



# TECHNICAL JOURNAL

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# Foreword

Welcome to the latest edition of our AtkinsRéalis Technical Journal. In this issue we are proud to feature papers which highlight the innovative work we have been doing in utilities planning, water and environment, geotechnical engineering, nuclear engineering and digitisation. It highlights our strong focus on improving the safety performance of new and existing infrastructure and improving the efficiency, sustainability and resilience of the new assets we create.

To improve the safety of existing infrastructure we have developed smarter monitoring techniques for railway embankments to identify potential for landslips and ground movement early, allowing asset owners to prioritise repairs and hence avoid sudden failures, preventing disruption and keeping passengers safe. To improve the safety of people using and constructing infrastructure we have developed a compact gas-capture system that reduces nuclear radiation exposure, using proven engineering principles relating to how gas bubbles behave and transfer contaminants out of the water. And we have set out the case for digitising rail permits to minimise delays, costs and gaps in oversight in the safety-critical rail environment and providing a realistic roadmap for implementing change.

To improve planning decisions and create more resilient infrastructure we have created a new hexagon-based mapping system to share useful information about underground pipes and cables without revealing sensitive details, helping planners, utilities, and local authorities to more easily plan and coordinate street works, new developments, and community projects. And we have developed an innovative method of predicting flood hazards in desert regions using a calculation combining water depth and speed to rank flood severity and create clear hazard maps, enabling smarter planning decisions, helping cities place infrastructure wisely, prepare for emergencies and reduce risk in flood-prone environments.

To facilitate efficient design and delivery of more sustainable infrastructure we have transformed the design process for reinforced-concrete structures in the nuclear industry by converting complex analysis results directly into calculated reinforcement requirements and design margin, presented in interactive 3D models that all stakeholders can interrogate. We have advanced circular economy practice in the water sector by defining water specific circularity principles and introducing a quantifiable Water Circularity Indicator and framework, enabling water utilities to assess, benchmark and implement measurable resource efficient circular strategies. And we have aligned artificial intelligence to the APM Competence Framework with digitally enabled workflows to reduce routine effort, improve clarity, and strengthen decision-making, helping our clients and teams by enabling more consistent, efficient, and transparent project delivery.

The above examples provide only a small insight into the wealth of innovation that AtkinsRéalis creates day to day and we hope you find this collection of papers enjoyable, helpful and thought-provoking.



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# Avant-propos

Bienvenue dans la dernière édition de la Revue technique d'AtkinsRéalis. Dans ce numéro, nous sommes fiers de vous présenter des articles qui mettent en lumière les travaux novateurs que nous menons dans les domaines de la planification des services publics, de l'eau et de l'environnement, du géotechnique, de l'énergie nucléaire et de la numérisation. Ils soulignent l'importance que nous accordons à l'amélioration de la sécurité des infrastructures nouvelles et existantes, ainsi qu'à l'amélioration de l'efficacité, de la durabilité et de la résilience des nouveaux actifs que nous créons.

Afin d'améliorer la sécurité des infrastructures existantes, nous avons mis au point des techniques de contrôle plus intelligentes pour les remblais ferroviaires, permettant de détecter précocement les risques de glissements de terrain et de mouvements de sol. Les exploitants peuvent ainsi hiérarchiser les réparations et éviter les défaillances soudaines, prévenant ainsi les perturbations et garantissant la sécurité des passagers. Afin d'améliorer la sécurité des personnes qui utilisent et construisent les infrastructures, nous avons mis au point un système compact de captage des gaz qui réduit l'exposition aux rayonnements nucléaires, en s'appuyant sur des principes d'ingénierie éprouvés concernant le comportement des bulles de gaz et leur capacité à extraire les contaminants de l'eau. Nous avons également présenté les arguments en faveur de la numérisation des autorisations ferroviaires afin de minimiser les retards, les coûts et les lacunes en matière de surveillance dans le secteur ferroviaire, où la sécurité est cruciale, et avons proposé une feuille de route réaliste pour la mise en œuvre de ce changement.

Afin d'améliorer les décisions en matière d'urbanisme et de créer des infrastructures plus résilientes, nous avons mis au point un nouveau système de cartographie basé sur des hexagones qui permet de partager des informations utiles sur les canalisations et les câbles souterrains sans révéler de détails sensibles. Ce système aide ainsi les planificateurs, les services publics et les autorités locales à planifier et à coordonner plus facilement les travaux de voirie, les nouveaux aménagements et les projets communautaires.

Nous avons également mis au point une méthode innovante de prévision des risques d'inondation dans les régions désertiques, qui utilise un calcul combinant la profondeur et la vitesse de l'eau pour classer la gravité des inondations et créer des cartes de risques claires. Cela permet de prendre des décisions de planification plus éclairées, aide les villes à implanter judicieusement leurs infrastructures, à se préparer aux situations d'urgence et à réduire les risques dans les environnements exposés aux inondations.

Afin de faciliter la conception et la mise en œuvre efficaces d'infrastructures plus durables, nous avons transformé le processus de conception des structures en béton armé dans le secteur de l'énergie nucléaire en convertissant directement les résultats d'analyses complexes en besoins en armature calculés et en marge de sécurité, présentés sous forme de modèles 3D interactifs que toutes les parties prenantes peuvent explorer. Nous avons fait progresser les pratiques d'économie circulaire dans le secteur de l'eau en définissant des principes de circularité spécifiques à ce secteur et en introduisant un indicateur et un cadre de circularité de l'eau quantifiables, permettant ainsi aux services des eaux d'évaluer, de fixer des références et de mettre en œuvre des stratégies circulaires mesurables et efficaces en termes de ressources. Et nous avons aligné l'intelligence artificielle sur le cadre de compétences pour un APM grâce à des flux de travail numériques afin de réduire les tâches routinières, d'améliorer la clarté et de renforcer la prise de décision, aidant ainsi nos clients et nos équipes en permettant une réalisation de projets plus cohérente, plus efficace et plus transparente.

Les exemples ci-dessus ne donnent qu'un petit aperçu de la richesse des innovations qu'AtkinsRéalis met en œuvre au quotidien; nous espérons que vous trouverez cette sélection d'articles intéressante, utile et stimulante.

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# 01: Obfuscation of Aggregated Spatial Data for Buried Infrastructure: A National Approach

## Significance Statement

Our work shows that it's possible to share useful information about underground pipes and cables without revealing sensitive details. By creating a new hexagon based mapping system, we help planners, utilities, and local authorities quickly understand what lies beneath an area - safely and at the right level of detail. This innovation supports better decisions, reduces risks and costs, and enables digital tools that make street works, new developments, and community projects easier to plan and coordinate.

## Énoncé d'importance

Nos travaux montrent qu'il est possible de partager des informations utiles sur les canalisations et les câbles souterrains sans révéler de détails sensibles. En créant un nouveau système de cartographie basé sur des hexagones, nous aidons les planificateurs, les services publics et les autorités locales à comprendre rapidement ce qui se trouve sous une zone donnée, en toute sécurité et avec le niveau de détail approprié. Cette innovation favorise la prise de meilleures décisions, réduit les risques et les coûts, et permet la mise en place d'outils numériques qui facilitent la planification et la coordination des travaux routiers, des nouveaux aménagements et des projets communautaires.



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## Abstract

This paper outlines a national approach for securely sharing aggregated spatial data on buried infrastructure, designed and implemented as part of the National Underground Asset Register (NUAR) project. It highlights the challenge of balancing the need for improved access to subsurface asset information—critical for safety, planning, and cost efficiency—with the requirement to protect sensitive details relating to critical national infrastructure. The paper evaluates grid based spatial referencing schemes, including raster, complex polygon, and hexagonal grids, and introduces n3gb/ni, a new hierarchical hexagonal indexing system aligned with the OSGB/OSNI coordinate frameworks. This system provides algorithmically generated, uniquely identifiable grid cells suitable for aggregating asset metrics while preventing disclosure of precise asset locations. Proposed service functions include tabular summaries of asset characteristics, grid traversal tools, and asset owner identification. The paper concludes that generalised, securely aggregated data can support numerous early stage planning and policy use cases while mitigating security risks and avoiding information overload.

## KEYWORDS

Aggregated spatial data; Buried infrastructure; Hexagonal indexing system; Secure data sharing; National Underground Asset Register

## 1. Introduction

The impact on the safety, cost and effectiveness of infrastructure projects of lacking access to reliable data on buried assets is well documented and is taking on an increasingly high profile across the world.

The National Underground Asset Register (NUAR) programme in the UK is an example of an initiative to address this issue and improve safety and efficiency by providing controlled access to data in an interactive and standardised form, and the economic business case for this intervention has been published [1]. This builds on previous analysis by initiatives such as Project Iceberg [2] and academic studies outlining the true costs of asset damages [3].

These issues are not restricted to the United Kingdom, and there is extensive literature from around the world about the importance of access to data on buried infrastructure, and the return on investment arising from improving access and quality [4], as well as initiatives getting underway in other parts of the world [5,6].

The security of data and physical assets is of paramount importance when implementing systems and processes for sharing data on the subsurface, as this may include reference to critical national infrastructure. It is important to consider the needs and the purpose for any access to such data, and to provide only a form of data and a level of detail that serves that purpose [7].

In addition to security considerations, many systems and users which consume information about buried assets and other subsurface information do not require precise details of the physical locations and detailed characteristics of features, especially not in the early stages of analysis and planning. This is also the stage at which large spatial extents are more likely to be under consideration, before focusing on specific locations for more detailed analysis. An example of this graduated approach, progressing from generic to specific, would be the RIBA Plan of Work [8].

Rather, general information about the presence, density, mix and ownership of buried infrastructure is sufficient for many analyses, and for combination with other datasets.

It has been announced [9] that the NUAR knowledge asset could be the basis for a number of services (Application Programming Interfaces, or APIs) which provide data at different levels of detail depending on user needs. Part of this mix may be access to generalised, aggregated information about buried infrastructure in a tabular form which could be related spatially to elements of one or more standardised grid schemes. This approach would serve the purpose of providing information at a level of detail suitable for many use cases, without exposing detailed information and without requiring specific logic related to those use cases to be implemented, as the responsibility for the visualisation or analysis of the generalised data remains with the consumer of that data.

The provision of more generalised summary data is consistent with user needs for various use cases, where too much detail can be overwhelming and detract from the information content required. Security considerations also dictate that providing too much information for a given purpose may present reconnaissance opportunities for hostile actors.

## 2. Grid Schemes for Representation of Generalised Data

The key to being able to return generalised, aggregated information that is usable in spatial analyses, is the ability to relate that generalised information to a known spatial extent (e.g. tabular data providing information about the lengths of linear asset types at a road junction). When considering generic services to provide such information it is important that the spatial extents being described are globally known and accessible, such that the consumer of the generalised, aggregated data can independently relate the data to referenced extents or the extents can be described by the generic service itself.

Regularised grids are a powerful and commonly used geospatial tool. They can be created in most GIS software applications and predominantly are of the types described below. The Raster and Hexagonal grids described below conform to the Open Geospatial Consortium (OGC) specification for Discrete Global Grid Systems (DGGS) [10] and feature a “hierarchical tessellation of cells to partition and address” an extent. The complex polygon “grids” are included for completeness to describe other, non-contiguous, means of addressing and subdividing a spatial extent.

### 2.1 COMPLEX POLYGON “GRIDS”

Complex polygon grids are a data format that uses the polygon data type to define a geographical boundary. They differ from DGGs in that each of the elements has a defined geometry which does not necessarily have a defined spatial relation with other elements in the “grid”. These types of grids are also widely used across the geospatial industry and come in many shapes and sizes. The Office for National Statistics (ONS) curates and manages a number of administrative boundary data sets [11] that are used to report aggregated statistics such as health data. In essence there is no difference within a GIS system between a regular polygon cell in a grid and an irregular local authority boundary polygon. The main advantage of this type of grid is that each grid cell can relate to multiple data fields in a single layer. See **Figure 1** for an example of a complex polygon “grid”.

FIGURE 1

Example of complex polygon “grid” showing regions in England [12]

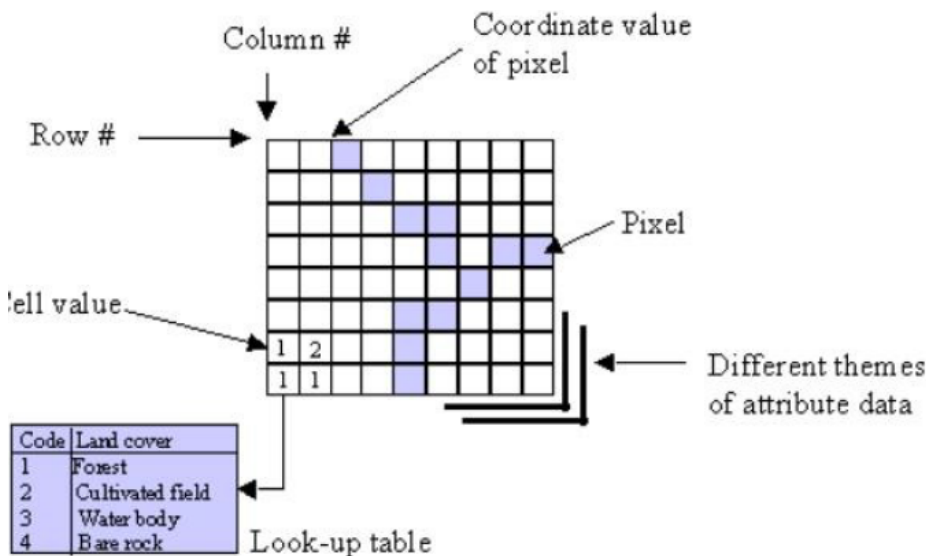


## 2.2 RASTER GRIDS

Raster grids are a core GIS data format in frequent use across geospatial disciplines to display and transfer data in a regular 'grid' format. The grid is usually georeferenced by a single corner coordinate and then the number of rows and columns and cell size is defined. The most common grid format is a de facto standard called ASCII grid (sometimes referred to as ESRI grid [13]). Processing can be very quick and simple to run using such grids, but their disadvantage is inflexibility. This inflexibility relates to the inability to employ varying cell sizes within a single layer, or mesh density, as opposed to vector grids. In theory a cell could contain text or numerical values, but common practice is that this data format contains primarily numerical values. Coordinates for each pixel/cell can be calculated using standard GIS software.

FIGURE 2

Elements of a Raster Grid



### 2.3 STANDARDISED HEXAGONAL GRIDS

Hexagon grids are widely used in spatial analysis as they reduce sampling bias as a result of them being easy to tessellate to form evenly spaced grids. They are most commonly used when the analysis is of data that contains elements of connectivity or movement, or where nearest neighbours is a common query due to the standard distance between cell centroids in all directions.

In the context of buried infrastructure data, hexagon grids may be more appropriate than squares for some use cases, as they may allow closer representation of the routes of linear features which are often aligned to streets rather than consistently following cardinal directions allowing a more even distribution of features in a utility network.

There are some publicly defined hexagon grids, including the open-source Uber H3 Hexagonal Hierarchical Spatial Index [14,15].

This scheme provides a global set of hexagons with unique identifiers, enabling global-scale consistent analysis. The approximate edge lengths of H3 hexagons at the proposed resolutions are given in **Table 1** [16].

**TABLE 1**

Edge length of cells at different zoom levels in the H3 indexing scheme

Zoom Level	Approximate Edge Length
6	~3750m
7	~1400m
8	~530m
9	~200m
10	~75m
11	~30m
12	~11m

It is possible that a smaller extent may be considered for the spatial referencing of generalised data, but only very generic information should be allowed at smaller extents given the possibility of inferring information about specific assets or sites by narrowing the search extent, thus circumventing one of the main reasons for generalised data.

More extensive attribution may be disclosed for larger extents, and there is less of an opportunity to equate this attribution to specific assets or small extents.

## 2.4 OTHER OPTIONS FOR GRIDS

Raster grids and hex grids may each be suitable for different scenarios and use cases. Hex grids may offer advantages in cases where connectivity and direction are important, and for modelling curved features, or those that may not proceed in cardinal directions. Set against this is the increased complexity of managing and calculating hex grids as opposed to raster grids, whereby hex grids need to be calculated separately for each different zoom level, rather than being directly derivable up and down the hierarchy from a single cell.

Analyses that require mapping to a spatial extent depend critically on a spatial referencing scheme that provides consistent, persistent, and calculable geometries, such that any analysis referencing a grid does not need to explicitly include a geometry but can reference a cell by an identifier from which a geometry can be derived or calculated, and the nature and shape of that grid should be selected in a way that balances ease of use with suitability of the grid for the use case.

Work has been done to create a Great Britain (GB)-specific analysis hexagon grid with consistent identifiers based on the Ordnance Survey GB National Grid [17] and this is described in detail in the next section. If a square grid is appropriate for some analyses, the standard Ordnance Survey National Grid itself may be used as a referencing scheme.

Other referencing systems may be suitable for use, and flexibility is possible so long as a common means of identification is available for a given indexing scheme - whether independently from a known, globally available source, or via dedicated functions of the generalised data services.

### **3. Introducing n3gb/ni – a Hex-Based Spatial Indexing System for Great Britain and Northern Ireland**

The NUAR project has defined a spatial indexing system inspired by the H3 spatial indexing scheme referenced earlier. The project had a requirement for a GB- and NI-based grid system suitable for the distribution of generalised asset information. Whilst H3 provides the ideal structure for aggregating this data, its global nature means it is based on WGS84 and therefore not ideal for use in a NUAR context where data under analysis is represented in OSGB or OSNI coordinate systems.

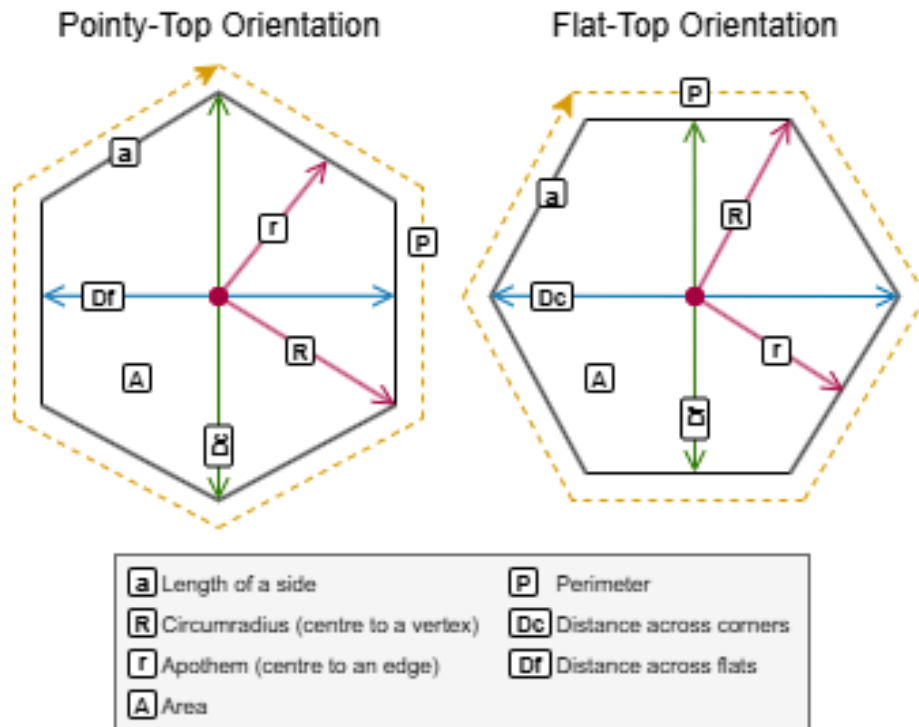
The project devised an approach following similar principles, setting the following requirements:

1. All hex cells **MUST** have a unique identifier
2. The unique identifier **MUST** be stable and consistent
3. The hex cell **MUST** be algorithmically generated
4. The hex cell **MUST** be different sizes at different zoom levels, with the size appropriate for analysis at that zoom level
5. The hex cell areas **SHOULD** be approximately similar to H3 cells at the same zoom level
6. It **COULD** be possible to determine the next child hexagon(s) from a given parent hexagon
7. It **COULD** be possible to determine the parent hexagon from a given child hexagon

Hexagons are useful for algorithmic generation as they can be regular polygons where one dimension can be calculated from one or more other known dimensions. For example, the n3gb system defines set cell widths and circumradius for all zoom levels from 0 to 15. These are then used, along with the bounds of the national grid, as the core dimensions to be able to generate fixed regular hexagons. **Figure 3** shows the different dimensions of a regular hexagon.

FIGURE 3

Regular Hexagon orientations and their dimensions



The n3gb system elected to use regular hexagons in the “pointy-top” orientation as they tessellate neatly and make the generation algorithms simpler. **Table 2** shows the dimensions (in metres) for the same zoom levels as discussed previously, note the close alignment of the edge size (dimension a) to the value for the H3 grid.

