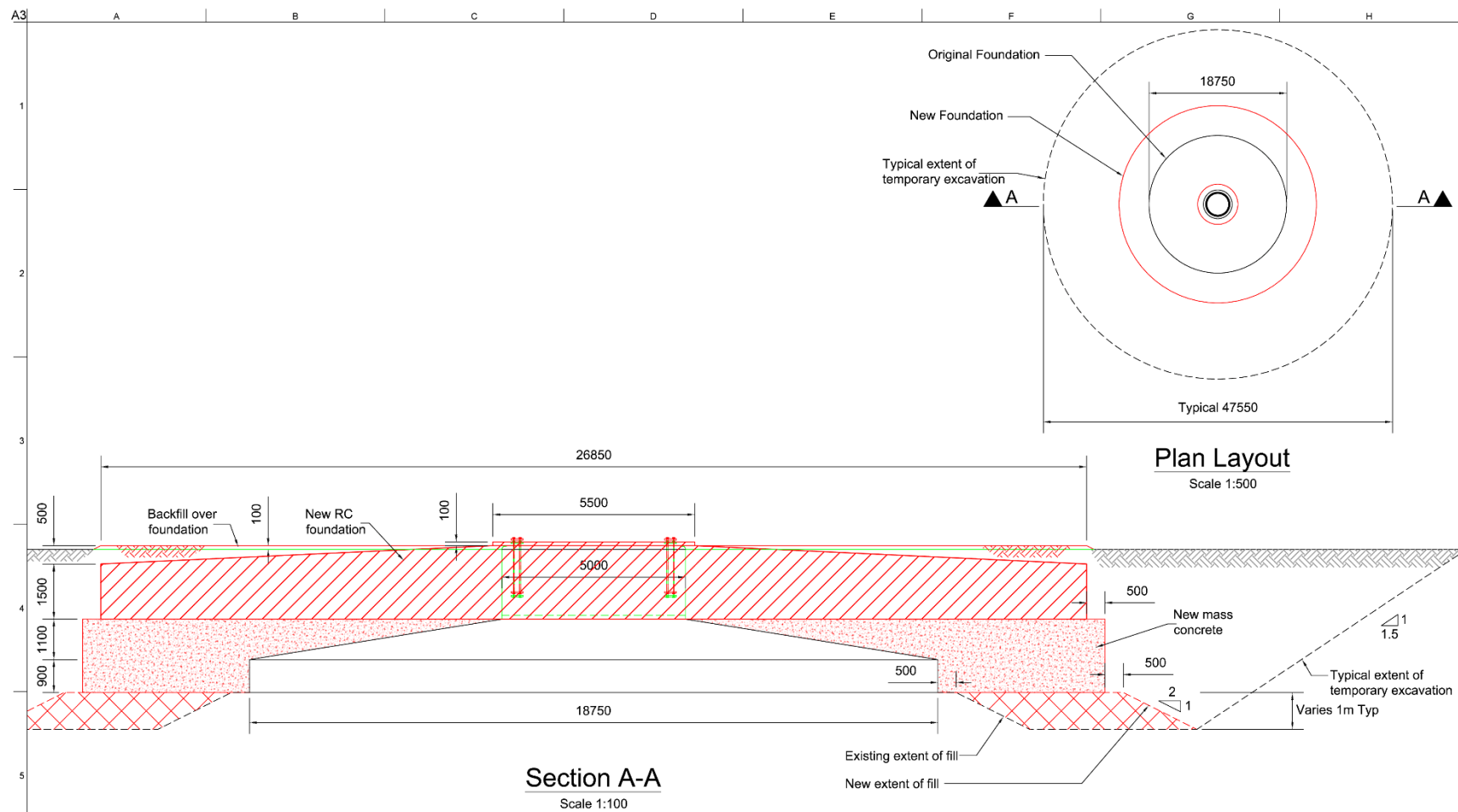
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Role	Structural
Suitability	- Information Only
Appr Job No	71854-01
Name	2300-3200-02
Rev	2

Do not scale

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Appendix 4: Arup Appendix B Foundation Reuse Options



DRAWING TO BE READ IN COLOUR

Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

2	24 /04/17	BM	NR	NR
Hatch added denoting new RC foundation				
1	11 /04/17	GMG	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

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Drawing Title
2.3MW Reuse for 3.2MW
Option 3

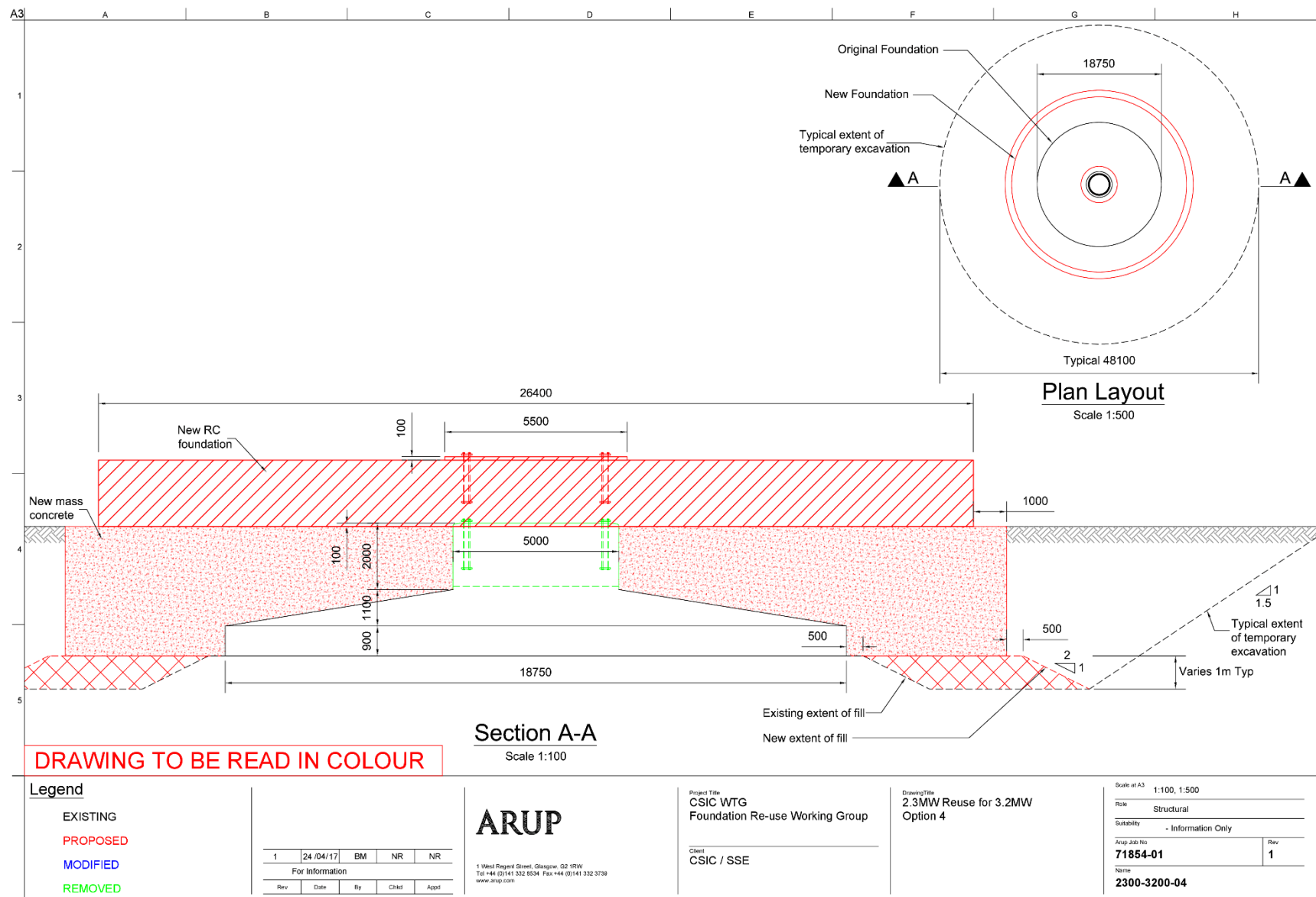
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Rev	2