**TABLE 2**

Dimensions of cells at different zoom levels in the n3gb indexing scheme

Zoom Level	a	R	r	Dc	Df	P	A
6	3719.87	3719.87	3221.50	7439.74	6443.00	22319.21	35950662.20
7	1399.50	1399.50	1212.00	2798.99	2424.00	8396.98	5088571.28
8	529.43	529.43	458.50	1058.86	917.00	3176.58	728231.24
9	199.76	199.76	173.00	399.53	346.00	1198.58	103677.10
10	75.06	75.06	65.00	150.11	130.00	450.33	14635.83
11	28.29	28.29	24.50	56.58	49.00	169.74	2079.33
12	10.39	10.39	9.00	20.78	18.00	62.35	280.59

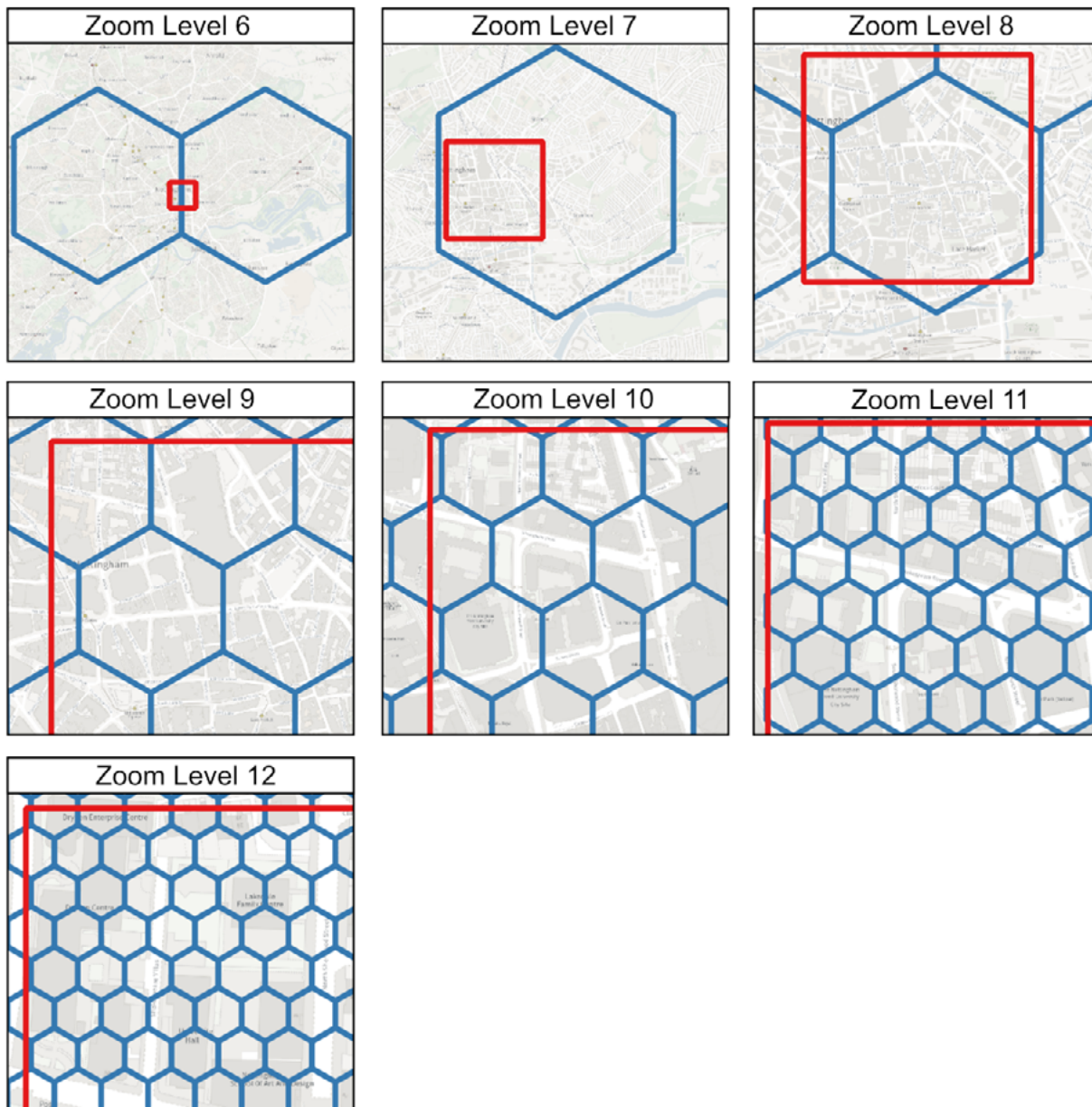
Figure 4 provides a comparison of the relative sizes of hexagons at the different zoom levels.

FIGURE 4

Example hexagon cells at different zoom levels.

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The key to making a consistent, repeatable, and reusable indexing grid system useful is the provision of unique identifiers for each cell at every zoom level. There are different approaches to the construction of unique identifiers but for the n3gb grid it was decided that the unique identifier would also be an encoding of the centroid of the hexagon along with its zoom level.

Basing unique identifiers on location information is, in normal circumstances, considered bad practice due to the potential for features to change shape and location over their lifecycle. However, in the case of n3gb it is a fixed grid whose cells (features) will neither move nor change shape and therefore a location-based unique identifier is appropriate. In fact, for this use case it is desirable since the encoded coordinates and zoom level can be used to reconstruct the cell geometry. Therefore, linked data can be shared without the need to explicitly share the geometry of the grid cells since this can be computed from the identifier.

The unique identifier is constructed from four components:

- A version number for the identifier schema
- The cell centroid easting coordinate
- The cell centroid northing coordinate
- The zoom level for the cell

The encoding process takes in these components then encodes to a short, url-safe, string. The easting and northing coordinates are scaled to integers to maintain a precision of 3 decimal places when decoded (providing millimetre-level spatial resolution). The four components are then packed to a binary structure using Python's format string of ">BQQB":

- ">" indicates use of big-endian byte order
- "B" Unsigned char (1 byte)
- "Q" Unsigned long (8 bytes)

The encoded identifier will be 18 bytes which is a small compact identifier and represented textually which lends itself well to being indexed and stored in a database and importantly will be unique for each cell at each zoom level. The following is an example identifier:

- Version = 1
- Easting = 252086.123
- Northing = 847702.123
- Zoom Level = 10
- Encoded identifier = AQAAAAAPBodrAAAAADKG6GsKHQ

The encoding and decoding functions also apply a checksum that is used to validate the identifier being provided, this ensures that the identifier is of the expected length and has not been corrupted from when it was encoded. This ensures that corrupted identifiers can be caught and flagged.

The project has created a GitHub repository [18] containing the algorithm and code samples for implementing the grid system. Further work will be done to develop a version of the indexing system suitable for Northern Ireland, and to provide reference implementations of some of the functions described in the next section which allow cell geometries to be retrieved, and traversal of the hierarchy for different zoom levels.

#### **4. Functions of Generalised Data Services for Buried Infrastructure**

The following functions are proposed for a “generalised data service” for buried infrastructure (for which there may be multiple variations/endpoints):

- A function to list and describe the grid referencing schemes supported by the service.
- A function to return a tabular representation of the type of assets within an Area of Interest (AOI - a bounding box or geometry), spatially referenced according to a specified grid scheme and with relevant aggregated information on characteristics and metrics appropriate for an asset and geometry type (e.g. status, count, length, density etc.) Different metrics may be exposed on different end points, or via parameterised requests to a standard endpoint.
- A function to return a spatial representation of the grid used to spatially reference the tabular data, and functions to traverse the grid cell hierarchy for different zoom levels.
- A function to return details of the Asset Owners with assets in an AOI and/or with operational areas that intersect it.

#### 4.1 TABULAR REPRESENTATION OF ASSETS

This function would return information about the characteristics of linear, point or polygon assets at a location as a collection of table rows.

As a default/minimum, the following information would be returned, with each row representing a distinct set of values:

- **Grid Scheme ID** – an identifier for the grid scheme to which the tabular data is spatially referenced
- **Grid Cell ID** – an identifier for the specific grid cell to which a record is spatially related
- **Asset Type** – an indication of the sector or asset type that the record represents (Gas, Electricity etc)
- **Operational Status** – an indication of the operational status of assets that the record represents (Live, Abandoned etc)
- An aggregated characteristic of the assets contained within the referenced grid cell, e.g. length of linear assets - the length in metres of all the portions of linear assets intersecting the grid cell that have common values for the foregoing attributes

Further iterations could allow additional attributes (from a constrained set) to be specified in the output, for example capacity, diameter, material etc. Any additional attribution would need to be constrained by the spatial extent of the enquiry and the zoom level, with fewer additional attributes being allowed at smaller extents (to avoid more detailed information/locations being inferred).

The inputs to this function would be:

- An area of interest polygon (or a collection of Grid Cell IDs)
- A resolution or zoom level within a specified range
- [Optional: Specification of additional attributes in the response - limited by zoom level]
- [Optional: Filter Query]

An example response from the default “tabular” function is illustrated in **Table 3**.

**TABLE 3**

Example of the response  
from the “Tabular  
Data” function

Record ID	Grid Scheme ID	Grid Cell ID	Asset Type	Status	Length (within the cell)
1	n3gb	AQAAAAAPBodrAAAAADKG6GsKHQ	gasnetworklink	Operational	50
2	n3gb	AQAAAAAPBodrAAAAADKG6GsKHR	gasnetworklink	Operational	30
3	n3gb	AQAAAAAPBodrAAAAADKG6GsKHQ	gasnetworklink	Abandoned	25
4	n3gb	AQAAAAAPBodrAAAAADKG6GsKHR	gasnetworklink	Abandoned	50
5	n3gb	AQAAAAAPBodrAAAAADKG6GsKHQ	electricitynetworklink	Operational	75
6	n3gb	AQAAAAAPBodrAAAAADKG6GsKHR	electricitynetworklink	Abandoned	60
...	...	...	...	...	...

Functions may also be specified to provide generalised information about other geometry types, for instance counts of point features (potentially with standard measures of spatial density), areas of polygon features or measures of the density of assets by type and status.

How these values are represented and visualised is the concern of the consuming application, for which such values may offer different insights depending on the use case and the target audience.

## 5. Example Use Cases

- A local government energy policy officer wants to assess the suitability of the town's road network for the deployment of district heating systems. To perform the assessment the policy officer needs to understand the complexity/density of the subsurface infrastructure. At this feasibility stage the policy officer does not need to know the location or nature of the subsurface assets.
- A mobile network operator is seeking to infill an area of poor coverage using local authority assets. Whilst some of these are lampposts it is a rural area and many will be road signs or specially erected masts. A key consideration for the operator will be the availability of an electricity supply within a reasonable connection range of the proposed new wireless assets. The operator needs to know whether there is a supply capable of supporting the equipment, its approximate distance (+/- 10m) and whether above or below ground.
- Highways Authorities and utilities seeking to maximise opportunities for coordination of street works may be able to use aggregated buried asset data at the street level, possibly filtered by sector, and combined with other data sources, to identify and prioritise planned works that may lend themselves to collaboration, based for example on the density and age of assets from other organisations and sectors at a location.
- Telecoms or electricity providers seeking opportunities to re-use ducts or abandoned pipes to accelerate installation, avoid complex excavations or to support supply to hard-to-reach locations, may be able to quickly gain an oversight of potential routes by accessing aggregated data about the operational status of assets from relevant sectors.

- Individuals and/or organisations considering using electric vehicles wish to consider the potential for installing an EV charge point at their premises, e.g. homes, offices, etc. Currently it is difficult to ascertain before taking ownership/custody of an EV whether there is sufficient capacity to install a charge point at the premises. The aim of this work would be to provide an indication of the available capacity within the local supply network for new EV installations, accommodation both current energy requirements (e.g., 7kW/charger) and likely faster chargers that may be deployed in domestic and workplace environments. Note - this use case could be extended over time to include the ability to assess capacity of new developments and/or the acceptability of additional local embedded generation and/or storage.
- A Local Authority Environment Officer wants to decide where to instigate and incentivise planting of urban trees. A major constraint is the availability of space for roots and the possible conflict with buried services, in particular sewers. A map of overall available subsurface space or “subsurface complexity” will be used to dedicate certain parts of the city for further investigation, de-risking the project from the outset.

For many of the use cases highlighted above, other online services allowing the real-world locations of Unique Street Reference Numbers (USRNs) and Unique Property Reference Numbers (UPRNs) [19] can be used to provide the base location for any queries and ultimately allow aggregated information about buried infrastructure to be related to meaningful real-world locations without having to disclose the full details of individual assets.

## 6. Future Work and Opportunities

The ability to locate and survey buried assets and the surrounding substrate (soil, archaeology, geology) in 3D space is likely to improve in the future through feedback of measured data from the field, improved imaging and scanning technology as well as use of AI and robotics (see the Government Office for Science Foresight report, Future of the Subsurface, 2024) [20].

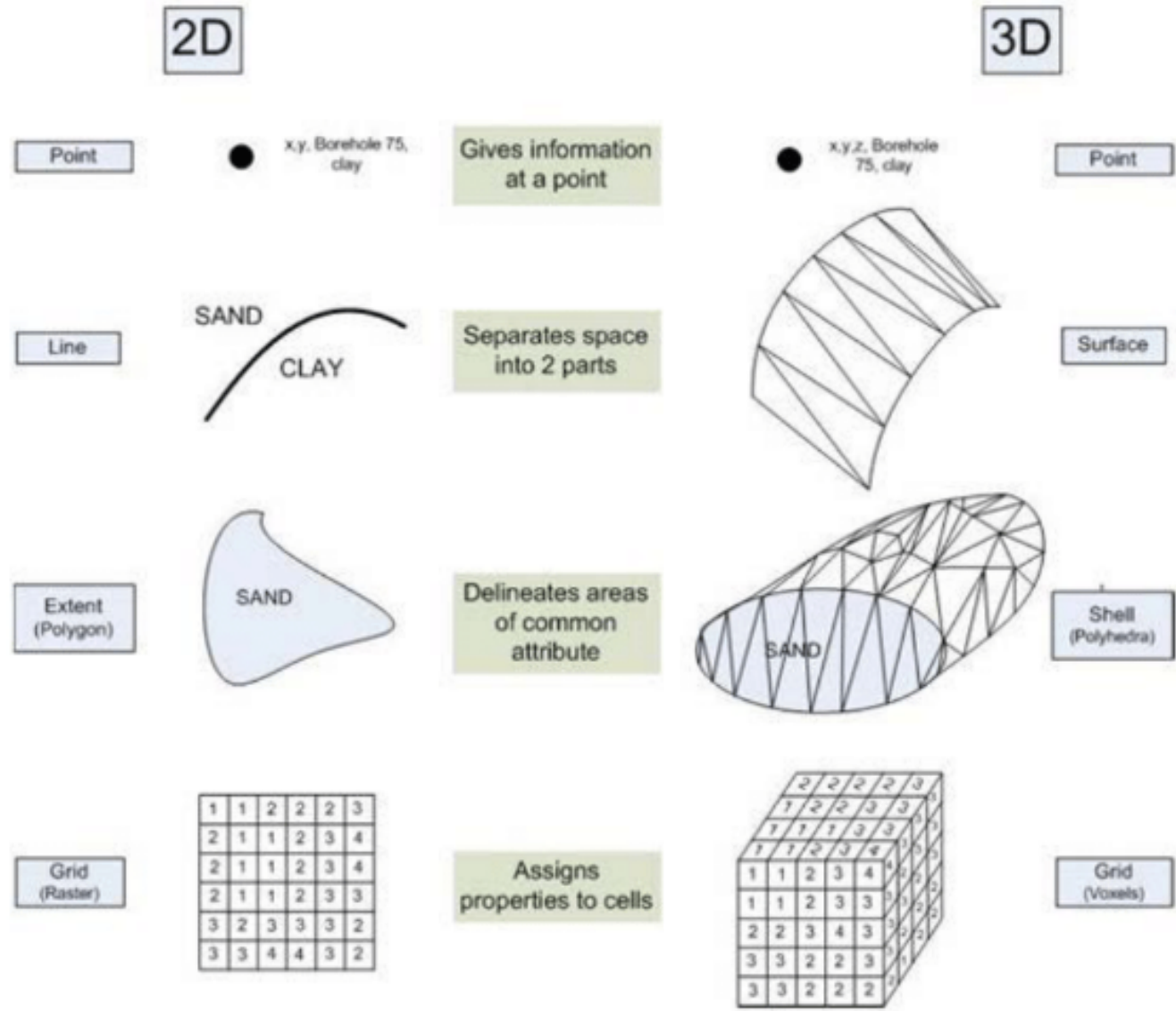
Use cases for the extension of the obfuscation model include any form subsurface construction such as tunnelling, piling and basement extensions. Technology requirements range from using subsurface data in 3D CAD environments for clash detection to using VR and AR headsets for navigation and exploration of subsurface space.

The most commonly used 3D grid is the Network Common Data Form NetCDF [21] widely used for meteorological and hydrogeological data visualisation and modelling.

Moving to a common 3D grid as a common exchange format will open up further interoperability with data and models from different domains, effectively extending the concept of BNG as the reference grid for sharing 2D information (see **Figure 5** [22] and Watson [23] and Stafleu [24]).

FIGURE 5

3D Grid representations



## 7. Conclusions and Summary

Knowledge of the location and characteristics of buried infrastructure assets can unlock significant value for many use cases, some of which are outlined in this paper, but of which there are many other examples. The NUAR Discovery Project [25] identified more than one hundred potential use cases for the buried infrastructure data held in the NUAR service.

However, there are downsides to openly sharing full details of buried infrastructure, not least the implications for the security of critical national infrastructure.

Moreover, many use cases, particularly in the early stages of assessment and planning, do not require detailed information about individual assets. In fact, this level of detail may constitute information overload and actively hinder the generation of insight at a suitable strategic level.

It is proposed that, for such use cases and project phases, aggregated information about selected characteristics of assets at a location may provide the right level of information to suit the needs of users, while limiting disclosure of detailed information which does not serve the use case and may also provide useful reconnaissance information to hostile actors.

A number of options for the generalised representation of such aggregated information using standardised grids are described, and hexagon grids are identified as being useful for the representation of information about buried infrastructure as they form easily tessellated, evenly spaced grids ideal for the representation of connectivity and flow.

A new indexing scheme is described for a hierarchical hexagonal grid with different sized cells at different zoom levels, and with immutable, algorithmically generatable cell identifiers based on the OSGB coordinate system.

Also described are a number of functions that could be usefully applied to such a grid to return insightful data at a level of detail suitable for numerous use cases, without the unnecessary disclosure of the location and characteristics of individual assets.

The authors believe that the provision of aggregated, generalised data for buried infrastructure, using secure services and spatially indexed to a standardised, openly-defined, grid system can provide value for many users and use cases.

## **Acknowledgements**

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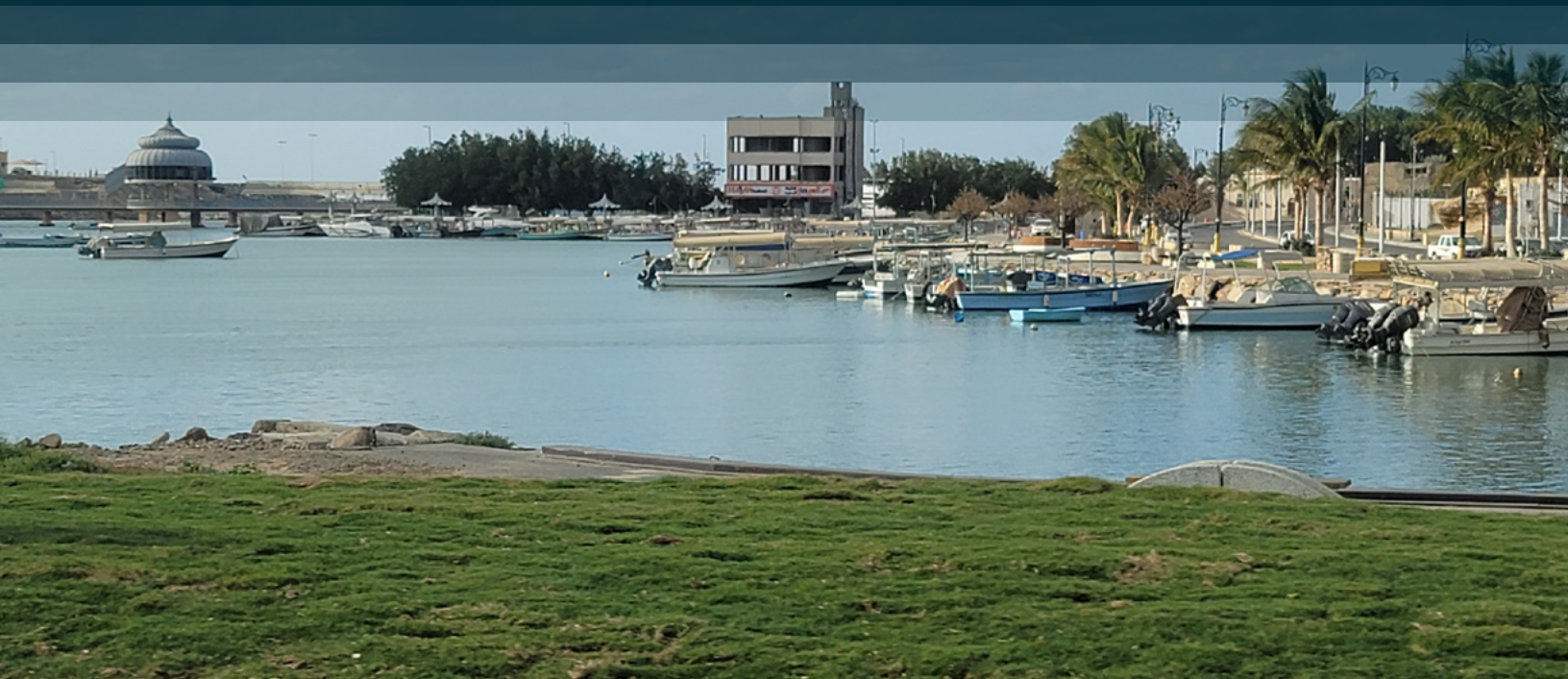
# 02: Innovative Flood Hazard Classification for Resilient Urban Development

## Significance Statement

A new way to understand and predict flood hazards in desert regions has been developed by AtkinsRéalis for NEOM in Saudi Arabia. By simulating how rainfall spreads across the landscape during intense storms, the study shows where floodwaters are likely to flow, how deep they may become, and how dangerous they could be. An innovative calculation combining water depth and speed is used to rank flood severity and create clear hazard maps. These maps support smarter planning decisions, helping cities place infrastructure wisely, prepare for emergencies, and reduce risk in rapidly growing, flood prone environments.

## Énoncé d'importance

AtkinsRéalis a mis au point, pour le compte de NEOM en Arabie saoudite, une nouvelle méthode permettant de comprendre et de prévoir les risques d'inondation dans les régions désertiques. En simulant la manière dont les précipitations se répartissent sur le terrain lors de tempêtes violentes, l'étude met en évidence les zones susceptibles d'être inondées, l'ampleur potentielle des crues et leur degré de dangerosité. Un calcul innovant combinant la profondeur et la vitesse de l'eau est utilisé pour classer la gravité des inondations et créer des cartes de risques claires. Ces cartes facilitent la prise de décisions de planification plus éclairées, aidant les villes à implanter judicieusement leurs infrastructures, à se préparer aux situations d'urgence et à réduire les risques dans des environnements en pleine croissance et exposés aux inondations.





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## Abstract

This paper presents an innovative approach to flood hazard classification aimed at enhancing resilient urban development in the NEOM region of Saudi Arabia. The study, conducted by AtkinsRéalis, involved comprehensive hydrologic and hydraulic analysis to evaluate flood risks in this arid region characterized by intense flash flood events. Utilizing a 2-dimensional rain-on-grid modeling approach with the USACE HEC-RAS model.

Key findings include the creation of detailed flood zone and flood hazard maps, which categorize the floodplain into three classifications based on flood extents for various AEP scenarios. The flood hazard classification integrates global methodologies and considers local conditions, providing critical insights for emergency response planning and infrastructure development. The innovative hazard classification formula— $\text{Depth} \times (\text{Velocity} + 0.5)$ —tailored for arid climates, offers a refined assessment of flood risks.

This framework supports sustainable land development and informs decision-making processes for infrastructure placement and emergency response, ultimately contributing to the resilience and safety of urban environments.

## KEYWORDS

Flood hazard; Sustainable urban planning; Innovation; Arid region hydrology

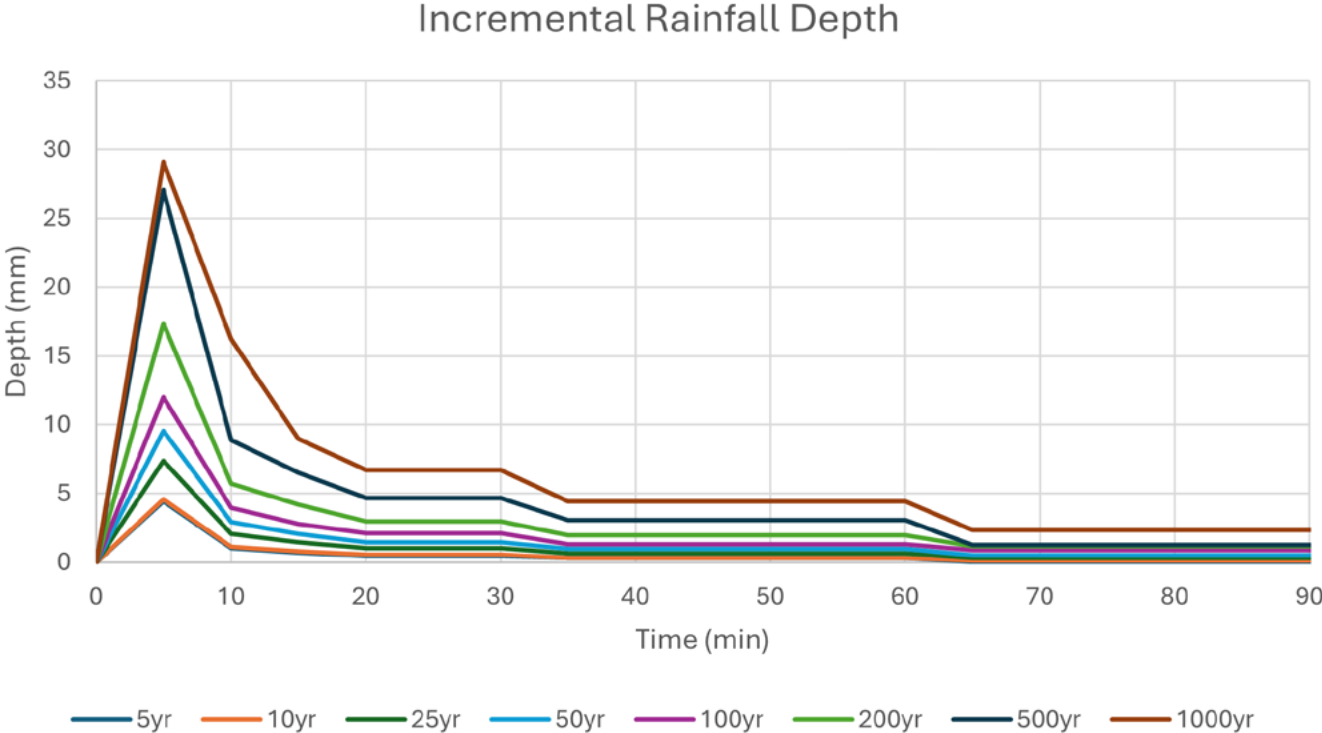
## 1. Introduction

As part of NEOM's visionary plan to develop a sustainable urban region within the Kingdom of Saudi Arabia, AtkinsRéalis was tasked to develop flood risk management data for the NEOM region. This involved detailed hydrologic and hydraulic modeling and using the outputs from the model to establish flood risk management products such as floodplains, flood zones, and flood hazard areas. The key principle underlying NEOM's flood risk management strategy is to protect the people and infrastructure/assets of NEOM's independent economic zones from flooding without increasing flood risk elsewhere in the region. Reliable flood zones and hazard classifications are vital for assessing flood risk and guiding sustainable and development near floodplains.

NEOM is in the northwest region of the Kingdom of Saudi Arabia. It has an arid climate with intense flash flood events. A review of the NEOM region-specific intensity duration frequency (IDF) curves and precipitation profiles, also developed by AtkinsRéalis, indicates that rainfall events are characterized by peak intensities within the first ten minutes (**Figure 1**). This implies limited warning time and underscores the need for a comprehensive and robust flood hazard study to support resilient urban planning.

FIGURE 1

Incremental Rainfall  
Depth for an area of  
interest in NEOM



## 2. Methodology

For the hydraulic model build and analysis, a 2-dimensional rain-on-grid modeling approach was employed. The hydraulic analysis was performed using the public domain United States Army Corps of Engineers (USACE) HEC-RAS model (version 6.5). The 'design runs' are based on flood probability (from 50% AEP to 0.1% AEP) and a suite of flood risk modeling simulations based on rainfall with durations up to 24 hours.

The model 2D domains, at a minimum, were equal to the contributing watershed for each model area or included inflow boundary conditions to ensure that all contributing flows into each model were accounted for. The computational mesh was also refined to capture all topographical features that impact the hydraulics, such as roads, floodplains, and dam embankments. A variable meshing scheme was implemented to ensure that detail was added in urbanized areas and within wide or steep Wadis (Channels), where detail was needed, without unnecessarily increasing the number of computational cells.

Another input for the geometry data was Manning's  $n$ . Manning's roughness coefficient ( $n$ ) is a critical parameter representing the resistance to flow due to channel surface roughness, vegetation, and other factors. These values influence the velocity and depth of water flow, which are essential for predicting flood behavior and developing flood hazard maps.

Rainfall losses were also modeled directly in the 2D rain on-grid models using the SCS Curve Number (CN) method by importing the developed CN grid into the model. The CN grid is a combination of land cover classes and hydrologic soil groups within the region. Rainfall losses are computed for each computational cell. Excess rainfall is then routed from computational grid cell to grid cell to generate flow rates and estimate hydraulic outputs such as water surface elevations (WSE), flow depths, and velocities. The land cover data and CN grid were generated for the NEOM region by AtkinsRéalis in 2022.

To appropriately calculate the overall maximum hazard map, the hazard calculation was done at each time step, rather than once, using the maximum depth and velocity values. The maximum of these individual time step calculations was then taken for each cell to produce an overall hazard value map. This was done because the maximum depth and maximum velocity may occur at different timesteps. A RAS calculator script was used to efficiently calculate the hazard value at each step. The script calculates the depth (D) and velocity (V) product, then classifies the D\*V, Depth, and Velocity values using the flood hazard classifications. For each watershed district, flood depths, water surface elevations, and peak velocity raster files were generated for each modeled scenario.

The flood hazard class RAS calculated layer was formatted to match the color schema from the original UNSW Water Research Laboratory reports classification plot (*Smith, Davey, & Cox, 2014*). This report provides comprehensive guidelines and methodologies for assessing flood risks by discussing the factors influencing flood hazards, including people, vehicles, and structural stability during flood events.

Floodplain and flood hazard maps were developed for each watershed district, delineating flood extents for 0.2% AEP, 1% AEP, and 10% AEP scenarios. The flood zones were categorized into three key classifications (**Table 1**):

- **Zone 1:** Areas between district boundaries and the 500-year floodplain.
- **Zone 2:** Areas between the 500-year and 100-year floodplains.
- **Zone 3:** Areas between the 100-year and 10-year floodplains, with the Channel Zone (Zone 3a) defined by the 10% AEP floodplain.

TABLE 1

Wadi Flood Zone Classes

Flood Zones	Level of Probability	Characteristics
<b>Zone 1</b>	Low	<ul style="list-style-type: none"> <li>✓ Land located outside of the 1 in 500-year flood extents (i.e., 0.2-percent AEP flood).</li> <li>✓ Land having a less than 0.2-percent annual probability of wadi flooding.</li> </ul>
<b>Zone 2</b>	Medium	<ul style="list-style-type: none"> <li>✓ Land located outside of the 1 in 100-year flood extents (i.e., 1-percent AEP flood) but inside of the 1 in 500-year flood extents (i.e., 0.2-percent AEP flood).</li> <li>✓ Land having between a 1-percent and 0.2-percent annual probability of wadi flooding.</li> </ul>
<b>Zone 3</b>	High	<ul style="list-style-type: none"> <li>✓ Land located inside of the 1 in 100-year flood extents (i.e. 1-percent AEP flood).</li> <li>✓ Land having a 1-percent or greater annual probability of wadi flooding. In general, development within this area should not be permitted.</li> </ul>
<b>Zone 3a</b>	Wadi Channel	<ul style="list-style-type: none"> <li>✓ Land forming the primary conveyance area of the wadi that must remain open in order to allow flood water to pass and to avoid significant flooding impacts. 1 in 10-year flood extents (i.e. 10-percent AEP flood) used to represent wadi channel</li> </ul>

These classifications, developed in collaboration with the client, integrate global flood risk methodologies and account for the region's lack of permanent rivers.

A flood severity grid was also created by integrating Depth, velocity, and depth-velocity metrics. This grid utilized benchmarks from studies in Australia (*Smith, Davey, & Cox, 2014*), the U.K. (*DEFRA, 2006*), and the U.S. (*FEMA, 2023*). Specific thresholds were established to evaluate impacts on people, vehicles, and buildings (**Table 2**):

- **Low Depth (0.0-0.3 m) with low velocity (0-1.0 m/s):**  
Small motor vehicles become unstable in flowing water.
- **Medium Depth (0.3-1.2 m) with Low Velocity (0.0-2.0 m/s):**  
Walking becomes dangerous.
- **Any Depth (0.0-4.0 m) with High Velocity (> 2.0 m/s):**  
Unsafe for people, vehicles, and buildings.

TABLE 2

Flood Hazard Classification  
Limits and Values

Hazard Classification	Description	Limiting Still Water Depth (m)	Limiting Velocity (m/s)	Depth*Velocity Range (m <sup>2</sup> /s)
1	Low Risk (Caution)	0.3	1.0	≤ 0.3
2	Medium Risk	1.2	2.0	≤ 0.6
3	High Risk	2.0	2.0	≤ 1.0
4	Very High Risk	4.0	4.0	≤ 4.0
5	Extreme Risk	-	-	> 4.0

### 3. Results

The final framework provided a detailed hazard classification matrix (Figure 2), offering critical insights for emergency response planning and infrastructure development (Figure 3 - HNFMSC, 2006).

FIGURE 2

Flood Hazard Classification

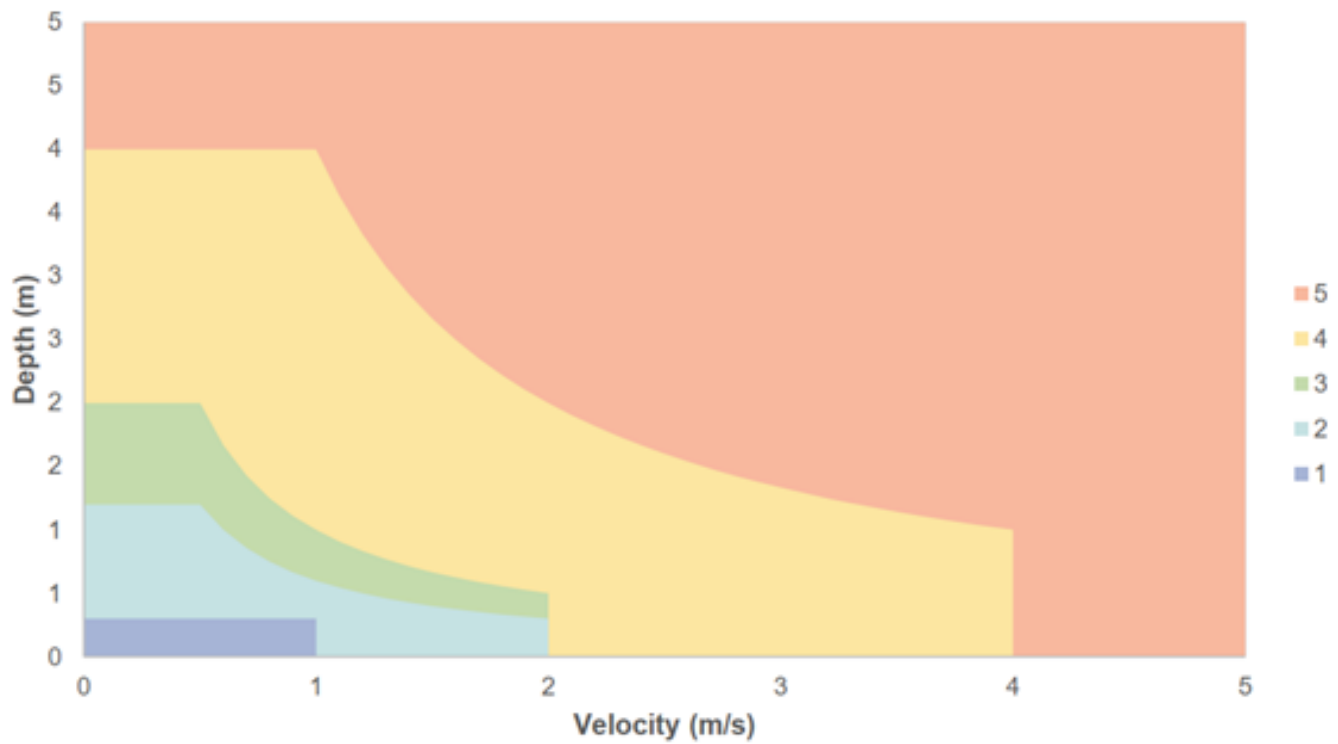


FIGURE 3

Distribution of Land uses  
on the Floodplain to reduce  
risk (HNFMSC, 2006)

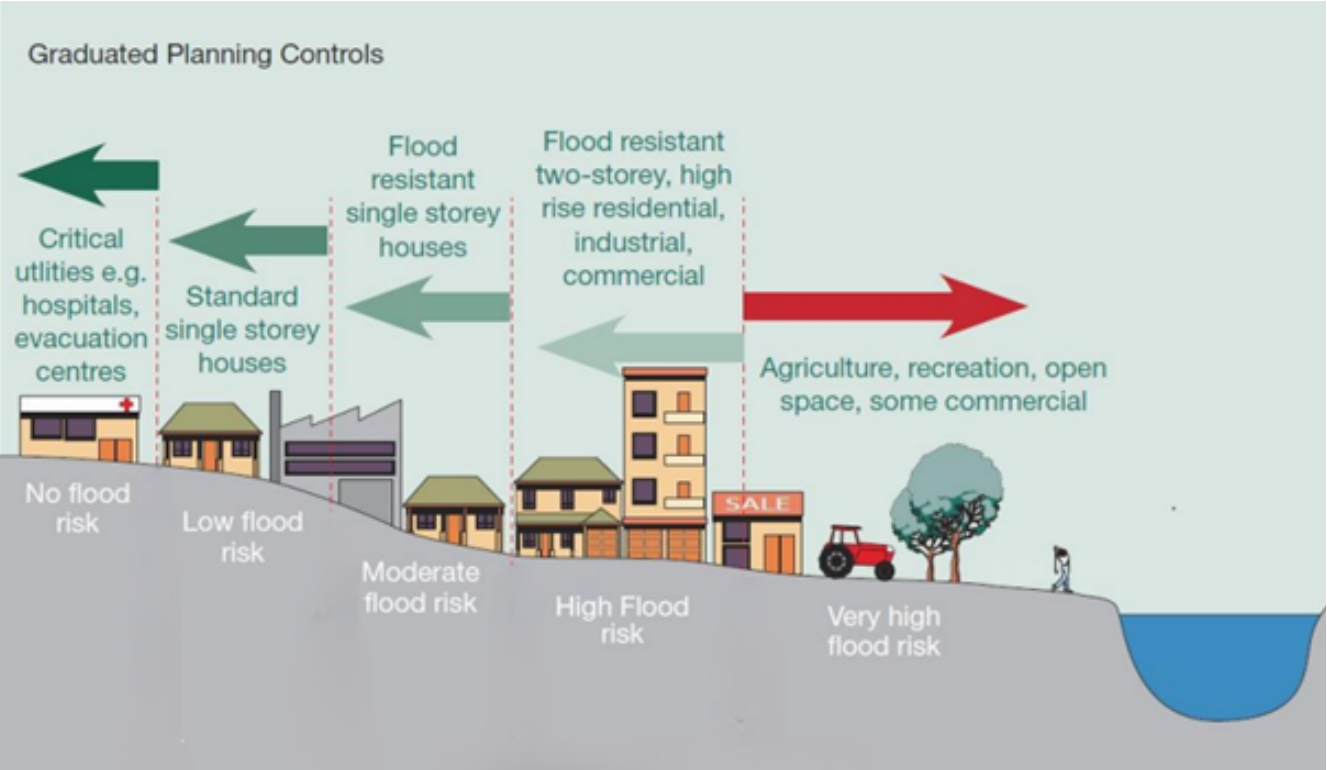
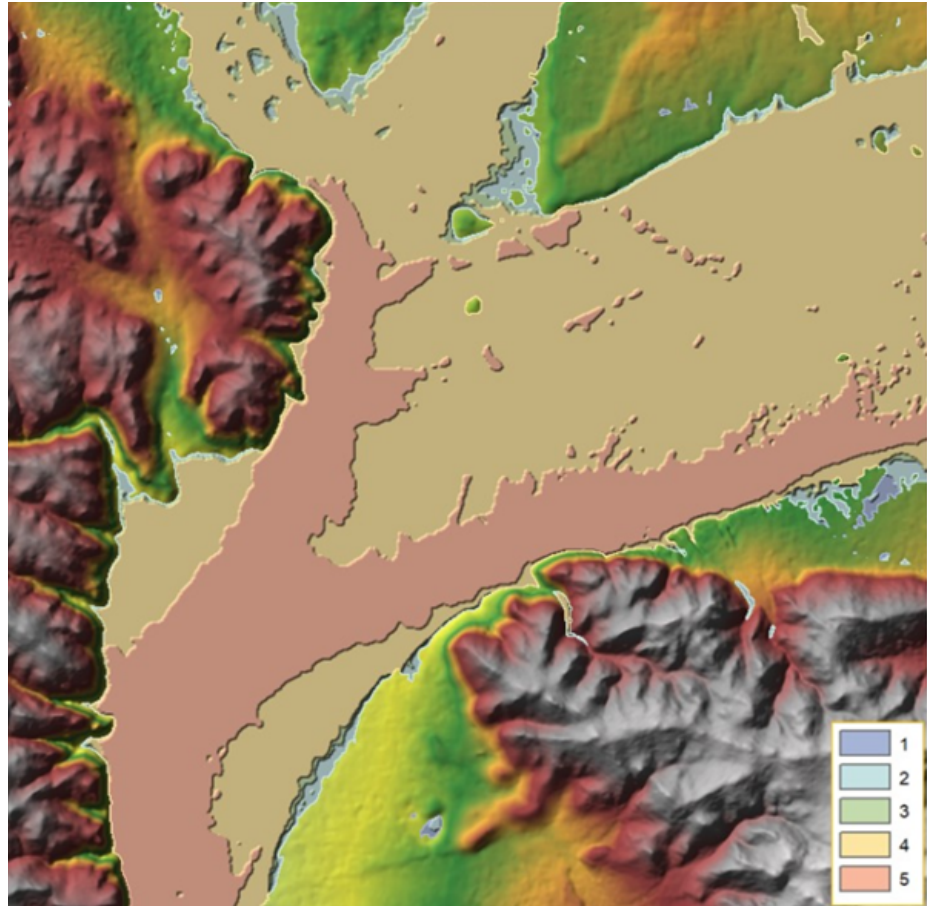


FIGURE 4

Example of the developed  
flood Hazard Map



Keeping the framework in mind, AtkinsRéalis created a Flood zone map and flood hazard classification for various areas of interest/economic zones (**Figure 4**).

## 4. Discussion

Flood risk assessment is an important consideration for those living in areas prone to flooding. Flood zone and hazard maps are commonly used to assess flood risk. A flood zone map typically shows areas likely to be affected by flooding, based on historical flood data, water flow patterns, and topography. Flood hazard maps, on the other hand, provide information on the likelihood and severity of flooding in a specific area, considering factors such as the depth and velocity of the flood. By analyzing these maps, individuals, communities, and government agencies can better understand the flood risk in a given area and take appropriate measures to prepare and mitigate the impact of potential flooding events.

Careful evaluation of development and construction in different flood zone areas is essential for ensuring public safety and minimizing the potential impact of flooding events. In areas designated as high-risk flood zones (Zone 2 and Zone 3), construction and development may be subject to stricter regulations and requirements to mitigate flood risk, such as elevating structures above the floodplain or building flood barriers. In some flood zones, development may be prohibited altogether in areas designated as very high flood-risk regions (Zone 3a) to minimize the potential loss of life and property damage. In lower-risk flood zones (Zone 1), development may be allowed with less stringent requirements, but still with some degree of flood risk assessment and mitigation measures in place. Additionally, in areas prone to flash flooding, development may require additional measures to address these events' sudden and rapid nature. Overall, the evaluation of development and construction in different flood zone areas must consider the potential risk and impact of flooding events and the need for appropriate mitigation measures to ensure public safety and minimize property damage.

The proposed classifications can guide regulatory authorities across the globe in determining suitable infrastructure placement and emergency response plans during flash floods. The hazard levels are defined as follows:

- **Low Risk:** Generally safe, with caution for individuals.
- **Medium Risk:** Unsafe for children and older adults.
- **High Risk:** Requires shelter-in-place warnings; unsafe for both people and vehicles.
- **Very High/Extreme Risk:** Evacuation is recommended; buildings may become structurally vulnerable.