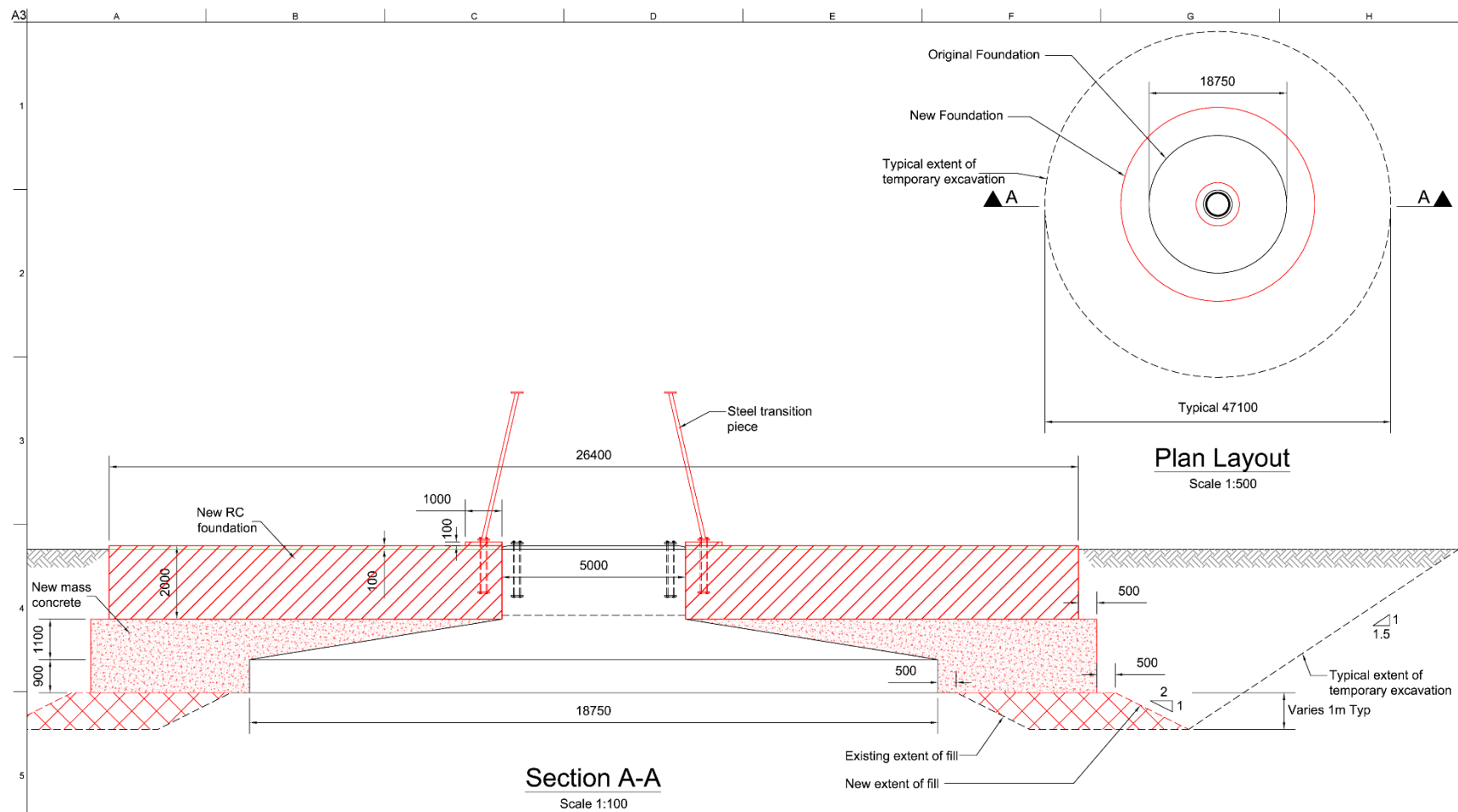
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Appendix 4: Arup Appendix B Foundation Reuse Options



Appendix 4: Arup Appendix B Foundation Reuse Options



DRAWING TO BE READ IN COLOUR

Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

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For Information				
Rev	Date	By	Chkd	Appd

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Drawing Title
2.3MW Reuse for 3.2MW
Option 5

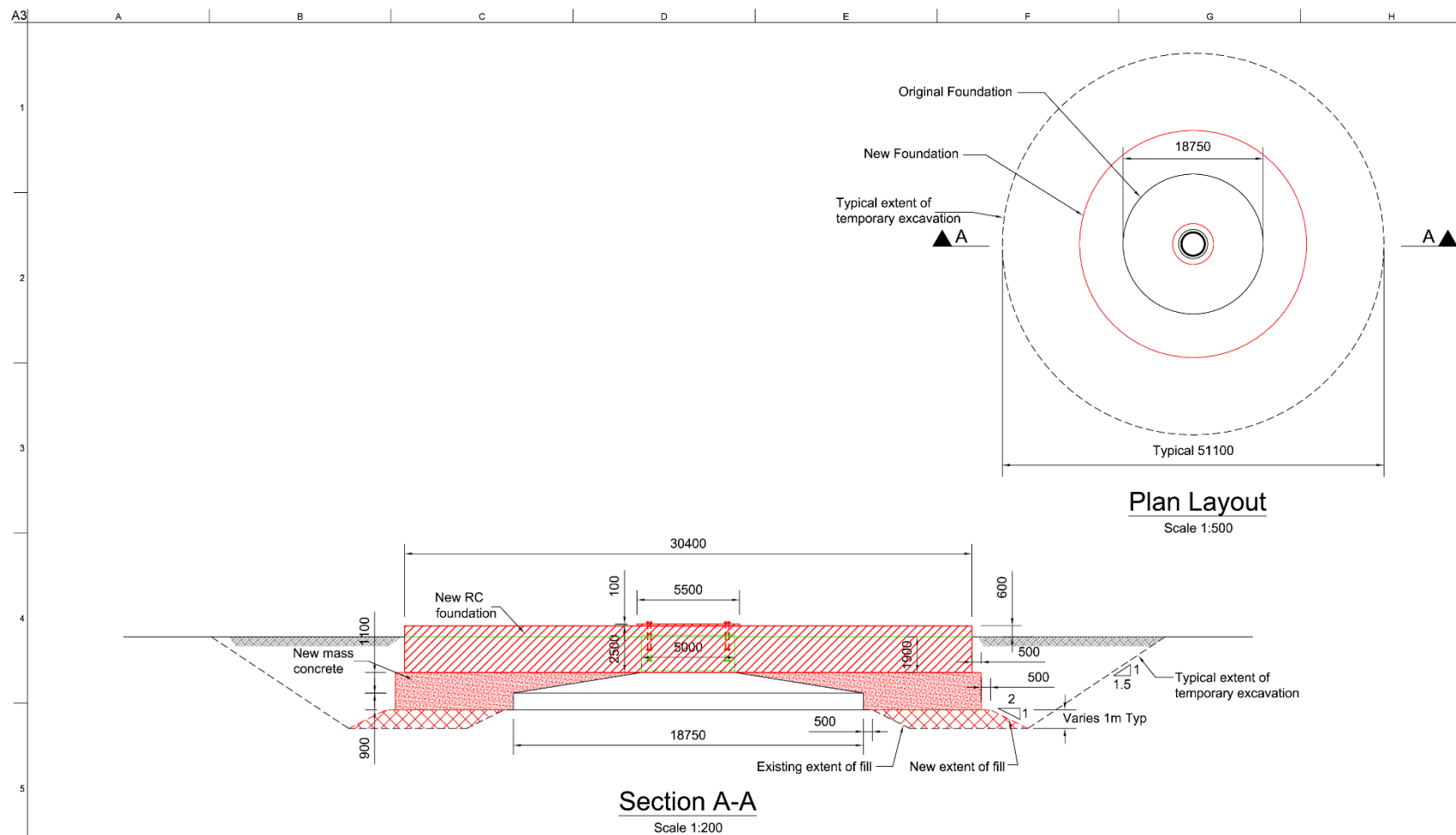
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Role
Structural
Suitability
- Information Only
Arup Job No
71854-01
Name
2300-3200-05
Rev
1

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Legend

EXISTING
PROPOSED
MODIFIED
REMOVED

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Hatch added denoting new RC foundation				
1	11 /04/17	GMG	NR	NR
For Information				
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Drawing Title
2.3MW Reuse for 5.0MW
Option 1