## 5. Conclusion

AtkinsRéalis developed an innovative approach for flood hazard mapping using hydraulic modeling outputs such as floodplain inundation, Flood Depth raster, and Flood Velocity raster to build information about the degree (class) of the flood hazard within the areas of interest. AtkinsRéalis introduced an innovative hazard classification formula— $\text{Depth} \times \text{Velocity} + 0.5$ —tailored for the arid regions. This refinement adapts the "Flood Risk to People" methodology and FEMA's  $\text{Depth} \times \text{Velocity}$  approach to suit local conditions. The flood hazard maps categorize areas from Class 1 (low-risk) to Class 5 (extreme-risk).

Developing flood hazard maps prior to any construction is a vital step in planning, particularly in regions susceptible to flash flooding. As these events become increasingly frequent across the globe, integrating flood risk data early in the design process is essential. These maps enable authorities to identify high-risk zones, guiding the placement of critical infrastructure and emergency routes away from flood-prone areas. Local planners can also use them to assess all viable access routes to and from vulnerable sites. Incorporating flood hazard maps into planning enhances urban resilience, reduces potential damage, and supports long-term economic stability.

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# 03: Circular Economy Implementation in the Water Sector: An Integrated Framework and Indicator-Based Approach for Sustainable Urban Water Management

## Significance Statement

Urban water systems worldwide remain largely linear, increasing vulnerability to water scarcity, climate variability, and resource depletion. This study advances Circular Economy implementation in the water sector by integrating a standardized 6R framework with the Water Circularity Indicator (WCI), a single, interpretable metric grounded in mass-balance accounting. By clarifying Circular Economy terminology, defining decision-relevant system boundaries, and linking strategy to quantitative assessment, the work addresses key gaps limiting practical adoption. The proposed framework and indicator enable utilities and planners to benchmark performance, compare intervention portfolios, and prioritize investments that reduce virgin water withdrawals and linear discharges while enhancing system resilience and sustainability.

## Énoncé d'importance

Partout dans le monde, les systèmes d'approvisionnement en eau urbains restent largement linéaires, ce qui accroît leur vulnérabilité face à la pénurie d'eau, à la variabilité climatique et à l'épuisement des ressources. Cette étude fait progresser la mise en œuvre de l'économie circulaire dans le secteur de l'eau en intégrant un cadre standardisé des 6R à l'indicateur de circularité de l'eau (WCI), un indicateur unique et interprétable fondé sur la comptabilité du bilan massique. En clarifiant la terminologie de l'économie circulaire, en définissant les limites du système pertinentes pour la prise de décision et en reliant la stratégie à l'évaluation quantitative, ce travail comble les lacunes clés qui limitent son adoption pratique. Le cadre et l'indicateur proposés permettent aux services publics et aux planificateurs d'établir des références pour les performances, de comparer les portefeuilles d'interventions et de hiérarchiser les investissements qui réduisent les prélèvements d'eau vierge et les rejets linéaires tout en renforçant la résilience et la durabilité du système.



REDUCE



REUSE



RECYCLE



RECLAIM



RECOVER



RESTORE



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## Abstract

Increasing urbanization and rapid depletion of natural resources have compelled authorities to transition from traditional linear models of take-make-use-dispose to circular systems centred on resource conservation. Circular Economy (CE) is a sustainable development approach that works on the waste management strategies of Reduce, Reuse, Recycle, and Recover (R strategies). Considerable work has been performed on CE in various sectors, including electronics, construction, and automotive. However, CE in the water sector has recently gained attention, driven by increasing water scarcity, uneven distribution of water resources, and the persistence of linear management practices worldwide. Water Circularity, built on the six R-strategies i.e., Reduce, Reuse, Recycle, Recover, Reclaim, and Restore; offers a transformative blueprint for sustainable development in the sector. Finally, an indicator called “Water Circularity Indicator (WCI)” is proposed as a quantitative tool that evaluates circularity in urban water systems. This paper synthesizes insights from two peer-reviewed publications and integrates them with new analysis to present a unified CE framework supported by a WCI indicator to assess, promote, and improve CE implementation in the water sector. The manuscript advances prior studies by clarifying CE terminology, demonstrating indicator-based application pathways, and presenting actionable strategies for utilities and practitioners.

## KEYWORDS

Water Circularity; Reduce; Reuse; Recycle; Reclaim; Restore

## 1. Introduction

Rapid urbanization, evolving consumption patterns, climate variability, and aging infrastructure are intensifying pressure on urban water systems. Globally, the urban share of population continues to rise, material consumption is increasing, and both water quantity and quality are under stress, with multiple regions classified as water-stressed or water-scarce (UN-DESA, 2018; Hoekstra et al., 2018; WRI, 2019). Untreated or insufficiently treated wastewater still accounts for a large fraction of discharges, posing persistent public health and ecological risks (WWAP, 2017; WHO, 2018). These pressures are compounded by a prevailing linear management model of extract-use-dispose, which maximizes withdrawals and outflows while minimizing internal recirculation of water and embedded resources (Daigger, 2009).

Circular Economy (CE) provides a systems framework to reconfigure urban water management toward reduced dependence on virgin sources, increased reuse, reclamation and recycling, recovery of energy and nutrients, and restoration of natural stocks. The CE concept, rooted in ecological economics and resource stewardship (Pearce and Turner, 1990; Stahel, 1982), has been widely propagated across sectors through the work of the Ellen MacArthur Foundation and others (EMF, 2017; Lieder and Rashid, 2016; Winans et al., 2017). In the water sector, CE adoption has grown steadily in the past decade across research and practice (Nika et al., 2020; Smol et al., 2020; Mhatre et al., 2021), supported by evidence of successful recycling, reuse, and reclamation programs at multiple scales, including city and utility examples from the United States, Europe, Israel, Singapore, and Australia (Angelakis and Gikas, 2014; Jiménez and Asano, 2008).

Operationally, CE in the water sector is articulated through the 6R strategies i.e., Reduce, Reuse, Recycle, Reclaim, Recover, Restore; that together target lower withdrawals, greater recirculation, and replenishment of stocks (Kakwani and Kalbar, 2020). Nevertheless, inconsistent usage of 6R terminology (particularly "Reuse," "Recycle," and "Reclaim") has been documented, complicating planning, stakeholder communication, and policy design (Blomsma and Tennant, 2020). Standardized definitions and system boundaries are required to ensure consistent implementation and reporting across utilities and jurisdictions.

Further, progress in urban water assessment frameworks, urban water metabolism, mass-balance models, and indicator suites has yielded valuable tools, but most were not designed to quantify circularity as a single interpretable outcome for the engineered urban water system. Literature reviews highlight several recurring limitations: (i) focus on a subset of lifecycle stages (e.g., treatment or supply) rather than the complete engineered cycle; (ii) aggregation of anthropogenic and hydrologic fluxes that reduces decision relevance for utility operations; and (iii) absence of concise metrics capturing the combined effects of reductions, reuse, recycling, reclamation, restoration, and losses on dependence on virgin withdrawals and linear discharges (Singh et al., 2009; Kalmykova, Sadagopan and Rosado, 2018; Parchomenko et al., 2019; Saidani et al., 2019). Complementary system-modeling tools—Aquacycle, UrbanCycle, UWOT, WaterMet, and dynamic metabolism models provide scenario insights but remain data-intensive and not directly aligned to a single circularity index for benchmarking and portfolio selection (Mitchell, Mein and McMahon, 2001; Makropoulos et al., 2008; Rozos and Makropoulos, 2012; Behzadian and Kapelan, 2015; Venkatesh et al., 2017).

Addressing these gaps, the Water Circularity Indicator (WCI) was formulated as a decision-support metric adapted from the Material Circularity Indicator (EMF and Granta Design, 2015) and grounded in urban water mass-balance accounting. WCI consolidates key engineered flows i.e., virgin inputs, returns from reuse/recycling/reclamation, restoration to ambient stocks, and losses/discharges—into a single index bounded between 0 and 1, where higher values denote lower dependence on virgin withdrawals and lower linear discharges. Validation across representative scenarios and comparison against established indicators indicate that WCI correlates with broader sustainability metrics while uniquely capturing the multidimensional effects of CE strategies in an interpretable form suitable for planning and long-term monitoring (Kakwani and Kalbar, 2022).

Beyond metrics, transitions to CE depend on enabling policy, governance, and market conditions. Reviews synthesize barriers including fragmented institutional responsibilities, uneven regulatory guidance, financing hurdles for decentralized/resource-recovery technologies, and variable public acceptance; conversely, opportunities exist in district-scale reuse networks, industrial symbiosis, biosolids valorization, and energy-positive treatment (e.g., anaerobic digestion) (Verstraete and Diamantis, 2009; Mo and Zhang, 2013; Batstone and Viridis, 2014; Puyol and Batstone, 2017). These findings motivate the pairing of a clarified CE vocabulary with a fit-for-purpose circularity metric to support credible roadmaps and investment decisions.

**Objectives.** Building on the prior peer-reviewed literature, this article advances a practitioner-oriented approach to CE in urban water systems with four objectives:

1. Standardize terminology and scope by harmonizing CE definitions for water and wastewater applications and mapping the 6R strategies to engineered system boundaries to reduce ambiguity in planning and reporting.
2. Position a circularity metric by summarizing limitations of existing indicators and outlining the WCI as a concise, interpretable metric for benchmarking and scenario analysis.
3. Link strategy to workflow by outlining implementation pathways that connect CE strategies and WCI-based analytics to master-planning and design workflows, identifying decision points where circular interventions yield the greatest system-level gains.
4. Demonstrate interpretability through an illustrative case application showing how WCI supports benchmarking and portfolio selection under realistic assumptions and constraints.

By positioning CE as the overarching framework and WCI as the quantitative anchor, the article proposes an actionable bridge between concept and day-to-day decisions that reduce virgin withdrawals and linear discharges while increasing beneficial recirculation of water and embedded resources in urban systems.

## 2. Circular Economy in Urban Water Systems

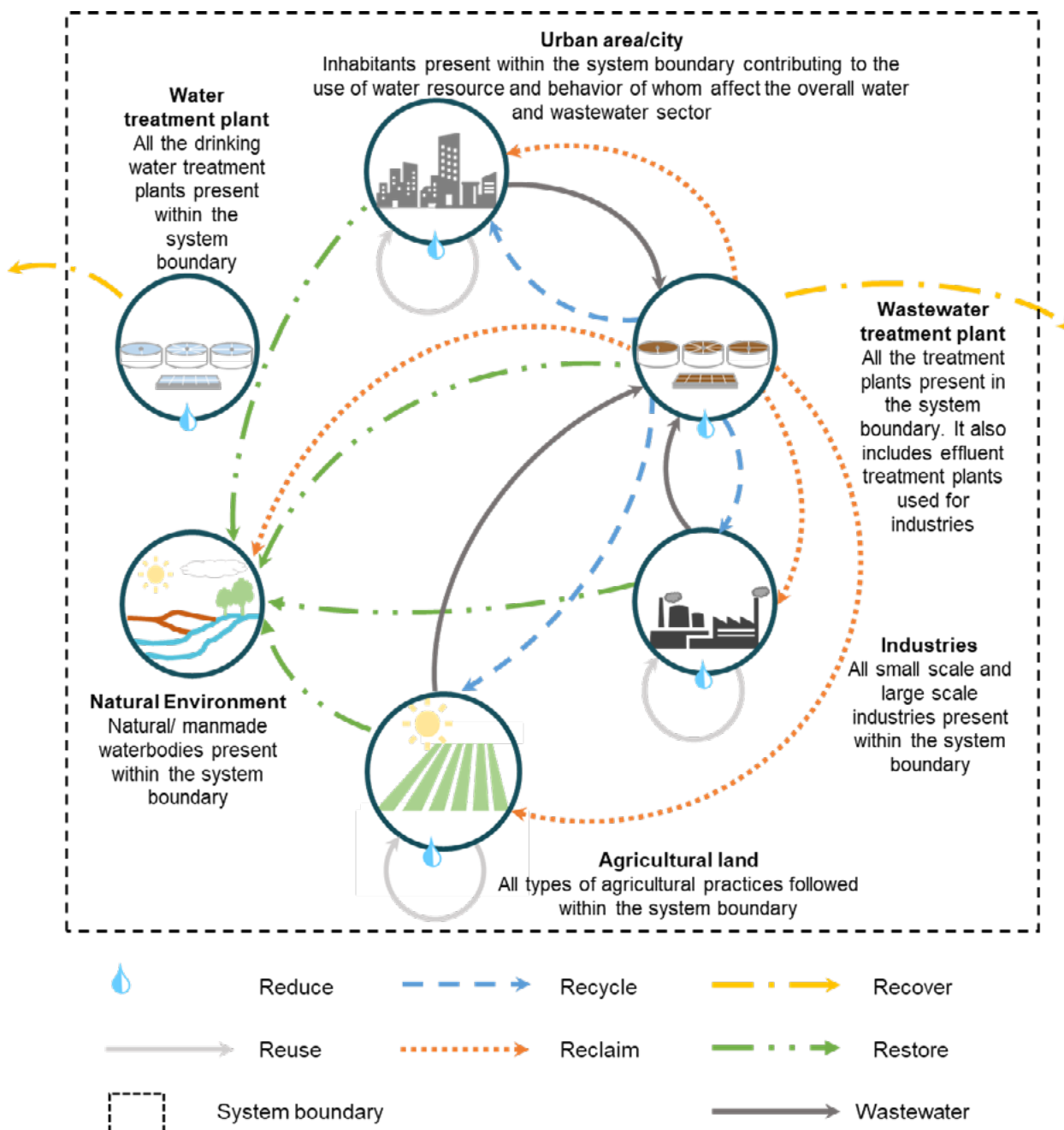
### 2.1 THE 6R STRATEGIES

CE in the water sector is anchored in resource stewardship and systemic efficiency. The 6R-strategies (Reduce, Reuse, Recycle, Reclaim, Recover, and Restore) as shown in Figure 1 have been widely referenced as the backbone of CE approaches (Kakwani and Kalbar, 2020). The earlier manuscript also identified frequent misuse and overlap among the terms “Reuse,” “Recycle,” and “Reclaim,” underscoring the need for standardized nomenclature to support planning and communication.

- **Reduce:** Minimizing water demand through efficiency measures and system optimization.
- **Reuse:** Utilizing water from a previously used source without treatment inside or outside the loop.
- **Recycle:** Applying advanced treatment processes to reintegrate water within the same loop.
- **Reclaim:** Reintroducing treated water for non-potable or potable applications outside the loop.
- **Recover:** Capturing nutrients, energy, or materials from wastewater streams.
- **Restore:** Rehabilitating ecosystems through artificial interventions.

FIGURE 1

Urban water cycle considering 6Rs strategies of Circular Economy in urban water sector. Adopted from Kakwani and Kalbar (2020)



## 2.2 BARRIERS TO 6R IMPLEMENTATION

### **Terminology and framework fragmentation.**

Inconsistent use of 6R terms and heterogeneous scope across frameworks impede comparability and inhibit coherent program design. Review of CE assessments reports a lack of consensus on definitions and indicator scope, reinforcing the need for sector-specific standardization.

### **Governance and regulatory alignment.**

Fragmented institutional responsibilities, unclear reuse/reclamation standards, and gaps in supportive policy instruments are widely cited impediments. Social and legal dimensions—policy acceptance, safety standards, and oversight—remain critical bottlenecks even where technology is available (e.g., governance analyses in urban reuse/reclamation and country-level CE adoption).

### **Economic and financial hurdles.**

Capital intensity for decentralized systems and resource-recovery retrofits, uncertain revenue streams for recovered products, and limited alignment of funding mechanisms with circular objectives constrain adoption. Literature emphasizes the role of robust business models and life-cycle costing to complement technology selection.

### **Technical readiness and operational risk.**

While anaerobic digestion, advanced nutrient recovery, and membrane processes have matured, reliability at different scales, integration with legacy assets, and site-specific effluent quality targets can challenge deployment. Decentralized systems offer circular benefits but may introduce health-risk management and O&M complexity if governance and monitoring are insufficient.

**Data, metrics, and decision relevance.**

Prior sustainability frameworks often mix anthropogenic and hydrologic fluxes or target only parts of the cycle (e.g., treatment or supply), making them less actionable for utility operations. The absence of a concise, **interpretable circularity metric** limits benchmarking and portfolio comparisons across cities and scenarios.

**Public acceptance and risk perception.**

Despite long-running successful programs internationally, potable and non-potable reuse can face acceptance hurdles without fit for purpose risk communication and engagement strategies.

**2.3 OPPORTUNITIES ACROSS THE 6R STRATEGY SET**

**Reduce - demand and loss management.**

Short-horizon, cost-effective measures include leakage reduction and efficient fixtures. Distribution losses of 30–40% reported in some contexts illustrate the scale of recoverable efficiency; targeted non-revenue-water programs directly lower virgin withdrawals and wastewater generation.

**Reuse - cascading use without treatment.**

Reuse can alleviate freshwater demand in water-scarce regions and is already practiced in multiple urban and peri-urban settings (e.g., agricultural reuse of partially treated flows), though health and environmental safeguards must be addressed.

**Recycle - treated water within the same loop.**

Greywater recycling and industrial process water recycling reduce peak demands on potable systems and can often be integrated through modular treatment with a relatively short payback in high-tariff contexts.

**Reclaim - treated water used outside the source loop.**

Advances in treatment allow reclaimed water to meet potable or non-potable standards, enabling city- or district-scale substitution for fresh sources in industry, irrigation, or indirect/direct potable reclamation schemes. Successful international cases demonstrate technical feasibility across climates and governance models (e.g., examples compiled for the United States, Israel, Singapore, Australia, Cyprus, Greece, Spain, and others).

**Recover - energy and materials from residuals.**

Anaerobic digestion, struvite precipitation, biosolids valorization, and emerging biorefinery concepts can convert treatment facilities from cost centers into resource hubs, supporting energy-positive operations and fertilizer production while mitigating sludge disposal challenges.

**Restore - recharging ambient stocks.**

Managed aquifer recharge and lake/river rejuvenation projects can buffer seasonal scarcity, enhance groundwater storage, and improve ecosystem services when aligned with source control and tertiary treatment.

**Enabling analytics - prioritization and monitoring.**

To translate opportunities into investment roadmaps, a circularity-specific metric is required. The Water Circularity Indicator (WCI) provides a bounded, interpretable index that consolidates virgin inputs including losses/discharges, reuse/recycling/reclamation returns, restoration outflows, for direct comparison of scenarios and long-term performance tracking. This addresses prior limitations of fragmented indicators and supports evidence-based portfolio selection and target setting.

**Implications for Practice.**

A programmatic CE roadmap benefits from: (i) terminology alignment across agencies and contractors; (ii) policy instruments that de-risk reuse/reclamation and resource-recovery investments; (iii) phased portfolios that start with Reduce/Recycle quick wins and evolve toward Reclaim/Recover at scale; and (iv) indicator-driven monitoring using WCI to benchmark progress and maintain transparency with regulators and communities. This integrated approach links the conceptual 6R framework to engineered system boundaries and day to day decisions, enabling credible reductions in virgin withdrawals and linear discharges while increasing beneficial recirculation of water and embedded resources.

### 3. Measuring Circularity: The Water Circularity Indicator (WCI)

#### 3.1 PURPOSE AND RATIONALE

The Water Circularity Indicator (WCI) provides a single, interpretable metric (0-1) that quantifies how effectively an engineered urban water system reduces dependence on virgin withdrawals and limits linear discharges by increasing internal recirculation via the 6R strategy set. Conceptually adapted from the Material Circularity Indicator developed by the Ellen MacArthur Foundation and Granta Design, WCI translates circular-economy principles into mass-balance accounting suitable for utility planning and monitoring.

#### 3.2 SYSTEM BOUNDARY AND SCOPE

WCI is defined on the engineered urban water system: centralized/decentralized supply, distribution, consumption, collection, treatment, reuse/recycling/reclamation, restoration, and discharge. Hydrologic processes (precipitation, evapotranspiration, infiltration, runoff) remain outside scope to preserve decision relevance for asset planning and operations. Within this boundary, WCI consolidates:

- **Virgin inputs:** volumes extracted from surface/groundwater or imported supplies.
- **Returns to use:** reuse (no treatment), recycling (treated water used within the same loop), and reclamation (treated water used outside the originating loop).
- **Restoration:** treated flows intentionally returned to ambient stocks (e.g., managed aquifer recharge, water body rejuvenation).
- **Losses/discharges:** leakages, evaporation and human-consumption losses, and untreated or unutilized treated effluents leaving the boundary.

Note on the 6Rs: WCI explicitly incorporates Reduce, Reuse, Recycle, Reclaim, Restore through the mass-balance terms; Recover (energy/nutrient/materials) is not directly volumetric and is therefore tracked in complementary indicators rather than in WCI's numerator/denominator.

### 3.3 DATA INPUTS AND NOTATION

The indicator uses standard flow terms and dimensionless fractions already familiar to utilities:

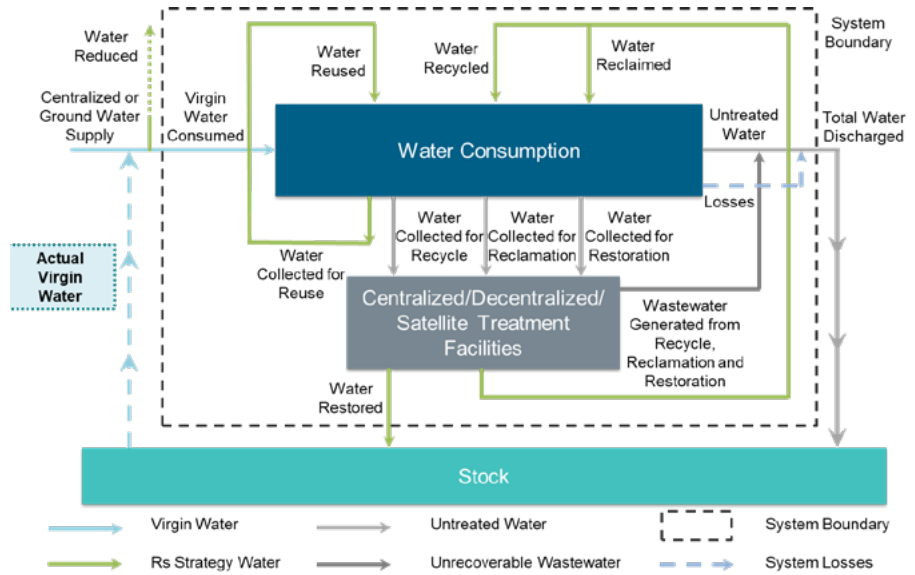
- $S$ : freshwater supplied;  $C$ : water consumed;  $V_c$  virgin water consumed;  $V$ : actual virgin water (after deducting restored volumes);  $W$ : total water discharged outside the boundary.
- Fractions:  $F_{Ru'}$ ,  $F_{Re'}$ ,  $F_{Rc'}$ ,  $F_{Rst}$  (Reuse, Recycle, Reclaim, Restore); collection fractions  $C_{Ru'}$ ,  $C_{Re'}$ ,  $C_{Rc'}$ ,  $C_{Rst'}$ ; usage efficiencies  $E_{Ru'}$ ,  $E_{Re'}$ ,  $E_{Rc'}$ ,  $E_{Rst'}$ ; losses  $L$ .
- Practical assumption often used for initial studies: **80% return factor** (wastewater fraction of water supplied), implying nominal **20% losses**—subject to local calibration.