Scale at A3 1:200, 1:500

Role	Structural
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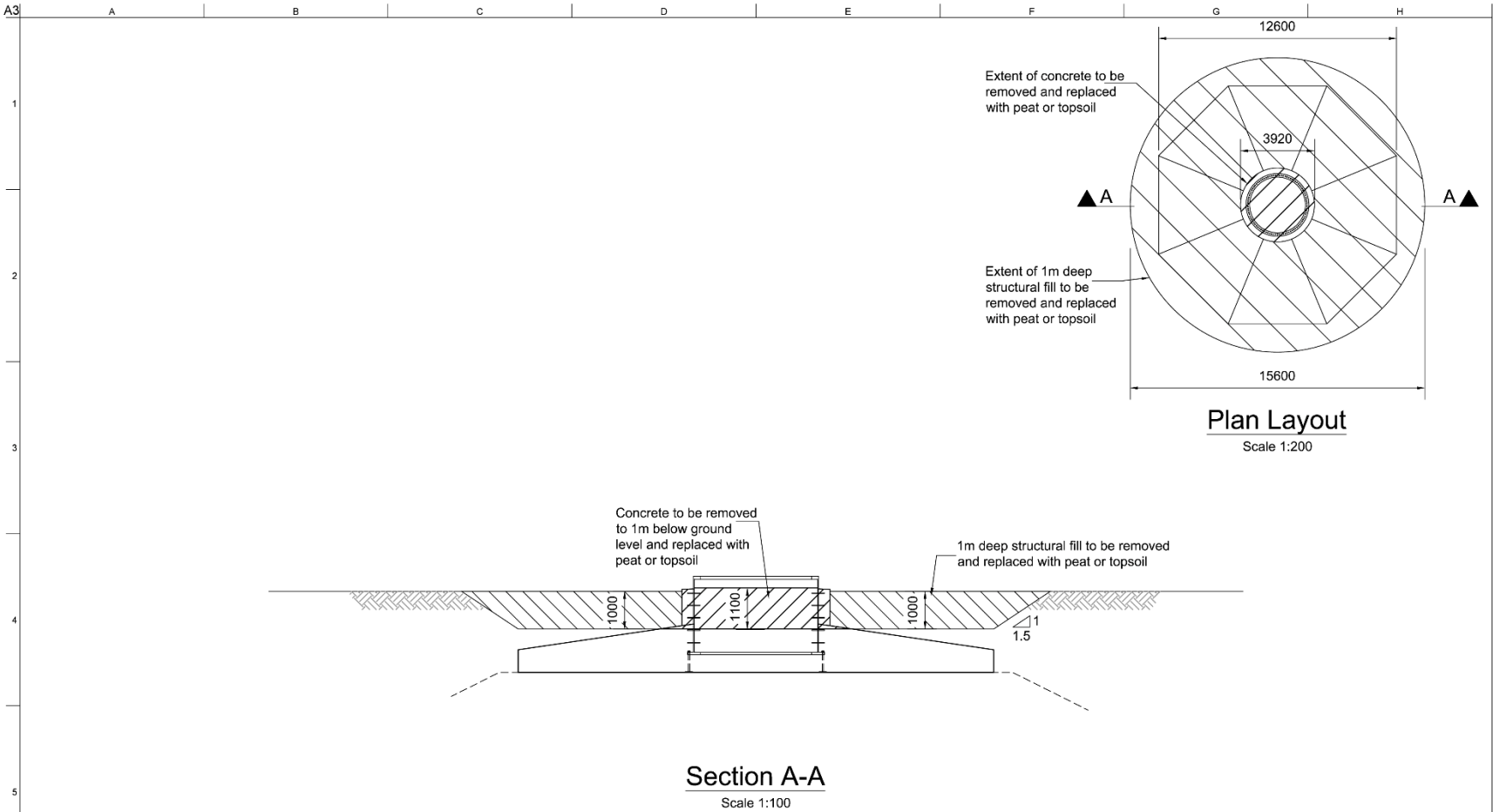
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Arup Job No
71854-01

Name
2300-5000-01

Rev	2
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Appendix 4: Arup Appendix C Reinstatement Works



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1	24 /04/17	BM	NR	NR
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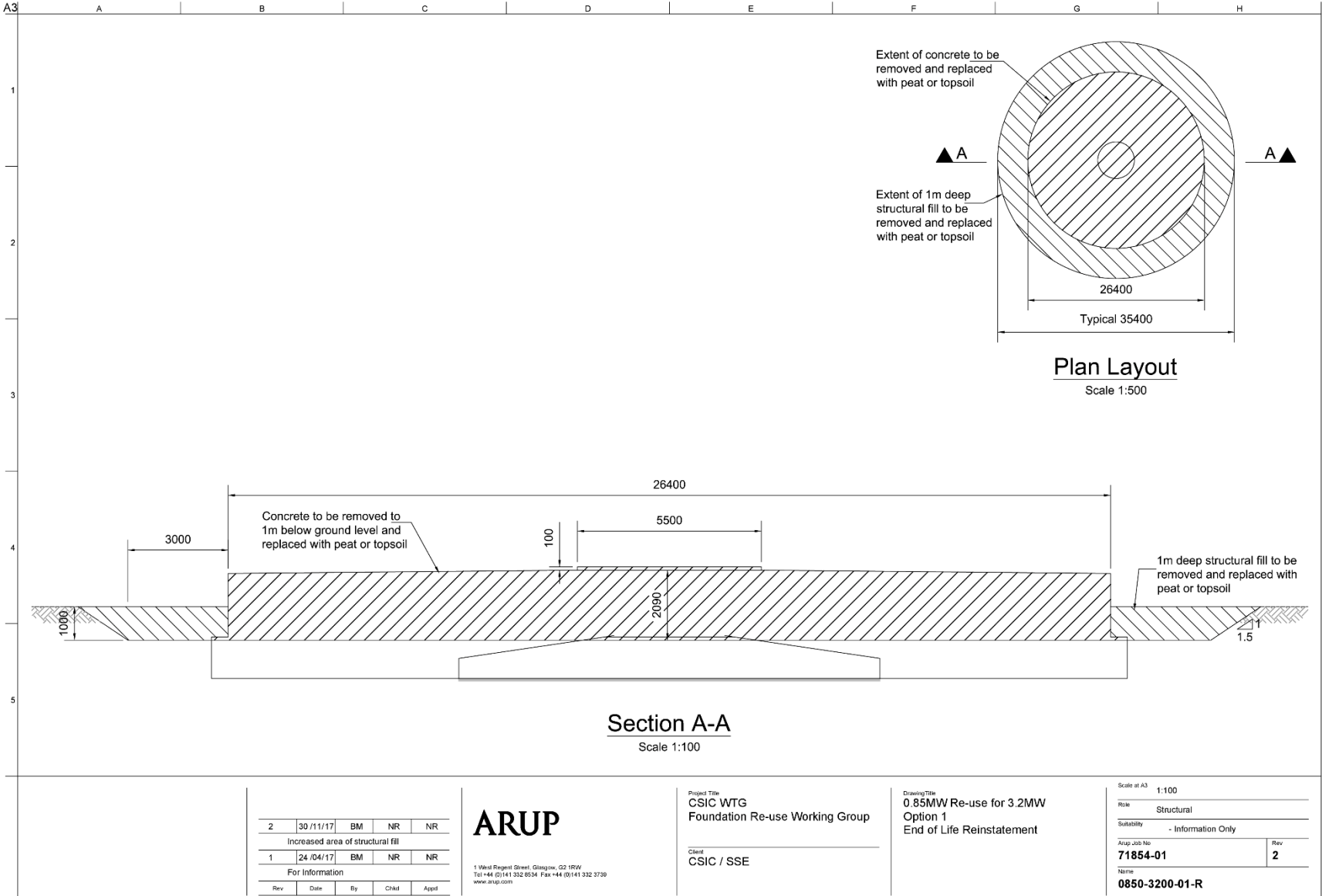
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CSIC WTG
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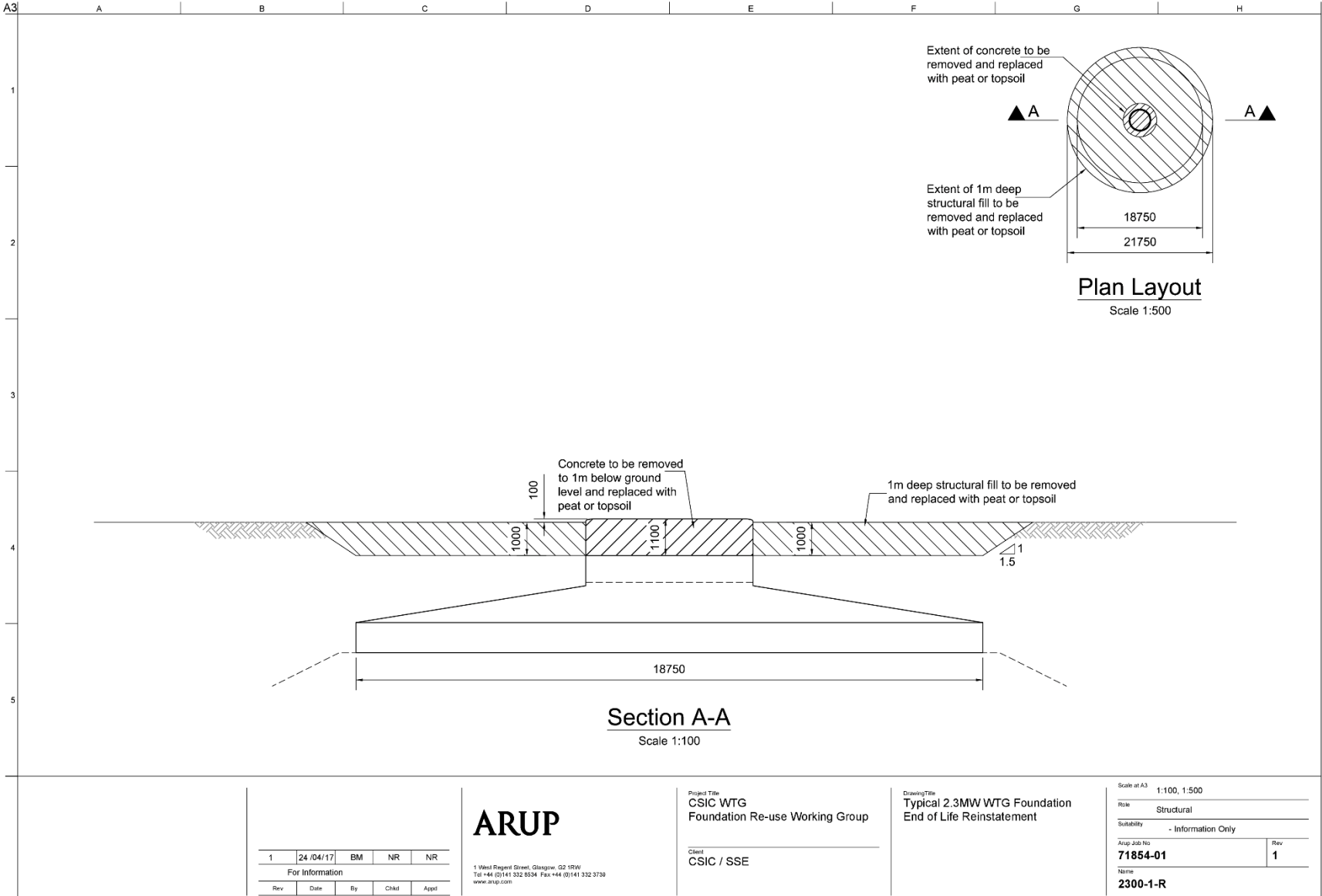
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End of Life Reinstatement