### 3.4 COMPUTATIONAL LOGIC (MASS-BALANCE VIEW)

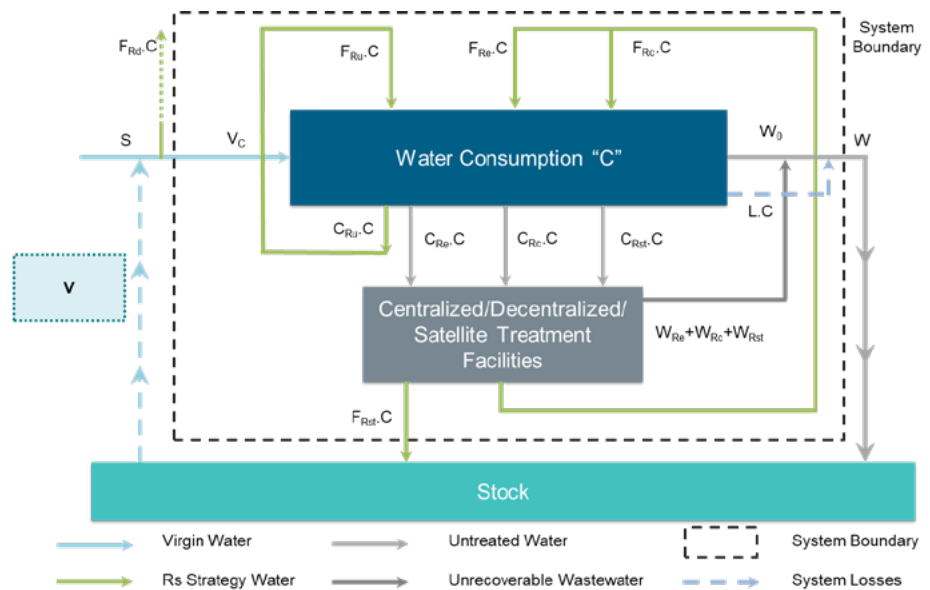
WCI aggregates linearity across consumption and disposal phases and expresses circularity as the complement (bounded 0–1). The derivation and full term definitions are documented in the original formulation; the workflow below mirrors that derivation while keeping utility data systems in mind. Refer to Figure 2 to understand the water flow inside the system boundary and terms used to derive WCI.

FIGURE 2

System boundary and water flows considered to determine Water Circularity Indicator. Dotted lines indicate indirect flows. Stock includes all types of water bodies such as lakes, rivers, ponds, large storage reservoirs, which are considered outside the system boundary. Urban water consumption and wastewater treatment take place within the system boundary. Adopted from Kakwani and Kalbar (2022)



(a) Water Circularity Indicator (WCI) actual flows



(b) Water Circularity Indicator (WCI) notations

**Step-wise workflow (for a given planning year or scenario):**

1. **Estimate total consumption  $C$**  from supply  $S$  and the Reduce fraction  $F_{Rd}$

$$C = S \times (1 - F_{Rd}).$$

2. **Compute virgin water consumed:**

$$V_C = C \times (1 - F_{Ru} - F_{Re} - F_{Rc}).$$

3. **Account for restoration** to ambient stocks and obtain actual virgin water:

$$V = V_C - (F_{Rst} \times C).$$

4. **Compute untreated discharge  $W_0$**  using the assumed/estimated return factor and collected fractions for reuse/recycling/reclamation/restoration and losses  $L$ ; include wasted portions of treated flows when usage efficiencies are <100% (i.e.,  $W_{Re}$ ,  $W_{Rc}$ ,  $W_{Rst}$ ).

5. **Total discharge** leaving the boundary:

$$W = W_0 + W_{Re} + W_{Rc} + W_{Rst} + (L \times C).$$

6. **Linear Flow Index (LFI)** across both phases (consumption and disposal):

$$LFI = \frac{V+W}{2C}.$$

7. **Water Circularity Indicator:**

$WCI = 1 - LFI$  the bounded output is **0** (fully linear) and near **1** (fully circular).

**Implementation tip:** LFI and WCI can be computed with monthly or annual data; monthly resolution improves sensitivity analysis for seasonal supply, demand, and restoration dynamics.

### 3.5 INTERPRETING WCI

**Directional meaning:** Higher WCI indicates lower virgin dependence and lower linear discharge for a given consumption level, achieved through gains in Reduce, Reuse, Recycle, Reclaim, and Restore.

**Portfolio comparison:** Scenario A may emphasize non-revenue-water reduction and greywater recycling; Scenario B may prioritize district-scale reclamation and managed aquifer recharge. WCI allows comparison on a common scale while component diagnostics reveal *why* scores differ.

**Benchmarking:** A city moving from modest reuse and high losses to expanded recycling/reclamation with 15% leakage reduction can exhibit a significant WCI increase— case analyses where composite changes in  $F_{Re}$ ,  $F_{Rc}$ ,  $F_{Rst}$ , and  $L$  drive the index upward.

### 3.6 ASSUMPTIONS, SENSITIVITIES, AND DATA QUALITY

Key sensitivities include the return factor, loss fraction, and usage efficiencies of treated streams. The 80% return and 20% loss figures frequently used for first-order analyses should be calibrated to local monitoring data (e.g., smart metering, NRW audits, plant SCADA) to avoid biasing WCI. Reported values must state assumptions, data year, and system boundary explicitly.

### 3.7 REPORTING GUIDANCE FOR UTILITIES AND PROJECTS

For transparent adoption in planning and reporting, the recommended practice is to:

1. **State the boundary** (engineered flows only) and **time basis** (monthly/annual).
2. **Disclose assumptions** (return factor, losses, usage efficiencies); include data sources.
3. **Report component contributions** (shares of reuse/recycling/reclamation/restoration and losses) alongside the single WCI value.
4. **Pair WCI with complementary indicators** for **Recover** (energy, nutrients, materials) to reflect non-volumetric circularity gains.

## 4. Implementation Pathways for Utilities

Effective adoption of Circular Economy (CE) in the urban water sector requires phased, pragmatic pathways that align technical, regulatory, operational, and financial considerations. The 6R strategies provide the structural backbone for designing interventions, while the Water Circularity Indicator (WCI) enables consistent monitoring and prioritization across scenarios. The pathways below synthesize actionable steps for utilities based on documented challenges and enablers within the literature.

### 4.1 SHORT-TERM PATHWAYS: FOUNDATIONAL ACTIONS

Short-term interventions emphasize low-cost, high-impact measures that reduce demand pressure and improve baseline system efficiency.

- **Non-revenue water (NRW) reduction** programs can significantly lower losses, especially in regions where **30–40% leakage** is documented. Such reductions immediately decrease both virgin water withdrawal and wastewater generation.
- **Greywater reuse pilots** in high-demand facilities (commercial, institutional) establish early circular practices and build public familiarity with non-potable reuse.
- **Awareness and behavioral interventions** (efficient fixtures, metering, tariff design) align with the Reduce strategy and can be deployed quickly without major capital investment.
- **Baseline WCI assessments** provide a diagnostic of linearity (virgin input + discharge) and identify immediate leverage points such as reducing losses or increasing reuse fractions.

These actions serve as entry points that build institutional momentum and support future phases.

## 4.2 MEDIUM - TERM PATHWAYS: SYSTEM INTEGRATION AND EXPANSION

Medium-term strategies involve integrating CE principles into major urban water subsystems while diversifying circular benefits.

- **District-scale reclaimed-water networks** for industrial, landscape, or commercial uses expand *Reclaim* pathways and reduce demand on potable systems.
- **Stormwater harvesting and infiltration systems** (aligned with *Restore*) strengthen local water security while providing climate-resilience co-benefits.
- **Energy and nutrient recovery upgrades** at wastewater treatment facilities transition plants toward resource-recovery operations, leveraging technologies such as anaerobic digestion and struvite precipitation.
- **Integration of WCI into master planning** helps utilities evaluate portfolios under different demand, reuse, and treatment configurations. The indicator's sensitivity to reuse/recycling/reclamation fractions makes it especially useful in scenario optimization.

These efforts typically require coordinated planning across engineering, regulatory, and operations teams and benefit from clear governance frameworks.

### 4.3 LONG-TERM PATHWAYS: TRANSFORMATIVE CIRCULAR SYSTEMS

Transformational pathways aim to embed circularity as a core principle in long-range urban water strategies.

- **Potable reuse**—direct or indirect—represents a high-impact shift that substantially reduces virgin dependence, supported by advanced treatment technologies and demonstrated success internationally.
- **City-scale CE-integrated master plans** embed 6R strategies, long-term leakage targets, reclaimed-water pipelines, biosolids valorization systems, and restoration corridors into capital planning cycles.
- **Digital twins paired with WCI monitoring** enable real-time tracking of circularity performance, giving utilities the capacity to model future interventions, monitor efficiencies, and communicate progress transparently.
- **Resource-recovery ecosystems**—energy-positive treatment plants, urban biofactories, decentralized reuse hubs—support broader circular-economy transitions across industrial, agricultural, and municipal interfaces.

Long-term interventions require institutional maturity, regulatory alignment, and sustained investment, but they deliver significant resilience, sustainability, and cost-recovery benefits.

#### **4.4 ROLE OF WCI IN UTILITY DECISION-MAKING**

WCI helps utilities:

- Prioritize interventions based on their influence on circularity (e.g., reducing losses vs. expanding recycling).
- Benchmark performance across districts or time periods.
- Support communication with regulators, funders, and the public using a single intuitive index.
- Design portfolios that balance cost, environmental benefits, and circularity improvements.

#### **4.5 CASE STUDY: ILLUSTRATIVE APPLICATION OF THE WATER CIRCULARITY INDICATOR (WCI)**

To demonstrate practical use of the WCI, an illustrative mid sized urban system is evaluated using the parameters, system boundaries, and computational structure defined in the WCI development framework. To validate the outcomes, a hypothetical case study where 100 scenarios were generated using random numbers to represent variations across all the 5Rs, reflecting real-life operational and environmental conditions. The results from these 100 scenarios were found to be adequate for capturing the impacts on WCI (refer Figure 3). Extending the analysis beyond 100 scenarios produced a similar trend in WCI values, confirming that 100 scenarios provide a robust basis for evaluating variations and their influence on overall circularity outcomes. The purpose of this case study is to show how circularity performance responds to changes in water-system configurations and to highlight how WCI can support utility decision-making and intervention prioritization.

#### 4.5.1 Baseline System Characteristics

The baseline scenario reflects a typical urban water cycle with centralized supply, conventional wastewater treatment, and limited reuse or reclamation. Urban systems of this type often exhibit substantial losses, estimated at 20% through human consumption, physical leakage, and evaporation in the WCI framework, and minimal return of treated water to beneficial use, resulting in low reuse/recycle/reclaim fractions. These mass-balance assumptions align with return factors of 80%, widely applied in urban water studies.

For the baseline condition, assumed parameters include:

- High external water dependency, with most freshwater sourced from surface or groundwater supplies.
- Limited reuse (<10%) and negligible recycling or reclamation.
- Conventional wastewater discharge pathways without systematic restoration to groundwater or surface water stocks.
- System losses consistent with documented values in comparable urban contexts.

These conditions produce a baseline WCI value in the lower range (e.g., ~**0.40–0.45**), signaling high linearity—high virgin extraction and high discharge relative to internal recirculation.

#### **4.5.2 Intervention Scenario**

The intervention scenario demonstrates how targeted changes in 6R strategies shift circularity performance. In the WCI validation work, 100 scenarios were tested to evaluate how variations in the 5Rs used in the WCI formulation influence overall circularity. The following intervention elements are consistent with those scenarios:

- Fifteen percent reduction in losses achieved through enhanced leak detection, fixture efficiency, and operational improvements.
- Introduction of decentralized reuse systems, increasing the reuse fraction significantly.
- Investment in wastewater treatment upgrades enabling recycling and reclamation, with treated flows returning to both the same use loop and external applications.
- A portion of treated water allocated to restoration (e.g., managed aquifer recharge), reducing the effective virgin-water burden.

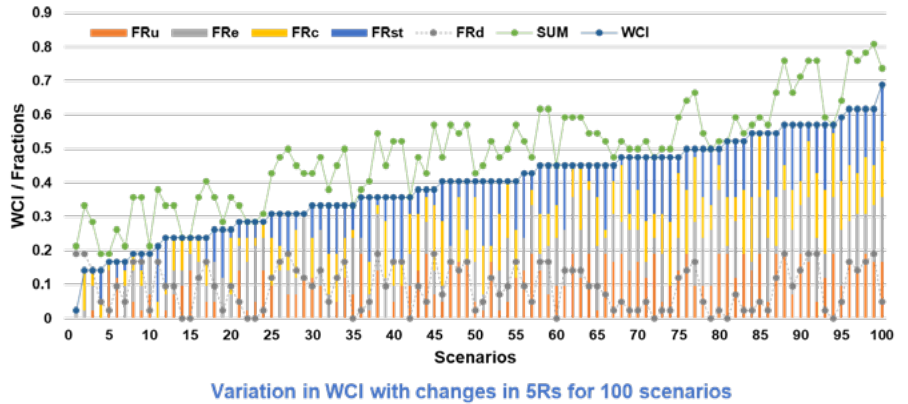
These improvements modify both supply-side and post-treatment pathways, tightening the engineered water loop.

### 4.5.3 Summary of Case Insights

The illustrative case underscores the value of WCI as a planning and benchmarking tool. Even modest shifts toward decentralized reuse, leak reduction, and recovery-enabled treatment can substantially improve circularity scores. WCI thus provides a diagnostic lens for utilities to compare scenarios, identify impactful investment pathways, and communicate progress transparently.

FIGURE 3

Variation of Water circularity indicator (WCI) in 100 scenarios with 5Rs (reduce, reuse, recycle, reclaim, restore);  $F_{Rd}$  – Fraction of water consumption reduced;  $F_{Ru}$  – Fraction of water reused;  $F_{Re}$  – Fraction of water recycled from wastewater treatment facilities;  $F_{Rc}$  – Fraction of water reclaimed from wastewater treatment facilities;  $F_{Rst}$  – Fraction of water restored from wastewater treatment facilities; Sum =  $F_{Rd} + F_{Ru} + F_{Re} + F_{Rc} + F_{Rst}$ .  
Adopted from Kakwani and Kalbar (2022)



## **5. Alignment with AtkinsRéalis Strategy**

The integrated Circular Economy (CE) and Water Circularity Indicator (WCI) framework aligns directly with AtkinsRéalis' organizational priorities in sustainable infrastructure, climate resilience, digital transformation, and resource efficiency. As global water systems face escalating stress from climate change, urbanization, and aging assets, engineering practices that prioritize circularity provide clear pathways for enhancing system resilience while enabling clients to meet emerging regulatory, environmental, and financial expectations.

### **5.1 SUPPORTING CLIMATE RESILIENCE AND RESOURCE OPTIMIZATION**

AtkinsRéalis places strong emphasis on climate-resilient infrastructure and reduced dependence on finite natural resources. The CE principles embodied in the 6R strategies—Reduce, Reuse, Recycle, Reclaim, Recover, Restore—enable utilities to lower vulnerability to supply disruptions, diversify water portfolios, and stabilize long-term operational risks. Increasing internal recirculation of water and reducing virgin-water withdrawals directly supports climate-adaptation objectives while contributing to decarbonization through optimized energy and treatment pathways.

### **5.2 ADVANCING DIGITAL AND DATA-ENABLED DECISION MAKING**

Digital transformation is a cornerstone of AtkinsRéalis' strategy, and the WCI serves as a quantitative anchor that integrates smoothly into digital planning tools, dashboards, and system-modeling environments. Its structure allows utilities and project teams to embed circularity tracking into master-planning workflows, digital twins, scenario evaluations, and performance-monitoring systems. By offering a single interpretable index, WCI enhances transparency for decision makers and supports data-driven project prioritization—key pillars of the company's digital-services vision.

### **5.3 ENHANCING SUSTAINABLE INFRASTRUCTURE DELIVERY**

AtkinsRéalis' sustainable-design philosophy promotes solutions that reduce lifecycle impacts and deliver long-term value. CE-aligned interventions—such as leakage reduction, decentralized reuse, reclaimed-water systems, and resource-recovery operations—align with this philosophy by simultaneously addressing environmental impacts, resource constraints, and operational efficiency. Embedding WCI in infrastructure planning further strengthens the firm's ability to quantify benefits, justify investments, and demonstrate measurable value to clients and external stakeholders.

### **5.4 STRENGTHENING INNOVATION AND TECHNICAL LEADERSHIP**

The integration of CE concepts with an explicit circularity metric reinforces AtkinsRéalis' role as a technical leader in water-sector innovation. By advancing analytical methods (such as WCI) and providing practical frameworks for implementing circularity at scale, the company contributes to industry knowledge, supports capacity building for utilities, and drives innovation in both conventional and emerging markets. These capabilities enhance the organization's ability to respond to complex client needs and position AtkinsRéalis as a partner of choice in sustainable water-infrastructure development.

### **5.5 ALIGNMENT WITH ORGANIZATIONAL VALUES AND GLOBAL PRIORITIES**

AtkinsRéalis' strategic direction emphasizes sustainability, resilience, decarbonization, and responsible resource management—areas where CE principles naturally apply. CE-aligned water solutions also support global objectives such as the UN Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). By integrating WCI as a monitoring tool and implementing structured CE pathways, the company strengthens its alignment with these broader societal goals while enhancing the impact and relevance of its technical practice.

## **6. Conclusion**

Urban water systems face intensifying pressures from population growth, climate variability, aging infrastructure, and increasing resource constraints. Conventional linear approaches—characterized by high virgin-water withdrawals and extensive wastewater discharge—are no longer sufficient to ensure long-term resilience and sustainability. Circular Economy (CE) principles provide a structured pathway to reconfigure these systems, using the 6R strategies to reduce demand, enhance reuse and recycling, reclaim high-quality water, recover valuable resources, and restore natural stocks.

This manuscript integrates conceptual CE strategies with a quantitative framework for measuring circularity through the Water Circularity Indicator (WCI). Together, these tools establish a coherent structure for identifying, implementing, and monitoring circular water-management interventions. By defining engineered system boundaries and consolidating key flows into a single interpretable metric, WCI enables utilities and practitioners to evaluate baseline system linearity, compare intervention portfolios, and prioritize actions that deliver the greatest circularity gains.

The accompanying case study demonstrates how targeted measures—such as loss reduction, decentralized reuse, and upgraded treatment enabling recycling and reclamation—can substantially improve circularity performance. These results highlight both the sensitivity of WCI to changes in engineered flows and its usefulness in guiding phased implementation strategies across short-, medium-, and long-term horizons.

Furthermore, the implementation pathways and practical recommendations presented here emphasize the importance of governance readiness, financial mechanisms, cross-departmental collaboration, and consistent terminology. Together, these enabling conditions support successful CE adoption and help translate strategic circularity goals into actionable planning and design decisions.

By aligning CE principles with a robust measurement framework, this work provides a practical foundation for utilities, planners, and engineering teams seeking to enhance water-system resilience, reduce environmental impacts, and support sustainable, circular urban development. The integrated CE-WCI approach offers a pathway toward future-ready infrastructure that is more efficient, adaptive, and environmentally responsible.

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# 04: Railway Embankment Failure Trends and Monitoring – Lessons Learned from the Anglia Route

## Significance Statement

This study draws upon the experience of AtkinsRéalis geologist's and engineers and the client team in managing the risks of instability of railway embankments across the Anglia region—many of which were built more than 150 years ago without modern engineering methods. As climate change brings heavier rainfall and more extreme weather, these ageing earthworks are becoming increasingly vulnerable to landslips presenting significant safety risks. The paper sets out best practice on appropriate monitoring strategies to control risks and target intervention providing sustainable outcomes. By understanding how slopes behave over time, asset owners can prioritise repairs in a more proactive way and keep passengers safe while protecting vital transport links for the future.

## Énoncé d'importance

Cette étude met en lumière les préoccupations croissantes concernant la stabilité des remblais ferroviaires dans toute la région d'Anglia, dont beaucoup ont été construits il y a plus de 150 ans sans recourir aux méthodes d'ingénierie modernes. Alors que le changement climatique entraîne des précipitations plus abondantes et des conditions météorologiques plus extrêmes, ces ouvrages de terrassement vieillissants deviennent de plus en plus vulnérables aux glissements de terrain et aux mouvements de sol. Cet article explique comment les ingénieurs d'AtkinsRéalis utilisent des techniques de contrôle plus intelligentes – allant des capteurs au sol à l'automatisation – pour détecter les problèmes à un stade précoce et prévenir les perturbations. En comprenant comment les pentes se comportent au fil du temps, les propriétaires d'infrastructures peuvent hiérarchiser les réparations, éviter les défaillances soudaines et assurer la sécurité des passagers tout en préservant les liaisons de transport essentielles pour l'avenir.





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## Abstract

UK railways were constructed with little consideration of engineering practice and with climate change and the associated greater frequency of extreme weather events, comes the impact on earthworks stability and risk to public safety. Many embankments on Network Rail's Anglia route have shown a gradual degradation through their steep upper slopes and progressive failure within predominantly clay embankment material and underlying soft deposits. A regional wholistic view allows identification of common geotechnical trends and risk categorisation to better enable prioritisation of asset management. Understanding when to intervene is crucial and monitoring the behaviour of earthworks is a vital asset management tool to control risk and extend lifespan. To be a wise investment, slope instrumentation must be properly thought out in line with a detailed interrogation of the site and alongside a well-developed conceptual model. Automated monitoring can bring greater control and allow more accurate evaluation of intervention but must be assessed in line with prioritising large areas with limited budgets. Correct targeting of ground investigation and ensuring sufficient and reliable data can optimise mitigation and provide confidence the solution has provided resilience to railway infrastructure.