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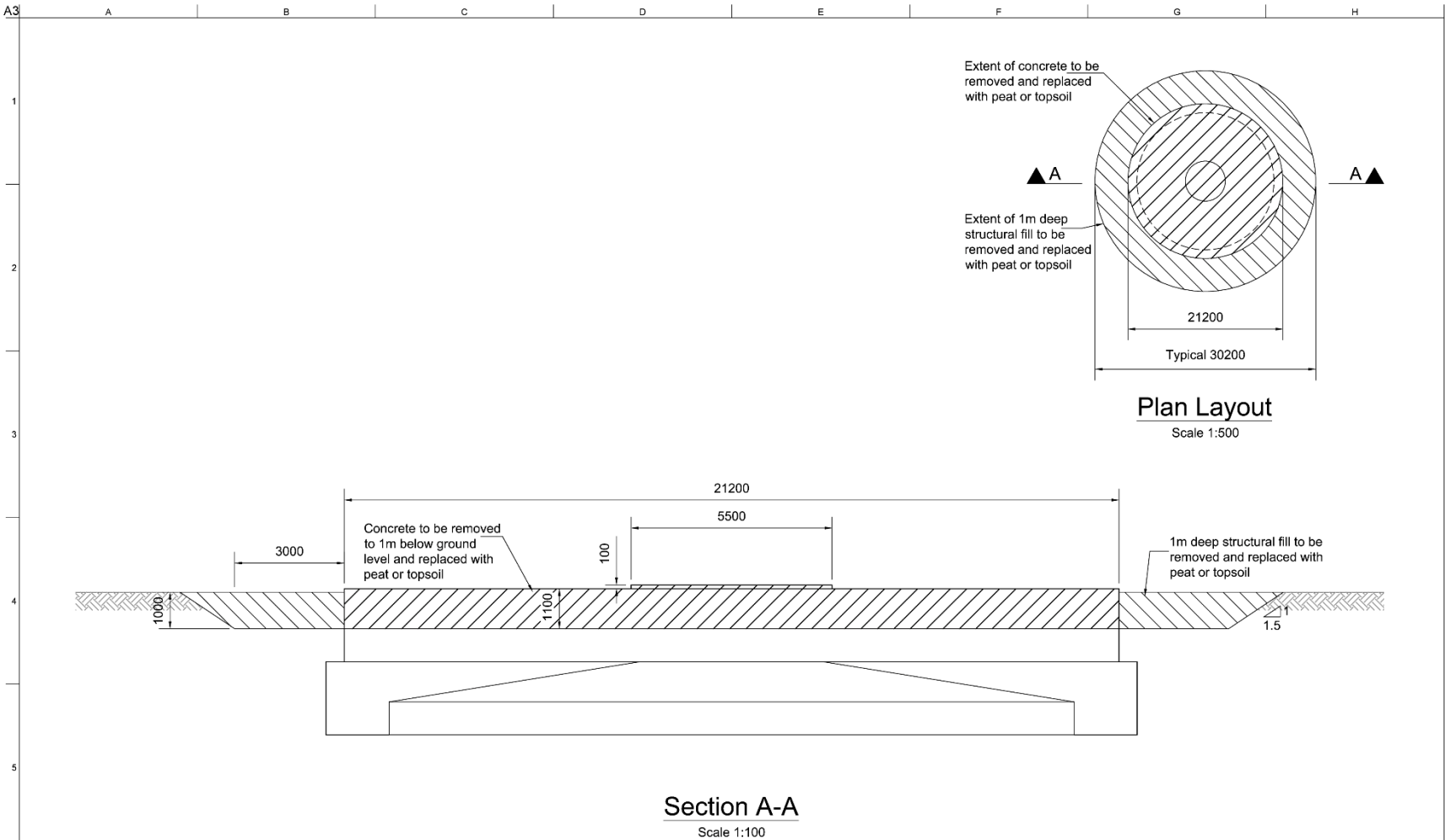
Appendix 4: Arup Appendix C Reinstatement Works



Appendix 4: Arup Appendix C Reinstatement Works



Appendix 4: Arup Appendix C Reinstatement Works



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Increased area of structural fill				
1	24 /04/17	BM	NR	NR
For Information				
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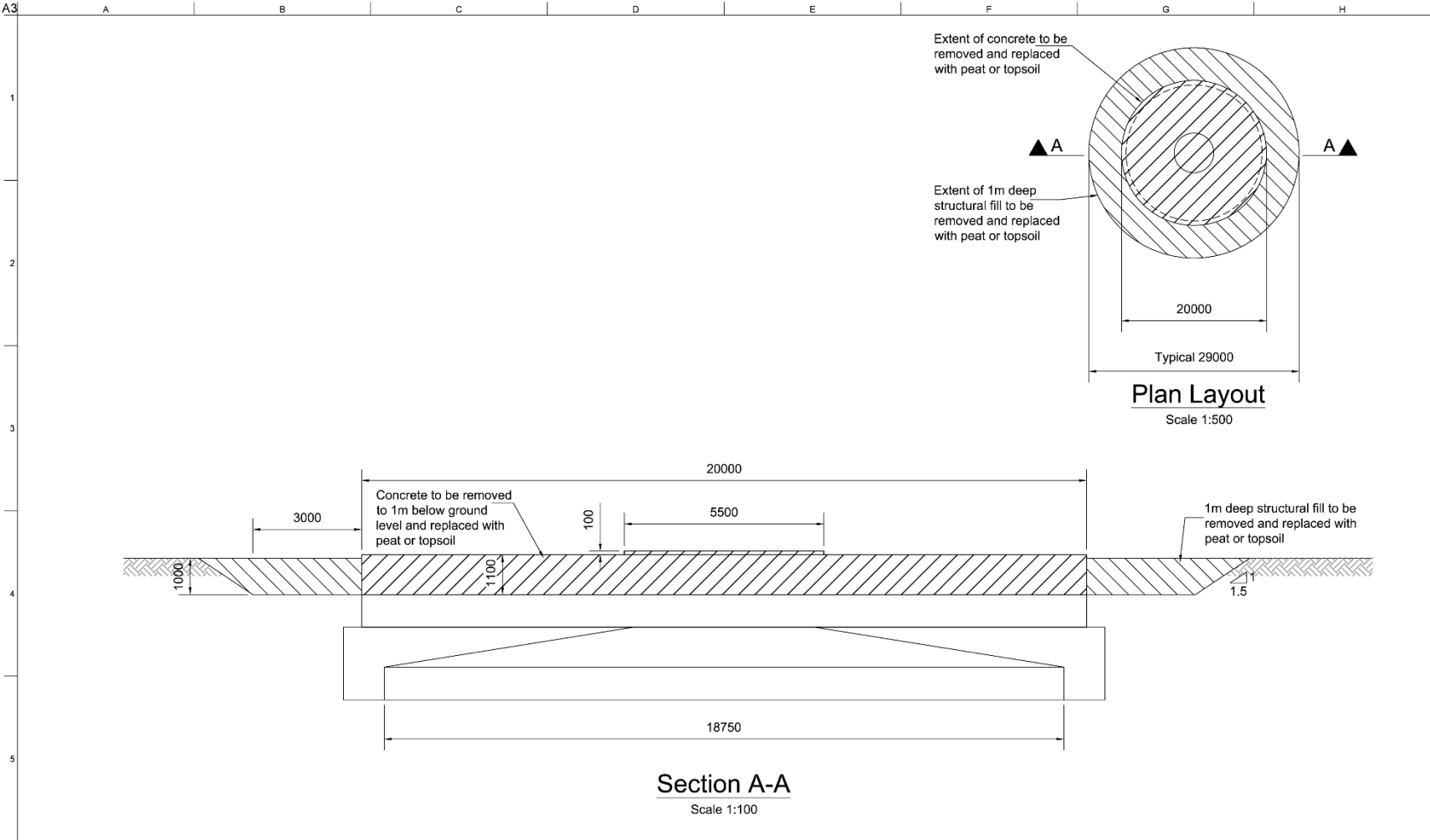
Project Title
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Foundation Re-use Working Group