## KEYWORDS

Geotechnical engineering; Monitoring; Railway tracks; Soils & ground conditions; Ground movements; UN SDG 9 & 13

## List of Notations

**CP**-Control Period

**ELR** - Engineers Line Reference

**NR** - Network Rail

**GI** - Ground Investigation

**CWR** - Continuously Welded Rail

**TAM** - Targeted Asset Management

## 1. Introduction

Over 75% of UK railway earthworks are over 150 years old and unlike more recent earthwork assets constructed on the road network, they have their own idiosyncrasies, particularly with regards to earthwork failure types. Clay embankments dominate earthworks in Anglia and they have a more prolonged deterioration and failure history compared to cuttings which allows the opportunity for effective slope monitoring to play an important role in maximising lifespan and managing risk.

Network Rail have Control Periods with 5-year timespans for financial and other planning purposes and the paper presents many lessons learned across the region spanning across two control periods between 2014 and 2024. A collaboration of client, designer and contractor experience looks to bring together many valuable experiences through a series of case studies from early concept to the use of monitoring to design and prove mitigation. Some of the authors have produced previous site-specific technical papers referenced herein, and this paper is intended to provide a regional and holistic assessment for managing risk. The aim is to help asset management teams in future Control Periods within Anglia and allow other UK regions to reflect on their own strategies.

Demonstrating the behaviour of an earthwork is key to getting the optimal engineering intervention correct and ensuring an asset receives the correct prioritisation given ever increasing pressures on budgets. The safety of the public remains of paramount importance on our ageing Victorian railway which has stood well to the test of time. With climate change and more regular extremes of weather, it has never been more important to have more control and better predictability allowing Network Rail to manage their earthworks pro-actively as opposed to more costly and disruptive emergency works.

The importance of starting with a thorough understanding of a problem site through effective desk study and then targeting ground investigation (GI) and monitoring is discussed. We can embrace technology to help further prolong the life of an asset before an intervention is required but it is vital to ensure we get the basics right.

## 2. Historical Setting and Building the Ground Model

Before intrusive investigation and installation of monitoring, it is key to undertake a thorough desk study. Network Rail Asset and Maintenance Engineers often have a deep knowledge of problem sites and together with available historical and published records can provide many clues to develop the initial ground model which must also include drainage considerations. It is important the right people with this knowledge visit site early in the process.

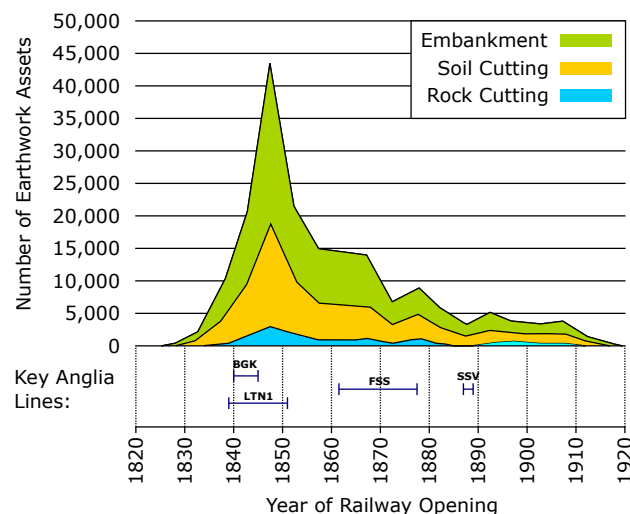
When considering an embankment, it is important to understand the history and ask the following:

- How old it is?
- How was it constructed and with what material types and what drainage provision?
- What changes have occurred to the asset during its life?
- As a result of the above what potential inherent issues are there within the embankment?

It can be seen on Figure 1 that embankments form most UK railway earthworks and that they were predominately constructed in the Nineteenth Century before the establishment of modern geotechnical engineering in the 1920s. Subsurface conditions were seen more as a construction challenge rather than a design challenge with construction based on “common sense, experience, intuition, and rules of thumb” (Coduto *et al.* 2011).

FIGURE 1

Graph showing number of railway earthwork assets constructed in the UK by year (Cobb, 2015 and NR Earthwork Policy NR (2018)) with key Anglian lines shown for reference

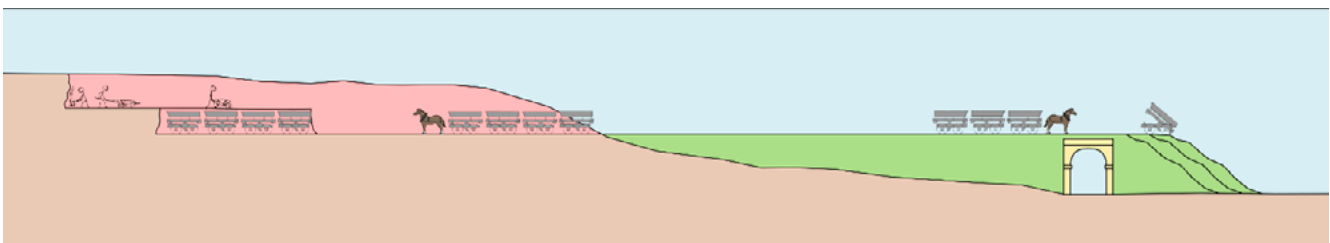


The method of railway embankment construction was predominantly undertaken by 'end tipping' methods as illustrated in Figure 2. The general construction method employed for most railways was to advance a cutting starting in one direction, with the excavated material being used to construct an embankment starting in the opposite direction. This method of construction led to post construction consolidation of embankment fill often resulting in failures during and immediately after construction, with potential to leave weakened relict failure surfaces.

FIGURE 2

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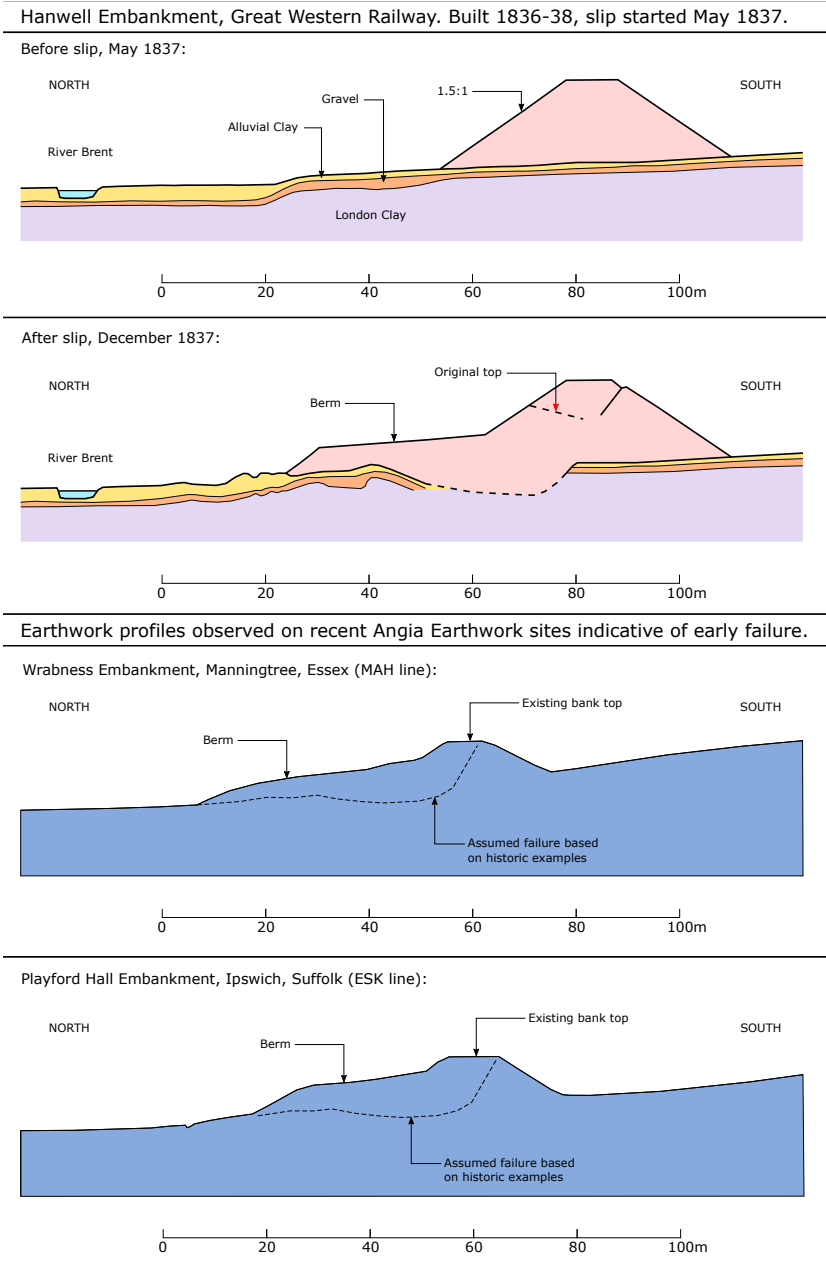
Historic construction using manual labour and horse and cart. End tipped material from cuttings forming steep embankment sides redrawn from illustrations in Skempton, 1996



Construction was based on the experiences of the earlier canals and quarrying, leading to slopes with over-steep angles that would lead to considerable slope stability issues and some notable early failures within the initial 10-50 years of their life as shown by the example on the Great Western Railway in Figure 3. Such early embankment foundation failures during and shortly after construction resulted in a counterweight berm being constructed as a quick and effective stabilisation measure and there are many examples of such profiles seen across Anglia with two examples also shown in Figure 3.

**FIGURE 3**

Example of an early post construction failure on the Great Western Railway at Hanwell embankment (based on Skempton, 1996) and comparisons with similar failures observed on 2 Anglia lines.



Little or no ground preparations were undertaken ahead of embankment construction and therefore a layer of relict topsoil is encountered under many embankments and underlying alluvium from existing and historical water courses as shown at Hanwell, Figure 3. Payne *et al* (2017) describe how the organic layer at the base of the Wrabness embankment shown in Figure 3 influenced the stability problems.

At desk study stage it is important to consider the geological units that the adjacent cuttings are cut through. Commonly this is not a single unit of homogenous material and in many cases a change in lithology occurs within cutting faces. All this variability in excavated fill is therefore reflected to a greater extent in the neighbouring embankment, where different lithologies have been end tipped together to form a large heterogenous mass of material. The exception to this is within sections of embankment immediately adjacent to the abutment of a viaduct, where compaction in layers were employed more frequently.

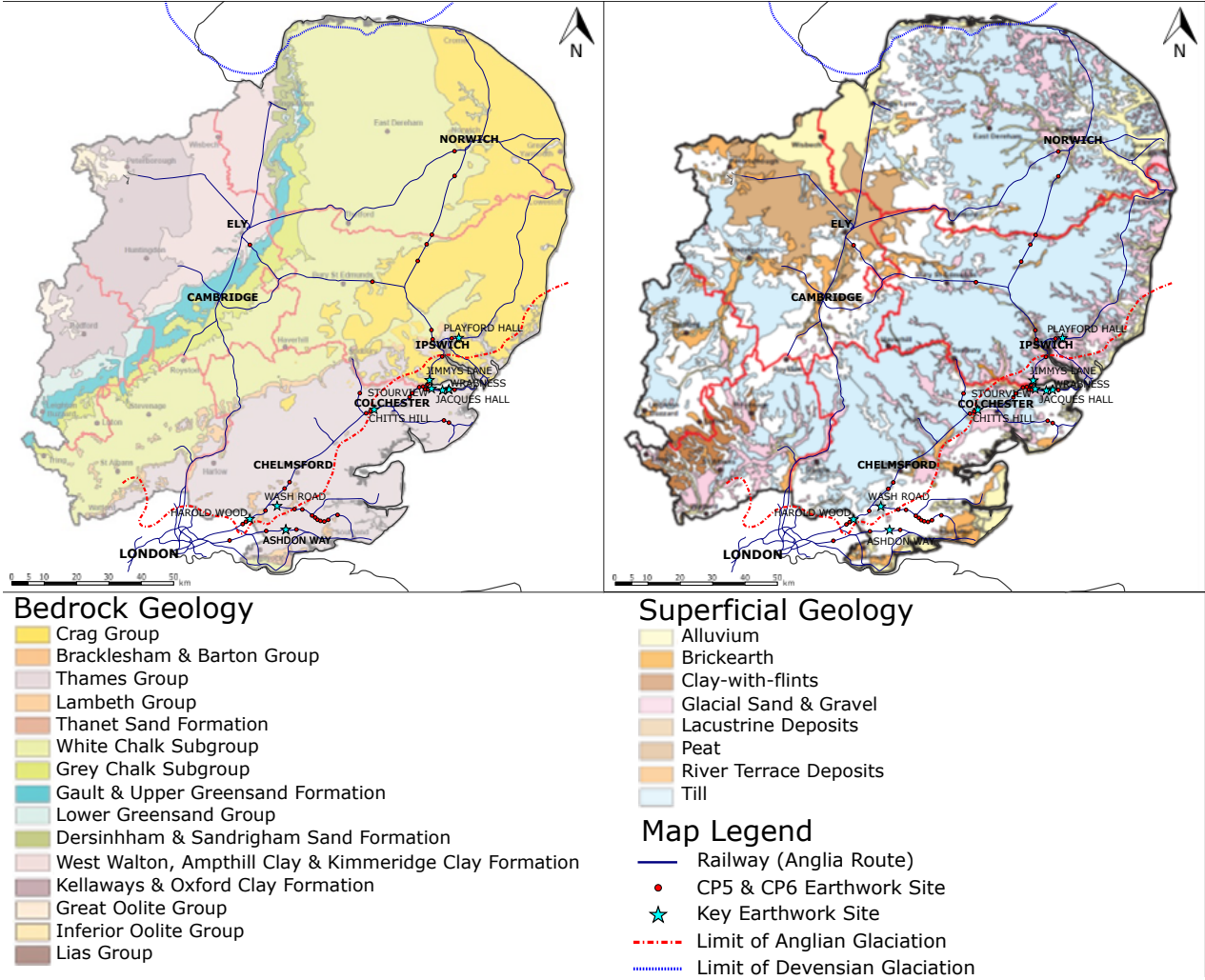
Many of the early lines were ballasted with ash and many embankments have an outer ashy layer from topping up over time which often causes embankment shoulder instability, discussed later and illustrated in Figure 13. As understanding of the loading through the ballast into subbase increased, the ballast thickness increased along with the use of coarser stone ballast from the 1930s (Claisse and Calla, 2006). Track levels were commonly raised to accommodate thicker ballast resulting in a wider ballast base. The shoulder resting on the previous ash cess further instigated instability with some steep upper slopes having a near surface ballast spill well illustrated at the Wrabness site (Payne *et al*, 2017).

Understanding the complexity of original construction, modification by failures and ongoing maintenance interventions and geomorphological features is essential. Once the initial ground model is live and an assessment of LiDAR information is complete, detailed mapping should be carried out by an Engineering Geologist with experience of the railway and knowledge of the site to further evaluate surface features.

The Anglia region is well known for its low lying topography and hence 60% of the earthworks are embankments. As illustrated in Figure 4, the superficial geology includes soft peat deposits of the Fens around Ely and embankments that are predominately reworked glacial tills in the north. Reworked London Clay embankments are more common in the south below the limit of the glaciations (Figure 4) and so overall embankments in the region comprise high plasticity clay slopes as outlined by Payne *et al.* (2020).

**FIGURE 4**

High level geological map of the Anglia Region. Key sites of interest referred to in this paper are identified



### 3. Ground Investigation and Monitoring Strategy

Following the initial desk study, it is important to have a hold point and present the findings to all parties including Network Rail and the appointed engineering works Contractor. The proposed GI strategy must refine the ground model and take into consideration the programme of planned intervention. Is there sufficient time for monitoring to aid the design? Can it be used to better control risk and delay intervention?

Payne *et al.* (2019) outline a Targeted Asset Management (TAM) approach that draws in all available data in conjunction with geomorphological mapping to fully characterise and risk zone a site. Typically, the problematic sites have existing monitoring records which must be considered alongside the maintenance history so that any supplementary GI can then be optimised. More details of specific GI at Anglia sites are reported by Payne *et al.* (2018 and 2019). The next section in evaluating movement trends relies on a good positioning of exploratory holes to ensure the whole embankment and underlying strata subject to movement influence is captured.

Enhancing the initial ground model through insitu and laboratory geotechnical testing and detailed logging of core is vital to characterise a site. Designing a suitable monitoring strategy to assess groundwater and slope movements is also key and the designer must appreciate the subtle complexities during the GI to decide on the most effective regime to best aid design. The full ground model can be used to target back analysis and optimise intervention and this shall be discussed later.

As the quality of ground related data increases so does the ability to make well informed asset management decisions. When GI is carried out, equipment is often installed into exploratory holes used for soil sampling as part of a longer-term investigation. In most cases the extra cost of installing a piezometer or inclinometer is minimal compared to the mobilisation and drilling and should not be overlooked. It is important to get the fundamentals correct including intelligent placement of instruments, number of arrays required and embedment depth (beyond zone of movement); Table 1 summarises the minimum information required, which unfortunately is not always available. Ensuring additional easy to obtain meta data is available will allow more effective use of data for potential later phases of development.

**TABLE 1**

Minimum information on  
GI monitoring data for  
effective risk management

<b>Essential information without which data cannot be interpreted</b>	<b>Important information without which it might not be possible to interpret the data</b>	<b>Useful information which will add significant value to data</b>
Unique reference number	Unique reference number at installation	Regular photographic records of installation showing situation and general condition of surrounding slope
Surveyed location & level	Location plan	Baseline readings on installation
Installation records	Monitoring strategy (i.e. purpose of installation)	Topographic survey data or plans/sections
Driller's borehole log	Engineer's borehole log	Geotechnical studies related to the installation
	Threshold alert & trigger values	

## 4. Characteristic Slope Movement Trends in Anglia

Common issues across the region are evaluated through monitoring data and presented using case study sites located in Figure 4. The sites are on the main commuter line between London and Norwich (LTN1), the Essex commuter line network radiating out from the east side of London and the commuter and freight line between Manningtree and the port of Harwich (MAH) in north Essex.

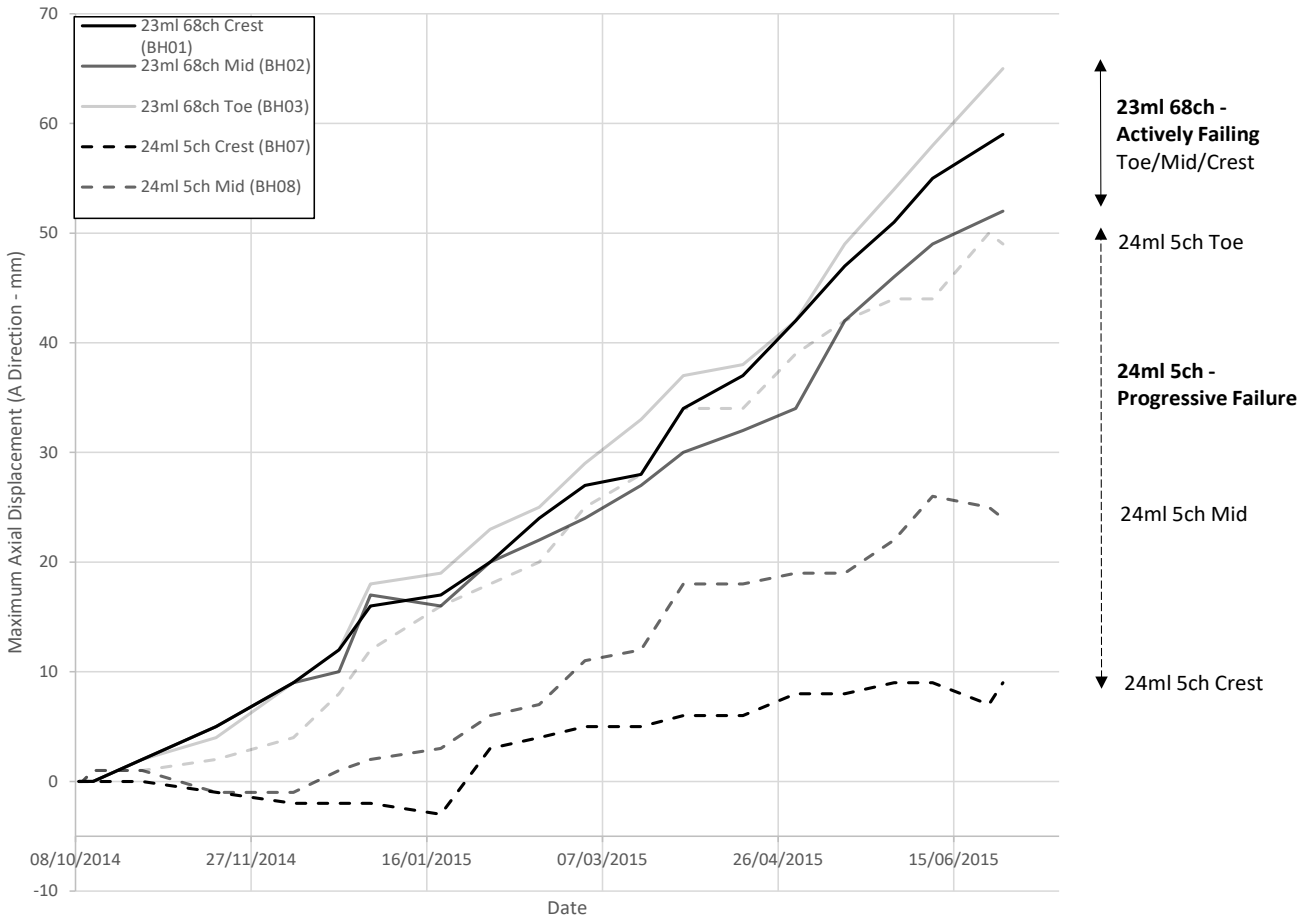
### 4.1 ACTIVE AND PROGRESSIVE SLOPE MOVEMENTS

Deeper movements are generally some of the most concerning as the full height of the embankment is impacted and failure could lead to movement of the whole track and ballast area. At the Ashdon Way site in Basildon, Essex on the SSV line (Figure 4) an 8m high 500m long embankment, predominantly comprising reworked London Clay fill is founded on the London Clay Formation (see Payne *et al.*, 2018). Slope movement is approximately 3m below ground level or deeper with active and progressive failure observed (Figure 5). These failure trends were observed by installing an array of three inclinometers in section down the embankment slope (at toe, midslope and crest). In actively failing locations movement was observed in all three inclinometers indicating that the whole slope was experiencing movement. In areas experiencing progressive movement, greater movement was observed at the toe with lower movements observed midslope and at the crest as shown in Figure 5, consistent with progressive failure mechanisms reported in other studies (see Potts *et al.* 1990, Potts *et al.* 1997 and Briggs *et al.* 2017).