Client
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Drawing Title
2.3MW Reuse for 2.3MW
Option 1
End of Life Reinstatement

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Suitability - Information Only	
Arup Job No 71854-04	Rev 2
Name 2300-2300-01-R	

Appendix 4: Arup Appendix C Reinstatement Works



2	30 /11/17	BM	NR	NR
Increased area of structural fill				
1	24 /04/17	BM	NR	NR
For Information				
Rev	Date	By	Chkd	Appld

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Drawing Title
**2.3MW Reuse for 2.3MW
Option 2
End of Life Reinstatement**

Scale at A3
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Role
Structural

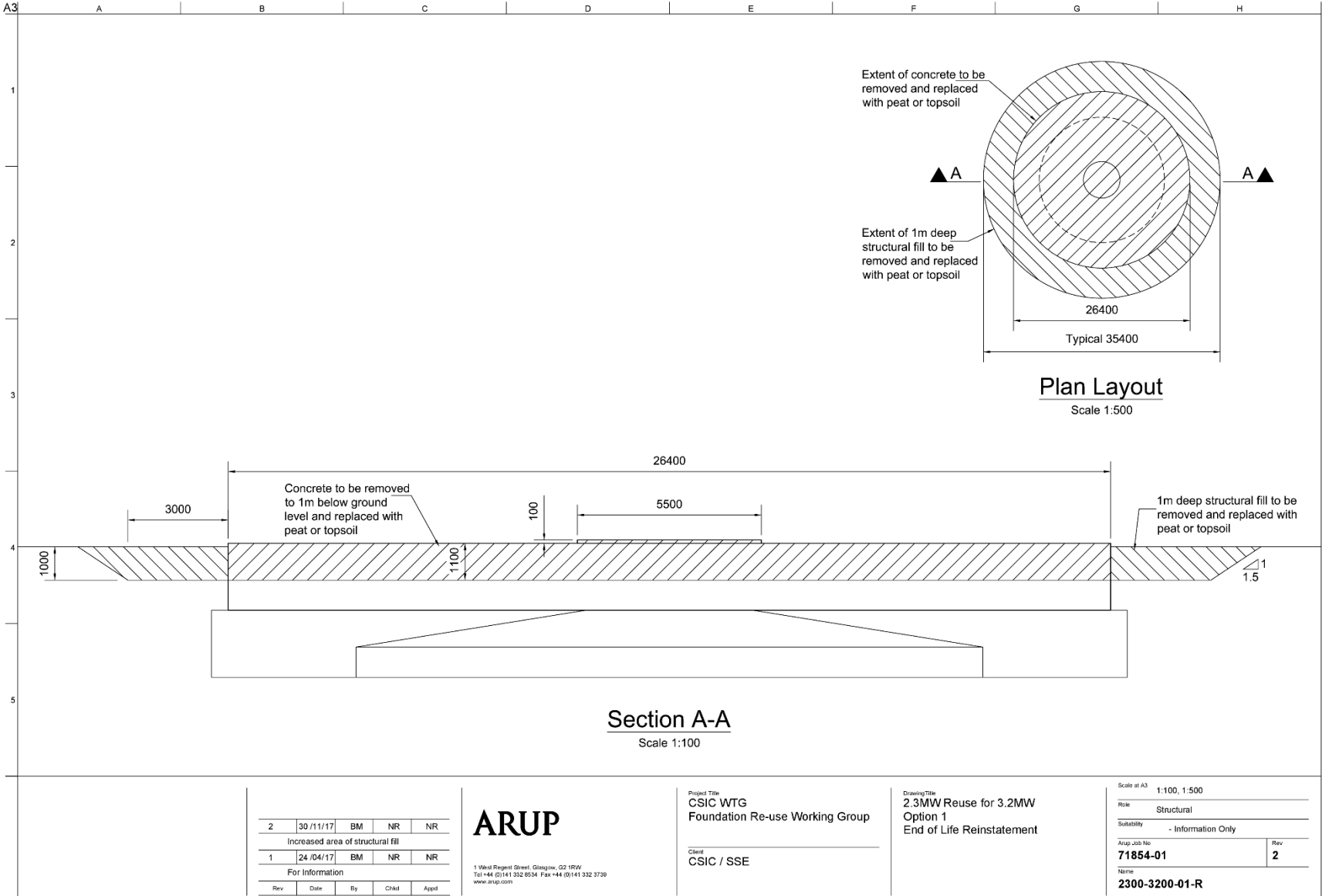
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Arup Job No
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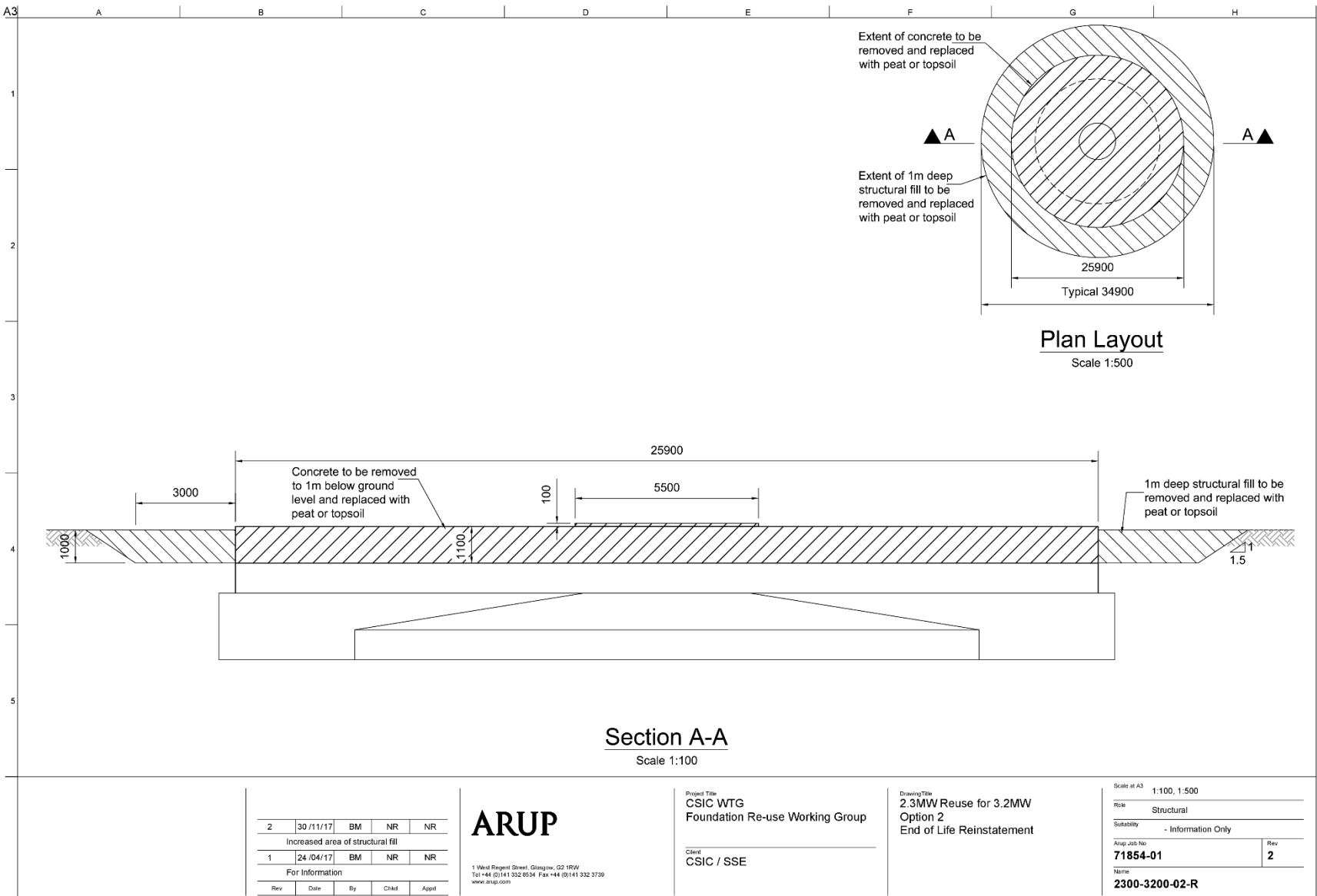
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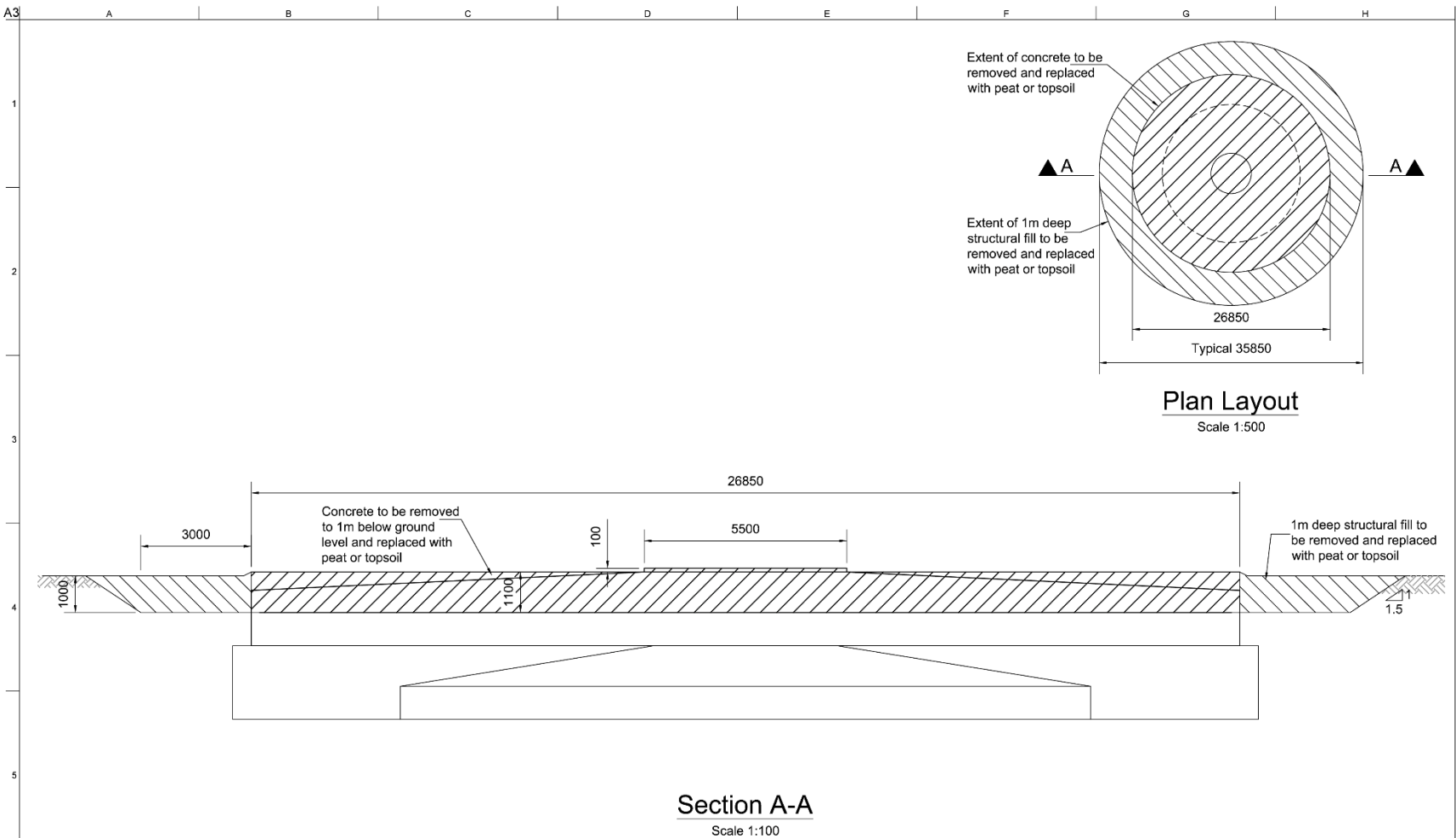
Appendix 4: Arup Appendix C Reinstatement Works



Appendix 4: Arup Appendix C Reinstatement Works



Appendix 4: Arup Appendix C Reinstatement Works



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Increased area of structural fill				
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Drawing Title
2.3MW Reuse for 3.2MW
Option 3
End of Life Reinstatement

Scale at A3
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Role
Structural

Suitability
- Information Only

Arup Job No
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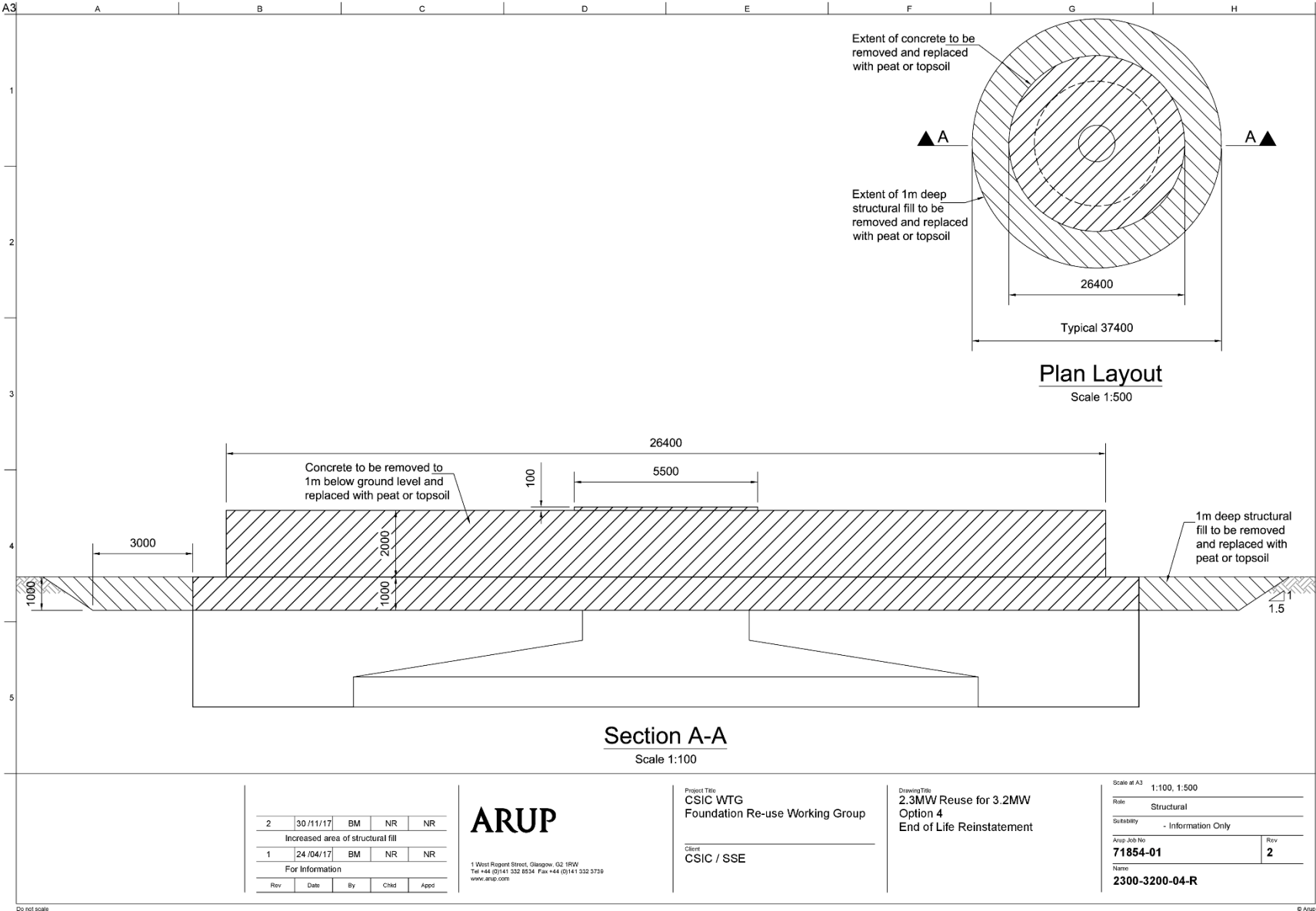
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Rev
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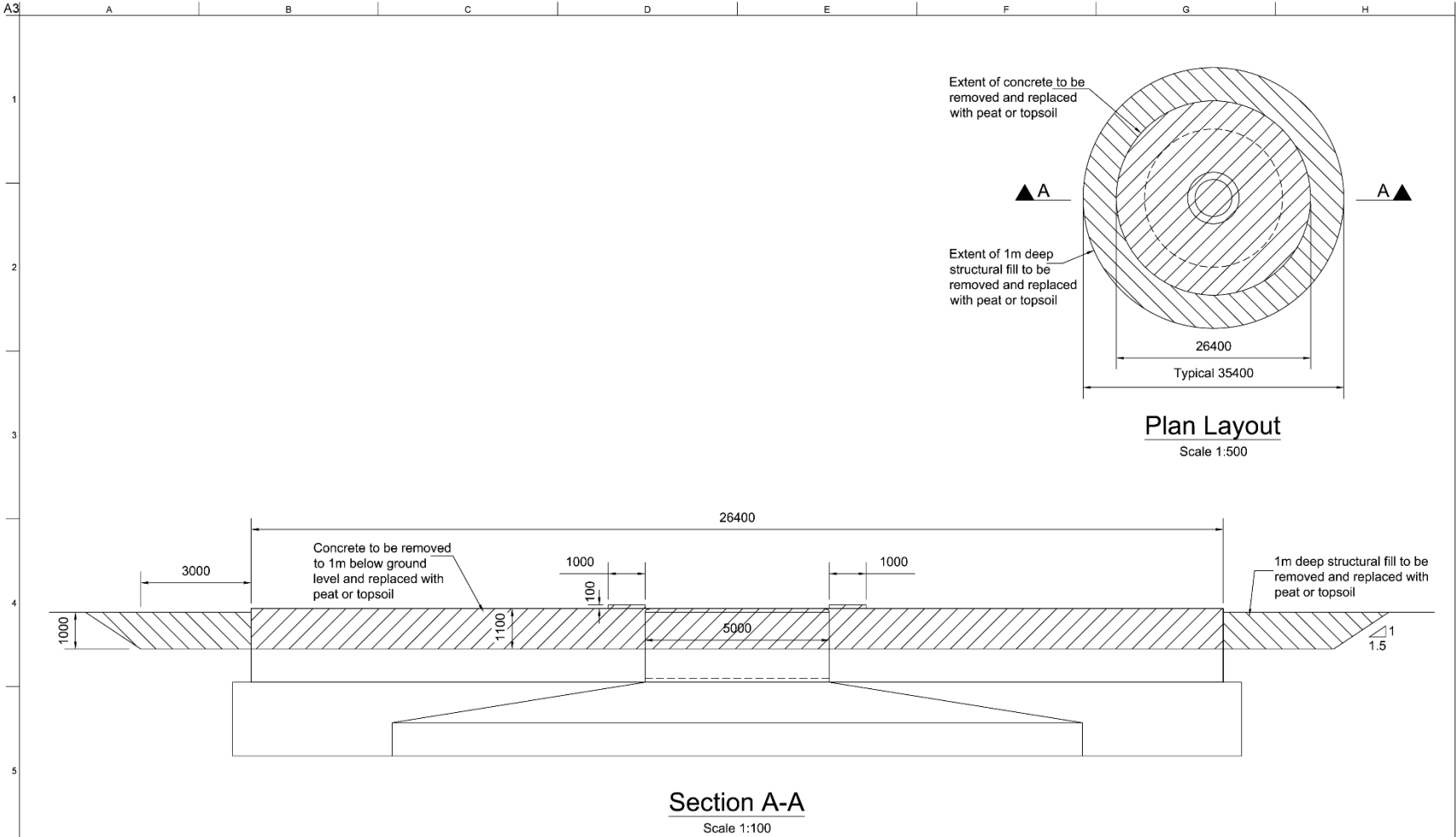
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Appendix 4: Arup Appendix C Reinstatement Works