These long-term, deeper seated failures with very large displacements are a feature of the high plasticity clay embankments in Anglia and contrast with the shallower, more rapid slope movements associated with low plasticity materials.

FIGURE 5

Inclinometer data  
 highlighting downslope  
 active and progressive  
 failure trends, Ashdon  
 Way embankment,  
 Basildon, Essex

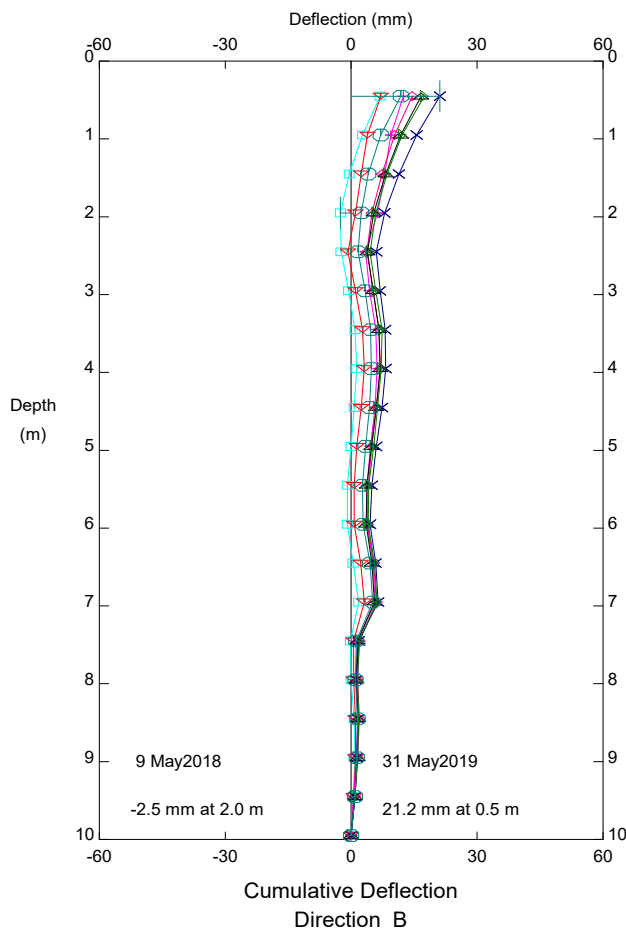


### 4.2 SHALLOW AND DEEPER SLOPE MOVEMENTS

Shallow slope movements are commonly attributed to the oversteep ashly crest as outlined earlier. Both shallow and deeper seated movement can be observed at the same site as illustrated at the LTN1 Chitts Hill site near Colchester (Figure 6 and see Payne *et al.* (2019) for further details). It is important to be vigilant for signs of failure during the site walkover and geomorphological mapping. Some clues of shallow slope movements are shown in Figure 7 at the same site.

FIGURE 6

Inclinometer monitoring results from the Chitts Hill site: 49ml 77.5ch WS03 (slope crest) 99mm max movement between 2014 and 2019. Two potential zones of movement are visible – one at 2.5mbgl and one at 7mbgl



**FIGURE 7**

Shallow and deep slope movement at 49ml 77.5ch at the Chitts Hill site. The shallow slope movement observed in Figure 6 is evident from the movement of the trough and cess walkway



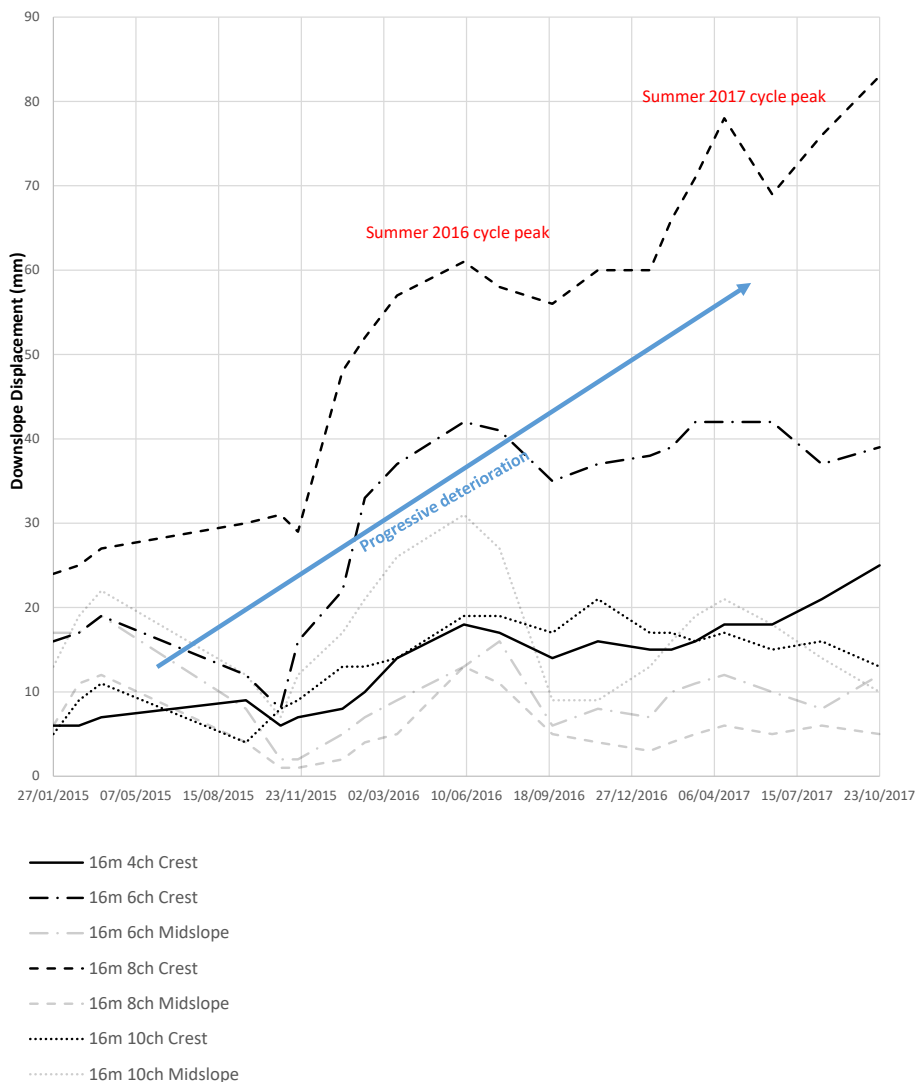
Near surface movements should be treated with caution given the upper part of an inclinometer tube can be moved by site activities or be affected by the excavated safety pit prior to drilling. It is important to view multiple readings over time to ensure that actual slope movement is being observed.

### 4.3 SHRINK SWELL MOVEMENTS

As with many heavily vegetated earthwork slopes across the country, seasonal wetting and drying can have a pronounced effect on slope movement which is more significant at the crest of the slope closer to track level. While it is commonly manageable in the short term, progressive deterioration can occur over time as illustrated by the inclinometer data at the LTN1 Harold Wood site in Figure 8. The embankment at the site is primarily clay composition and there are well established trees that influence the soil moisture trends.

FIGURE 8

Inclinometer monitoring from the Harold Wood site. Seasonal shrink-swell can clearly be seen between summer and winter. Progressive deterioration is also observed whereby movement is not fully recovered on each shrink swell cycle; this is most evident close to the embankment crest



#### 4.4 SETTLEMENT AND LATERAL SPREAD ON PEAT

The East Anglian Fens, England's largest area of peat soils, are in the north-western part of the Anglia Route as shown in Figure 4. Peat is a permeable, fibrous and highly compressible material. The Fens have been subject to extensive drainage since the 1600s for agricultural purposes and as a result, peat wastage has gradually resulted in mass widespread subsidence of the peat soil areas. Furthermore, large amounts of peat soil have been removed from the fens to supply the peat-based compost industry.

In the mid 1800's pumped drainage was introduced to the fens which significantly lowered groundwater levels in the area and increased peat shrinkage to an alarming rate; this is demonstrated dramatically at the location of Holme Post, where a post, driven into the underlying clay with its top at ground level in 1851, now stands 4m above ground level.

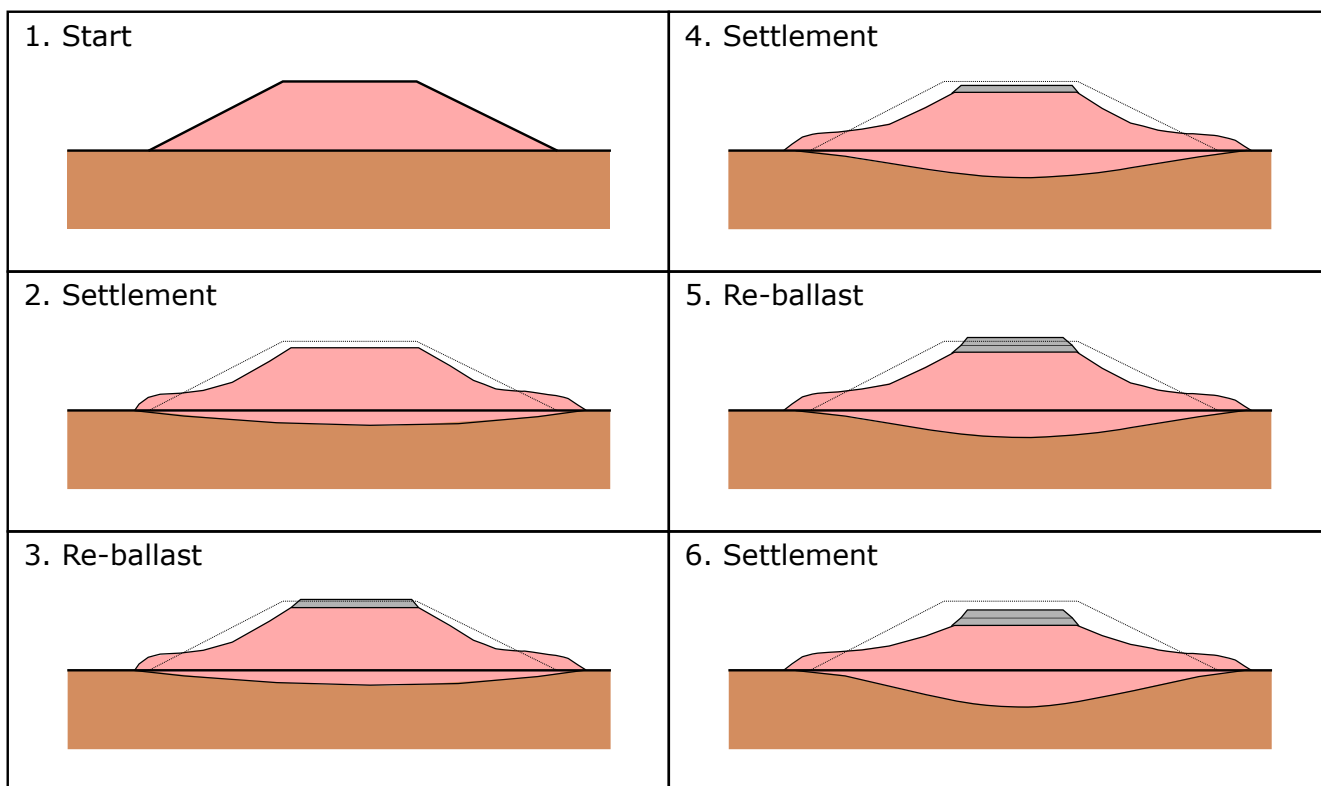
Many of the railways north of Cambridge and to the west of Bury St Edmunds are constructed over these expansive peat deposits and were constructed in the mid to late 1800s, when increased drainage of the fens commenced. As a result, where railways were originally located on very shallow earthworks, no more than 1m above the surrounding ground level, they are now raised on more significant embankments due to the ongoing wastage of neighbouring fields and the removal of soil. Furthermore, the embankments have sunk along with the overall ground level, resulting in long troughs between structures.

Continuing settlement of peat also leads to lateral spreading and settling of the embankments themselves, resulting in shallow instability. This instability to the ballast shoulder is further exacerbated by repeated cyclical maintenance interventions to maintain the track alignment in the form of re-ballasting, resulting in narrow cess widths and steep ballast shoulders as demonstrated in Figure 9.

While monitoring including evaluation of settlement through extensometers could be adopted to assess such trends and rates of movement, it is imperative to understand the processes in play and call upon experience in dealing with such sites. Continued maintenance is commonly the choice given the high capital costs associated with overcoming settlement.

FIGURE 9

Visualisation of the change in embankment profile over time due to peat settlement, lateral spreading and the re-ballasting of the trackbed



## 5. Comparing Movement Trends and Risk Evaluation

Table 2 shows a range of sites across the Anglia region (see Figure 4 for locations) that have been monitored for 5 years or more with typical annual rates of movement. While many sites have similar attributes such as slope geometry and underlying ground conditions, an assessment has been made on what factors influence rate of movement. A regional overview helps better prioritise investment in remedial works.

TABLE 2

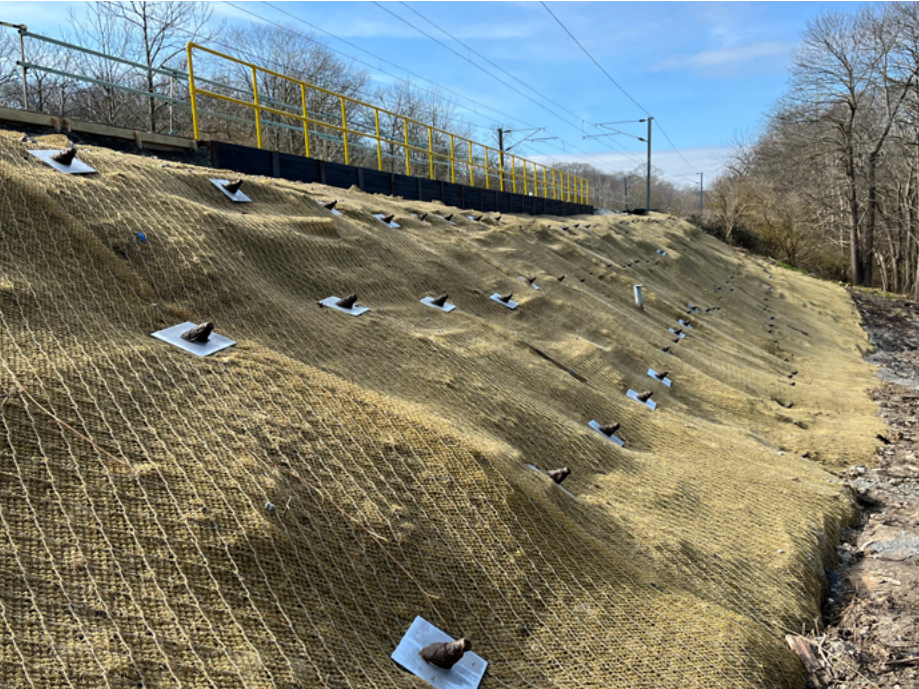
Anglia site examples  
of embankment slope  
movement trends  
and assessment

Site and ELR	Typical annual movement rates	Outline assessment of trends and mitigation considerations
Chitts Hill, LTN1 (Figure 7)	Combination of shallow and deeper-seated movement (Figure 6), average annual movements of c. 20mm up to 9m below track level observed with a maximum downslope movement (since baseline) of c. 140mm.	10-12m high clay embankment with underlying alluvium, toe drainage restricted, deeper movement.  Planned soil nail solution, cess retention piles and improved drainage (on both sides of the embankment). Automated monitoring and camera systems active in the interim to better control risk (Figure 14).
Wrabness, MAH	Deep seated movement occurring 6m below ground level with an average annual movement of 20mm and a maximum downslope movement of c. 140mm.  Instruments in high mile area located at mid slope showed deeper seated movement between 4-8m below track level, typical average annual movement of c. 15mm and a maximum downslope movement of 95mm. Larger jumps in movement (10mm over a few weeks) after heavy rain periods.	10m high embankment on sidelong ground with groundwater movement through clay embankment, underlying organic relict topsoil layer.  Exacerbation through some shrink swell trends (large oak trees).  High movements resulted in Temporary Speed Restrictions and a temporary toe berm. Active large jumps resulted in high priority and installation of automated instrumentation to continuously monitor.  Site remediated through a phased approach; drainage improvements on side receiving the surface/groundwater flow slowed movements on the opposite side with less infiltration through the embankment. After a further 3 years, cess retention piles and soil nailing completed on the opposite higher slope side (Figure 10).

Site and ELR	Typical annual movement rates	Outline assessment of trends and mitigation considerations
Jimmys Lane, LTN1	Shallow movement noted in majority of instruments, identified between 1-2m below track level, occasional deeper-seated trend visible with average annual movement of c. 15mm and a maximum downslope movement (since baseline) of 131mm.	<p>Shallow movement within granular embankment, some localised underlying alluvium, embankment +12m high on a curve.</p> <p>Ongoing monitoring (manual) ready for further optioneering.</p> <p>Granular embankment allows dissipation of pore pressures more easily compared to the first 2 examples and is continued to be watched but lower priority.</p>
Jacques Hall, MAH	Movement between 3-4m below track level with average annual movements of 6mm and a maximum downslope movement (since baseline) of 40mm observed.	<p>3m-5m high embankment on sidelong ground, underlying organic relict topsoil.</p> <p>Ongoing monitoring (manual) ready for further optioneering but general maintenance continues as not high risk.</p>
Playford Hall, ESK	Most instruments showing reasonably steady movements. Deep movement noted in one borehole down to 11m below track level with average annual movement 4mm observed. Some shrink swell also visible in data.	<p>Embankment likely to have failed during construction (Figure 3).</p> <p>Possible groundwater influence, presence of peat leading to sustained but low rates of movements.</p> <p>Large track distortions resulted in Temporary Speed Restriction and heavy maintenance.</p> <p>Ongoing monitoring (manual) ready for further optioneering and assessment of drainage improvements.</p>
Wash Road, SSV	Shallow movement 2.5m below track level with average annual movements of 6.5mm Per Annum and a maximum downslope movement (since installation) of 32mm observed.	<p>Localised alluvium, possible settlement as limited surface evidence of rotational failure. Continued to be monitored.</p>

**FIGURE 10**

2021 Soil nailing and cess retention at Wrabness on the freight and commuter line between Manningtree and Harwich following drainage intervention in 2018 - continued monitoring over 10 years allowed a phased intervention and management of risk. More details in the Ground Engineering Magazine Article, 6 July 2022



The NR Asset Management team in Anglia have devised a tool which helps them prioritise their workbank, future planning and assesses monitoring frequency to optimise budgets aligned with Network Rail’s national earthwork asset policy (2018). It is important that seasonal movement fluctuations are not incorrectly interpreted as deeper seated failures as many such tree related winter movement spikes recover in summer (Figure 8). Hence average downslope movements since baseline have been successfully used as a basis of a risk ranking as shown in Table 3. The trigger levels are continually assessed but are derived from many years of data and experience across the region of the asset behaviour and deterioration. It should be noted that this is not a substitute for comparing movement rates in all instruments from one reading to another given that movement rates can change quickly but it provides a high level means of comparing trends across many sites as highlighted in Table 2.

TABLE 3

Network Rail Anglia  
 Earthwork Asset  
 Management Team’s  
 high level overview tool  
 summarising earthwork  
 monitoring frequency  
 and risk based on average  
 downslope movement rates

Risk rank based on average downslope rate		
Average Downslope rate (mm/yr) since baseline	Monitoring frequency	Risk <small>** only reliable following 10 month baseline period**</small>
-500mm - 5mm	Yearly	<b>Low</b> Movement negligible and no significant cause for concern under normal circumstances
5mm - 10mm	6 monthly	
10mm - 20mm	4 monthly	<b>Moderate</b> Sites that recover most of their downslope movement due to ongoing cyclical movement
20mm - 30mm	2 monthly	
30mm - 40mm	Monthly	<b>High</b> Sites that do not recover their downslope movement. This suggests movement is not cyclical and is due to ongoing failure
40mm - 80mm	Weekly	
>80mm	Daily on engineers instruction and consider remote condition monitoring	<b>Very High</b> - Ongoing rates of movement not manageable by earthwork monitoring alone, early speed restriction and track monitoring required

Once the risk rating of an embankment becomes high it is often subject to more rigorous monitoring and moved through the mitigation design process. The Network Rail maintenance and asset teams prioritise such sites and the warning signs are often present well before the high-risk trigger. The high active movements at Ashdon Way (Figure 5) resulted in automated slope and track monitoring and accelerated intervention while the progressive movement trends at Wrabness allowed for a phased approach with drainage improvements lowering the slope movement risk category sufficiently allowing for a planned and more cost-effective optimised slope engineering solution.