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2	30/11/17	BM	NR	NR
Increased area of structural fill				
1	24/04/17	BM	NR	NR
For Information				
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Client
CSIC / SSE

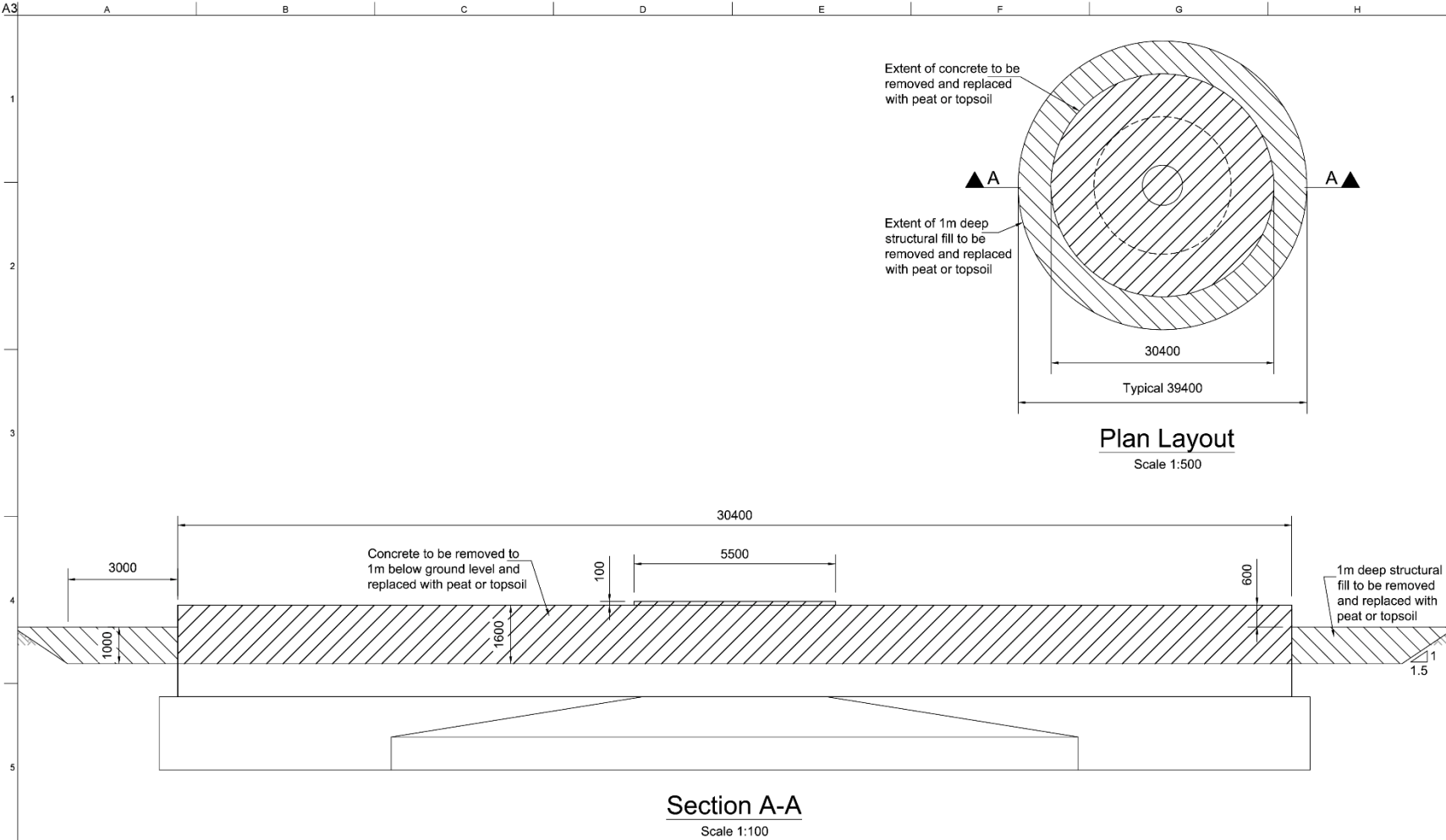
Drawing Title
2.3MW Reuse for 3.2MW
Option 5
End of Life Reinstatement

Scale at A3
1:100, 1:500
Role
Structural
Sustainability
- Information Only
App. Job No.
71854-01
Name
2300-3200-05-R
Rev
2

Do not scale

© Arup

Appendix 4: Arup Appendix C Reinstatement Works



2	30/11/17	BM	NR	NR
Increased area of structural fill				
1	24/04/17	BM	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

ARUP

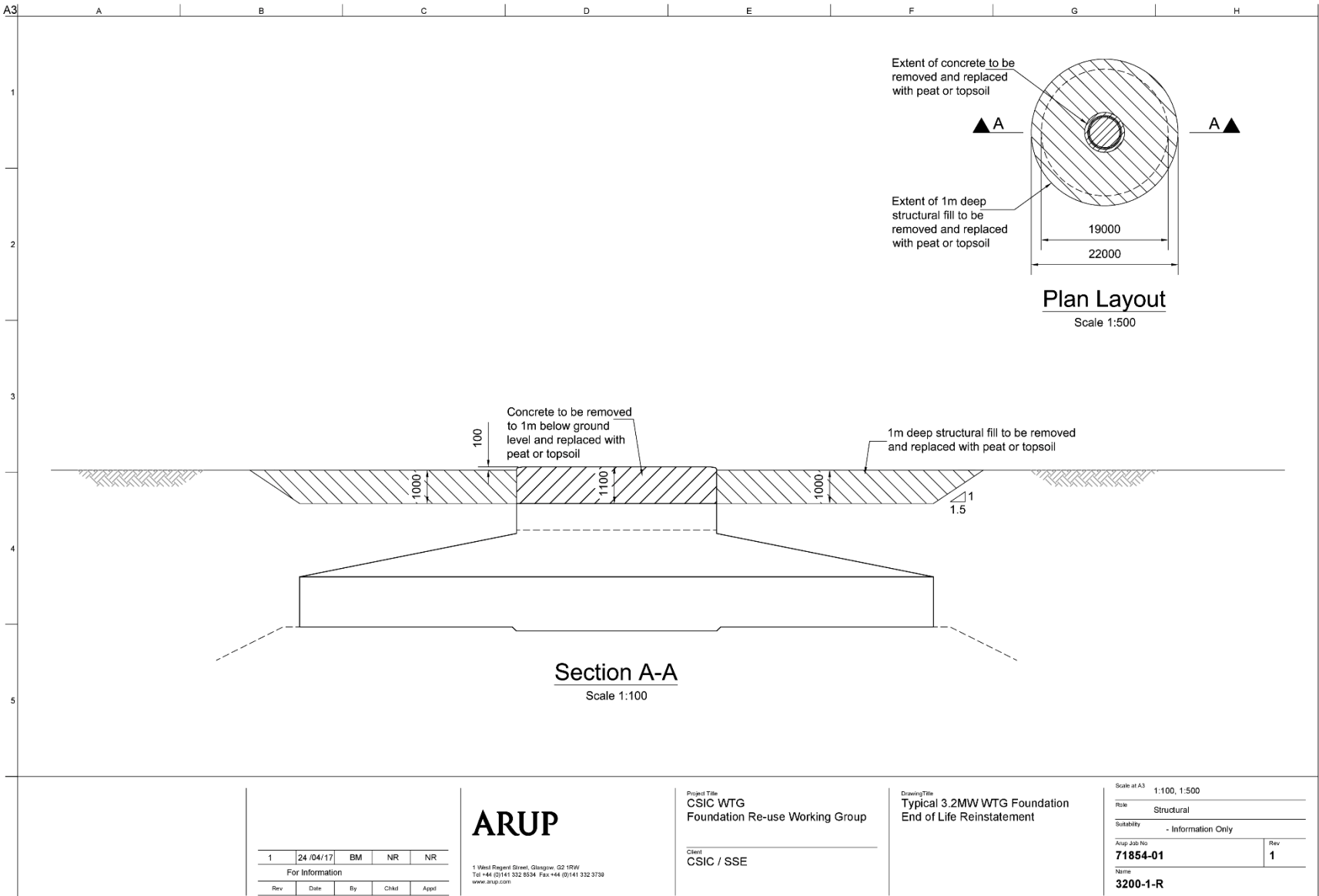
1 West Regent Street, Glasgow, G2 1RQ
Tel +44 (0)141 332 6534 Fax +44 (0)141 332 3739
www.arup.com

Project Title
CSIC WTG
Foundation Re-use Working Group
Client
CSIC / SSE

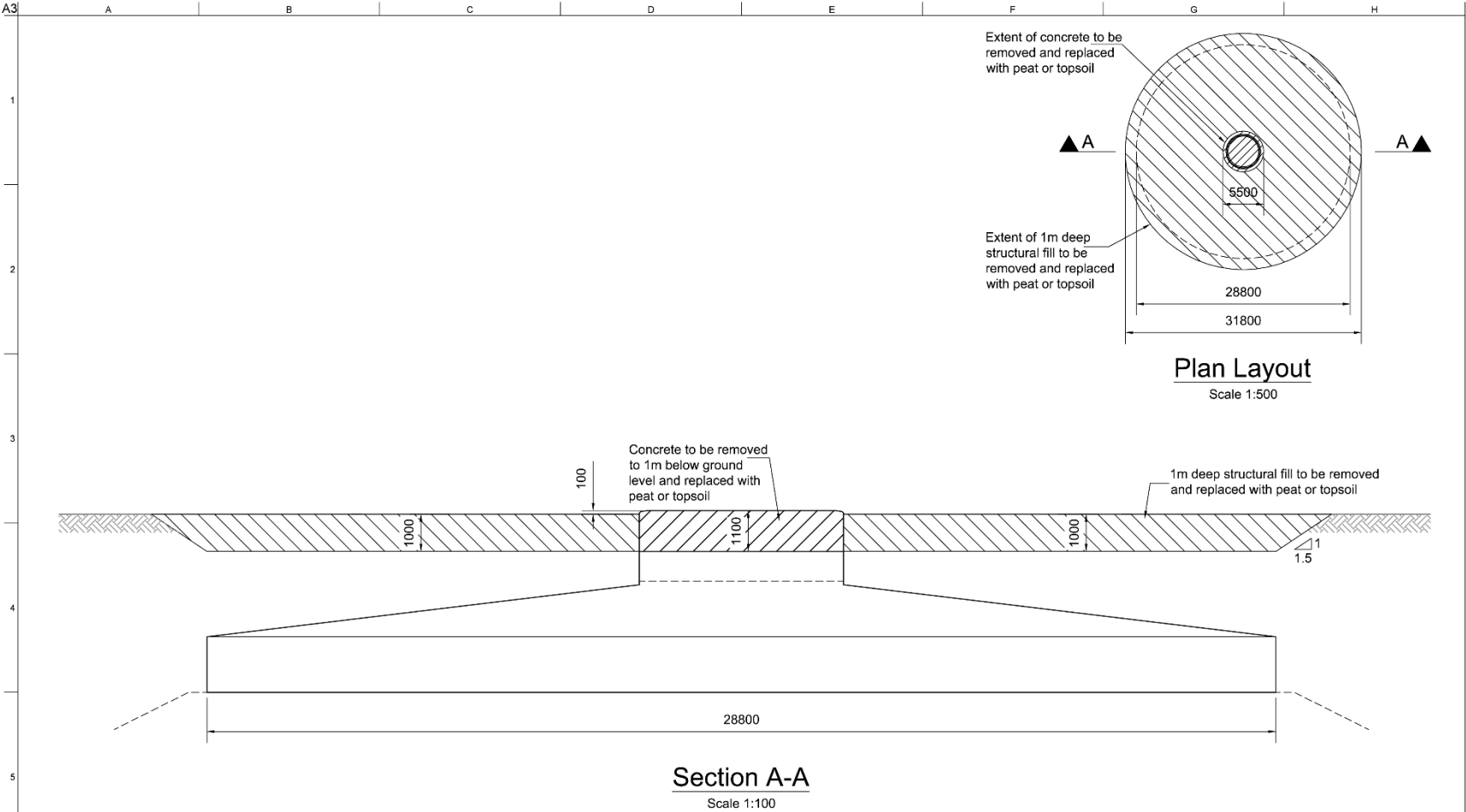
Drawing Title
2.3MW Reuse for 5.0MW
Option 1
End of Life Reinstatement

Scale at A3
1:100, 1:500
Role
Structural
Suitability
- Information Only
Arup Job No
71854-01
Name
2300-5000-01-R
Rev
2

Appendix 4: Arup Appendix C Reinstatement Works



Appendix 4: Arup Appendix C Reinstatement Works



1	24 /04/17	BM	NR	NR
For Information				
Rev	Date	By	Chkd	Appd

ARUP

1 West Regent Street, Glasgow, G2 1RW
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www.arup.com

Project Title
CSIC WTG
Foundation Re-use Working Group
Client
CSIC / SSE

Drawing Title
Typical 5.0MW WTG Foundation
End of Life Reinstatement

Scale at A3
1:100, 1:500
Role
Structural
Suitability
- Information Only
Arup Job No
71854-01
Name
5000-1-R
Rev
1

Do not scale

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Appendix 4: Arup Report Verification Table

Document Verification

ARUP

Job title		WTG foundation reuse working group		Job number 71854-01	
Document title		Engineering assessment of foundation re-use		File reference	
Document ref					
Revision	Date	Filename	report draft 02.docx		
Draft 1	11 Apr 2017	Description	Draft Report		
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Nathan Roberts	Gordon Barbour
		Signature			
Issue 1	26 Apr 2017	Filename	report issue 01a.docx		
		Description	Issue		
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Nathan Roberts	Gordon Barbour
		Signature			
Issue 2	27 Apr 2017	Filename	report issue 02.docx		
		Description	Minor updates		
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Nathan Roberts	Gordon Barbour
		Signature			
Issue 3	17 Aug 2017	Filename	report issue 03.docx		
		Description	Recommendations for further research on new build WTG foundations with extended design life, and peat excavation volumes added		
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Nathan Roberts	Gordon Barbour
		Signature			
Issue Document Verification with Document					☒ ☐

Appendix 4: Arup Report Verification Table

Document Verification

Page 2 of 2

Job title		WTG foundation reuse working group		Job number 71854-01	
Document title		Engineering assessment of foundation re-use		File reference	
Document ref					
Revision	Date	Filename	report issue 04a.docx		
Issue 4	5 Dec 2017	Description	Addition of perimeter access round above ground re-use options and quantity take off corrections.		
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Jonathan Morrison	Gordon Barbour
		Signature			
Issue 5	9 April 2018	Filename	report issue 05.docx		
		Description			
			Prepared by	Checked by	Approved by
		Name	Nathan Roberts	Jonathan Morrison	Gordon Barbour
		Signature			
		Filename			
		Description			
			Prepared by	Checked by	Approved by
		Name			
		Signature			
		Filename			
		Description			
			Prepared by	Checked by	Approved by
		Name			
		Signature			
Issue Document Verification with Document ☒					