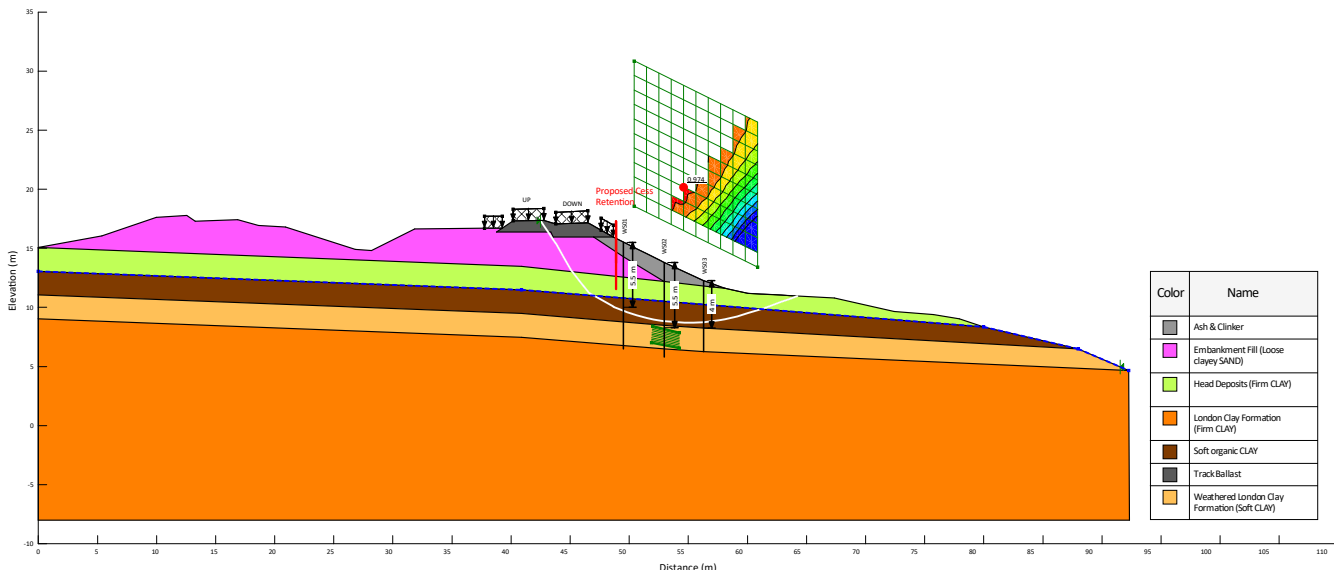
Caution must be used as a slope can show signs of failure without any obvious signs of causation and there may be no time to install equipment for safety reasons or ready access for GI. The selection of a monitoring system would then be chosen on a basis of expediency. In this case it provides assurance that a static fault is not progressive and not affecting the track performance, which may require an intensive regime of monitoring focussing more on surface movements or track distortion. Although perhaps not suitable for back analysis the purpose of monitoring here is to maintain safety and train operations. In certain circumstances the Asset Engineering team may have to inspect a failed embankment immediately and engage a contractor to undertake a vegetation strip and potential reactive emergency works. Speed restrictions or line closure may need to be imposed and timber pegs are sometimes a quick and crude means to give an idea of movements in the early stages, but these are temporary and then reliance is on track and structure (OLE stanchions) monitoring. GI may be undertaken to validate the reactive works which may also include monitoring to further verify the fix and to 'watch' adjacent areas. Tiltmeters in Anglia are generally limited to cuttings and dominate more in the north of the region.

## 6. The Role of Monitoring in Mitigation Design

Assessing how close to failure a slope is, can be difficult, especially if data is missing or assumed. With targeted GI, accurate surveying of the slope profile and determination of groundwater fluctuations, a better risk assessment and failure model can be made by obtaining more reliable estimates of mass properties via back analysis. So, it is sensible, if not obvious, to provide monitoring data that can be applied directly to the ground model as part of an overall and on-going investigation and back analysis. Figure 11 shows a Slope W analysis section where inclinometer data has enabled good definition of the failure surface at the Stourview site with a target factor of safety of 1.0. The failure surface was originating between both lines and this was backed up with the significant track dips observed on visual inspection and maintenance records. The underlying deposits had a large influence on the Factor of Safety and cohesion was reduced in the organic clays and weathered London Clay Formation with back analysis also suggesting the embankment fill was granular. Establishing a back analysis model then allowed comparison between levels of remedial work varying from just targeting the active failure surface to the full Eurocode 7 compliant design. A cost vs risk assessment could then be made on the level of intervention.

FIGURE 11

Back analysis model cross section at Stourview showing how longer term movement data from 3 inclinometers were able to define the failure surface



In most circumstances pore-pressure and groundwater is a major contributory factor (see Briggs *et al.*, 2017) and often simply assumed conservatively rather than being established accurately through monitoring over at least two annual cycles showing seasonal fluctuation. In the absence of groundwater monitoring at Stourview, hydrostatic groundwater was considered at the toe of the embankment and a B-bar of 0.2 within the embankment fill. It is more common for there to be an absence of reliable groundwater monitoring data and consideration must go to the envisaged duration of the monitoring in parallel with the inclinometer monitoring to determine whether it is cost effective.

## 7. Monitoring Intervention Performance

To help define the monitoring risk mitigation strategy on the CP6 Anglia framework, a simple monitoring communications plan was devised ahead of construction works setting out clear responsibilities of the client (NR), contractor and designer. In addition to slope monitoring, track and OLE stanchion monitoring was carried out and the designer provided weekly reports that linked to site activities in controlling risks which will be illustrated later. Monitoring frequency must be agreed early by all parties and it is a worthwhile investment having more data leading up to, during and post construction. Automated monitoring should be considered in critical areas with active movements to provide real time visibility of the embankment behaviour, assess effects of enabling works and provide confidence of the fix. Any temporary works monitoring requirements should not be overlooked and it is important that the construction sequence is understood and agreed early with the designer and contractor.

The Stourview site mitigation highlights the implementation of a monitoring plan, managing risk during construction and assessing performance using the monitoring. Prior to intervention with cess retention H piles at the crest and soil nails in late 2020 and early 2021 (Figure 12), the site was subject to monitoring since 2014 and Figure 13 shows the progressive failure before intervention with downslope movements slowing typically during winter months.

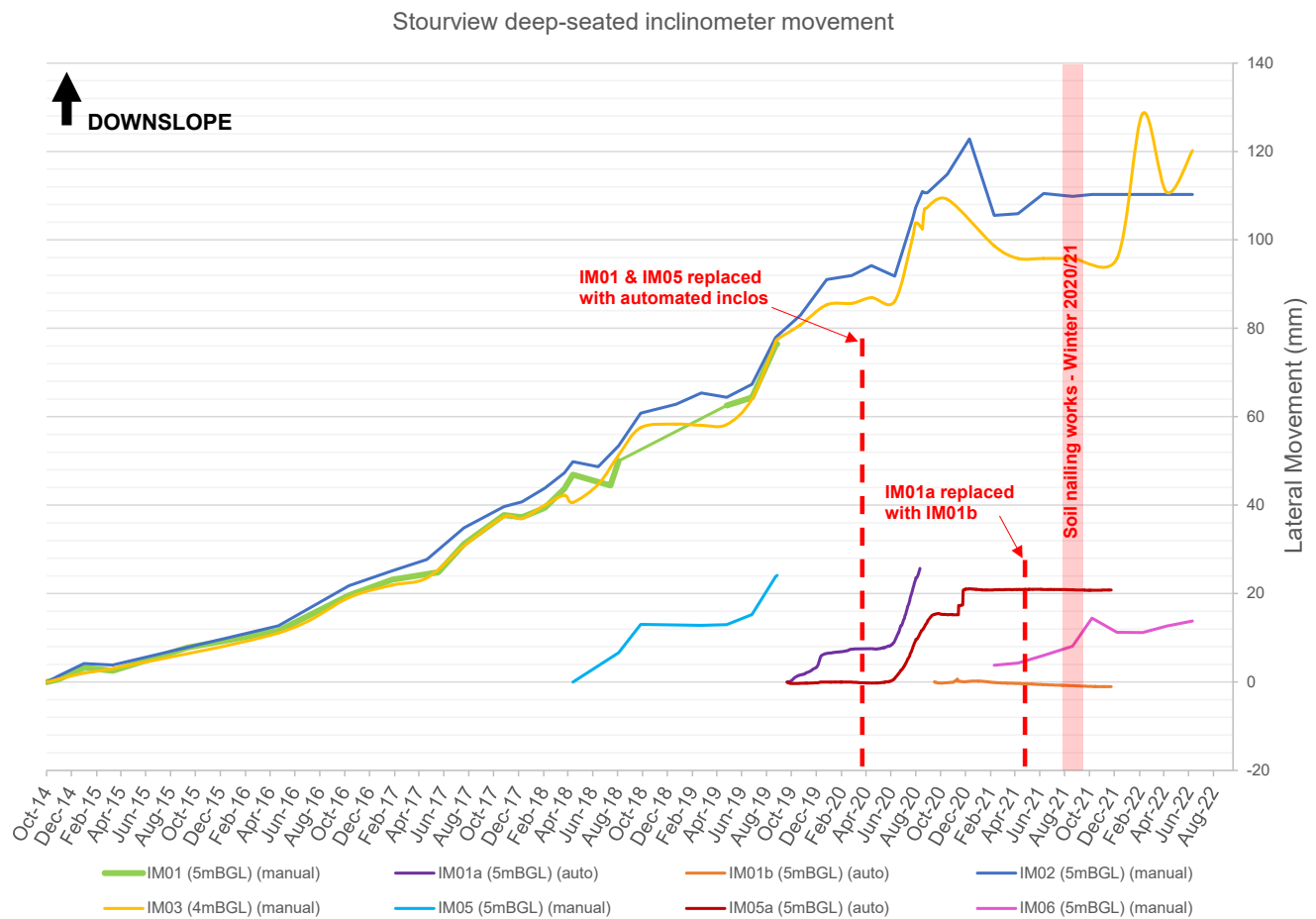
**FIGURE 12**

Top Photo: H Pile cess retention and soil nailing stabilisation works were monitored with automated slope instruments (Bottom photo) together with crest, OLE and track targets



FIGURE 13

Stourview Site - Horizontal movement from Inclinometer readings showing reduced movements following intervention stabilisation



Prior to intervention, movements increased and the NR risk profile changed. The manual instruments were read more frequently and some inclinometers were installed including an automated system (Figure 12) with a ccess facing camera in addition to regular track monitoring. Slope and track movements peaked in September 2020 (Figure 13) and led to accelerated planned intervention and a temporary speed restriction. Additional monitoring of targets on OLE stanchions and at the embankment crest was added during the works. This was critical to assess a steady increase in the recorded track elevation and lateral movements of OLE, some of which was attributed to continued ground heave.

The benefits of installing automated instruments at the site are clear to see and provided control during construction and quantification of the level of improvement with the slope movements stabilising quickly after the reactive works and decreasing after the main soil nailing and ccess H Piled wall installation.

Based on assessment of the monitoring results, in addition to a 5.5m deep rotational slip it was concluded that the direction of movement of OLE stanchions, track and embankment crest from surface monitoring was likely to be affected by shallow shrink-swell deformation of high-plasticity, high-permeability embankment fill material, characteristic of railway embankments constructed from dumped clay fill (Briggs *et al*, 2016).

## 8. Manual v Automated

There are scenarios that would point towards certain types of monitoring systems to be used where more or less data is essential to meet the objective. For example, there are many railway slopes that have shown obvious but manageable shrinking and swelling movements and with evidence of creep failure over several years. These are often served well by a manual regime of monitoring, which also permits visual examination which can be often overlooked as essential site feedback during monitoring visits. Conversely, there are slopes that have been assessed as low risk that have failed rapidly without warning due to a serious weather event or construction activity; arguably a circumstance where automated and alarmed remote monitoring could have provided advanced notice. The previous Stourview site example moved from a manageable manual data set to more controlled real time monitoring when the risk profile increased significantly.

Monitoring data can indicate progressive failure in a slope, or an increased likelihood of it. Increasing risk of failure should action a reading frequency increase. Increased frequency for manual observations requires more access to site, and with that, a risk of injury to the surveyor accessing slopes that are uneven and steep. Automated systems to measure groundwater, slope movement (both deep seated and surface deformation) and other parameters such as rainfall and track stability provide a continuous and event driven record, which is critical when fluctuations or variations in readings can occur quickly.

In recent years advances in sensor technology and remote communications have driven more monitoring applications to be automated and remotely controlled to provide data for assessment. The installation of sensors in the field is now far simpler and can be described as 'plug and play'. The equipment is battery operated and sustainably powered by small solar arrays. With such a variety of multi-functional and compatible instrumentation providing groundwater and movement data combined, more attention must be paid to in-field conditions. Remote and automated systems are, by definition, left unattended and subjected to often harsh and aggressive site conditions. Field equipment must therefore be robust and suited to the conditions that can present a real challenge to ensuring uninterrupted and meaningful results.

Data from each point or array of points is downloaded automatically on to web-based data platforms. An automated monitoring system quickly becomes critically important to the overall assessment of the asset and data from it used to guarantee the on-going operation of trains. Unexpected changes to results or trends must be quickly validated and actioned. Automated systems do not mean automated decision making, that always remains the remit of the Asset Engineer.

Today, data is invariably streamed directly and continuously to online data management websites, where it is presented in a form that provides the asset manager, decision maker or stakeholder the simplest means of comparison using graphical and analytical tools. The presentation of the data must be such that it is augmented by other data recorded as part of the monitoring strategy, such as photographic or video images (Figure 14), diary entries, examination reports, borehole detail, evidence of pre-existing failure, vegetation, water courses, structures, construction activity, live loading and other points of consideration.

Using advanced technology with easily accessible, accurate data that is updated in a timely manner is now a critical tool for earthworks management, and an opportunity to improve understanding of slope behaviour.

FIGURE 14

LTN1 Chitts Hill, near Colchester. Top: Automated camera monitoring in addition to automated slope instrumentation (bottom photo) provides real time closer control until intervention



## 9. Conclusion

It is vital to establish a robust desk study and ground model early in the process, and it is equally important not to underestimate the value of experienced practitioners mapping the site and considering the wider context, including the opposite side of embankments and adjacent cuttings. GI must target the unanswered questions and evolve the ground model to optimise the design. Taking a step back and looking at the regional trends can help understand where a particular site lies in the risk ranking and having a regional categorisation of annual movement helps the prioritisation of when to intervene. Many case studies have been presented and compared to show typical movement trends. While every site has its own subtle complexities, many ground models and failure causations are consistent across the region. We can learn so much from having a holistic view and not rushing to conclusions. Having data over a few years allows us to understand seasonal fluctuations and determine the rates of progressive failure. It has been shown at the Wrabness site that monitoring can help manage a phased and more sustainable approach to intervention and highlights the importance of effective drainage.

The installation of monitoring needs careful consideration to allow effective risk management, potentially prolong the life of the asset and be used effectively in design. Reliance on soil test data will typically result in very conservative assessment of performance and normally back analysis will provide a much more realistic assessment of geotechnical properties, provided that adequate monitoring data is available. The Stourview site had a vast and reliable data set prior, during and post construction which allowed for optimised design and provided confidence that movements had ceased restoring a safe railway and ultimately successful investment.

While it is not always possible to have time to build up a sufficient bank of data, deciding on the monitoring strategy with all stakeholders early and combining it with other data such as track performance and the history of the asset is key. Particular attention is required to install inclinometers correctly and make sure they are baselined and have a series of reliable manual readings before considering automation.

In sharing a wealth of information gained from vast experience in the Anglia Region, it is hoped that this information can be used to improve the effectiveness and optimised use of embankment slope monitoring in other regions and applications. Future asset management teams in region can continue to further evaluate trends which will no doubt be increasingly influenced with ongoing climate change. It will be interesting to compare approaches and trends to other UK regions and overseas, as an industry we need to foster innovation to continually improve the resilience of railway infrastructure.

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# 05: Making Bubbles: Using Sparging to Remove Radioactive Gases from Reactor Coolant Samples

## Significance Statement

This paper turns an important safety challenge into a substantiated concept: how to quickly remove dissolved radioactive gases from reactor coolant samples during a rare fault condition, without damaging the sample needed for rapid laboratory analysis. The work links key project constraints (ALARP dose reduction, short analysis window, portability and limited gas storage) to a practical process design using nitrogen sparging and recirculation. By breaking performance down into sparging, vacuum degassing and bubble nucleation, it shows why for this system, sparging dominates whilst identifying the variables that matter most for design optimisation.

## Énoncé d'importance

Cet article transforme un enjeu de sûreté important en un concept étayé : comment éliminer rapidement les gaz radioactifs dissous des échantillons de fluide de refroidissement de réacteur lors d'une défaillance rare, sans altérer l'échantillon nécessaire à une analyse de laboratoire rapide. Les travaux établissent un lien entre les principales contraintes du projet (réduction de la dose selon le principe ALARA, fenêtre d'analyse courte, portabilité et capacité limitée de stockage des gaz) et une conception de procédé pratique reposant sur le barbotage à l'azote et la recirculation. En décomposant les performances entre le barbotage, le dégazage sous vide et la nucléation des bulles, l'étude montre pourquoi, pour ce système, le barbotage est le mécanisme dominant, tout en identifiant les variables les plus déterminantes pour l'optimisation de la conception.





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## Abstract

This paper describes the development and performance assessment of a compact degassing system for removing dissolved radioactive gases from primary-circuit coolant samples during a postulated reactor fault condition. Candidate degassing methods were screened against operational, radiological, and sample-integrity constraints, and a nitrogen sparging concept was selected for detailed analysis. A physics-based assessment of diffusion-driven gas-liquid mass transfer was used to quantify the influence of bubble diameter, interfacial area, and gas-liquid contact time, and to estimate overall degassing effectiveness. The results indicate that nitrogen sparging with gas recirculation delivers strong degassing performance despite a limited nitrogen inventory and is significantly more effective than vacuum degassing alone. Operational experience also suggests that initial depressurisation from primary-circuit pressure provides an additional, but comparatively minor, contribution through bubble nucleation. Overall, the study demonstrates that a recirculating sparging-based concept will confidently meet the performance goals for this application providing a robust basis for further development.

## KEYWORDS

Nuclear Reactor; Degassing; Vacuum degassing; Sparging; Bubble nucleation

## **1. Introduction**

A nuclear reactor operator routinely samples primary circuit coolant water as part of reactor health and condition monitoring. In a particular fault condition, fission products can contaminate the primary circuit water, resulting in active gases being released from the sample water when it is handled. With no means to separate and store these active gases at the sampling location, this off gassing would introduce an elevated radiological inhalation dose to operators. This paper focuses on the process engineering design optimisation in the context of satisfying wider project requirements.

## 2. Methodology

### 2.1 CONCEPT OUTLINE

Table 1 provides a high-level view of the requirements that had the greatest influence on the process design development.

TABLE 1

Requirements Overview

Requirement Theme(s)	Operational Context	Design Drivers	Influence on design development
Radiological Safety / Degassing Performance	Without intervention radiological exposure is tolerable within legal limits but not As Low As Reasonably Practicable (ALARP).  It will not be possible to verify that the sample has been acceptably de-gassed after processing.	Radioactive degassing effectiveness must be high.  High reliability and confidence in processing.	Utilise best applicable techniques in industry for systems requiring fast batch degassing.  Quantify expected degassing performance within a given time frame, through scoping calculations appropriate for concept phase.
Degradation of Coolant Sample	The half-life of the non-gaseous products required for laboratory analysis is short (minutes).	Fast degassing methods required.  Fewer or faster procedural operations.	
Material compatibility	Cannot contaminate the sample.	Material compatibility compliance.	Use material compatibility as an initial go/no-go filter on alternative options.
Deployable Conventional Safety & Human Factors	The probability of the fault event is very low.  Transportation through the facility is needed to bring the sample to a nitrogen supply point for sparging.	Lightweight.  Small footprint.  Robust (desirable).	Reducing the volume envelope brings many benefits.  Favour Commercial Off The Shelf (COTS) items.
Storage of active gases to permit decay and subsequent release	Storage for captured gases may be limited at site  In addition to the active gases intended for capture, a much larger volume of hydrogen is off-gassed.	Reduce gas storage volume.	Favour designs that reduce gas storage burden.

Through consideration of these requirements alongside research into applicable degassing methodologies and industrial techniques a recirculating sparging concept was selected for performance evaluation.

## 2.2 SYSTEM ELEMENTS

The degassing system comprises three portable rigs plus supporting services:

### Sampling Rig

- A sealed vessel used to collect a representative reactor coolant sample.
- Designed to operate under vacuum and to contain sample water with dissolved active and non-active gases.
- Houses the sparger during the degassing phase.
- Contains the sample when transported.

### Processing Rig

- Contains a vacuum pump capable of evacuating vessels and recirculating sparging gas.
- Interfaces with the facility nitrogen supply.
- Provides controlled nitrogen sparging and subsequent gas recirculation.
- Transfers extracted gases to a pre-evacuated storage vessel.

### Flushing Rig

- Functionally similar to the Sampling Rig but used to remove stagnant coolant from upstream pipework and hoses.
- Ensures that the subsequent sample drawn into the Sampling Rig contains fresh coolant with the short half life non-gaseous products representative of current reactor conditions present in detectable quantities.
- Degassing of flushed coolant is performed without time pressure.

### Gas Storage Vessel

- A pre-evacuated vessel used to capture and store sparge gas and removed off-gases.

## 2.3 OPERATIONAL SEQUENCE OUTLINE

The following outlines the how the system will be used:

### 1. System Preparation

- The Sampling Rig is evacuated using the Processing Rig vacuum pump. This removes air and establishes sub-atmospheric conditions prior to sampling.
- The evacuated Sampling Rig is connected to the reactor sampling outlet.

### 2. Coolant Sampling

- A coolant sample is drawn into the rig, containing dissolved active and non-active gases in a supersaturated state inherited from reactor operating conditions.
- The Sampling Rig remains under vacuum following sample collection.

### 3. Sparging and Gas Capture

- The Sampling Rig is connected to the Processing Rig at a nitrogen supply point.
- High-purity nitrogen is injected through the sparger, producing fine bubbles within the sample water.
- Dissolved gases transfer from the liquid phase into the bubbles and headspace.
- A pump recirculates the sparge gas to extend effective contact time while conserving nitrogen gas inventory.
- After a defined sparging period, the gas mixture is transferred into the pre-evacuated Gas Storage Vessel.
- The degassed sample remains under vacuum

#### 4. **Sample Discharge**

- The rig is vented to atmosphere and the sample drained into an open vessel.
- The sample is made available for time-critical laboratory analysis.

To address degradation of coolant retained in pipework and hoses a Flushing Rig is used immediately prior to the above sampling operations. The steps are the same, except that the Flushing Rig is used in place of the Sampling Rig and the last bullet is redundant.

### 3. Sparging Performance

#### 3.1 MASS TRANSFER EQUATION

Sparging is the process of introducing an inert gas such as nitrogen into a liquid through a diffuser, porous medium, or injection lance to generate fine bubbles. Sparging is widely used for degassing, chemical reaction control, impurity removal, and improving process homogeneity in industrial systems. Sparging promotes a large gas-liquid surface area that allows dissolved gases to diffuse from one medium into another; in this case, from the sample water into the sparge gas.

The following formula determines the Rate of Mass Transfer and clarifies the variables that influence sparging degassing performance [1]:

$$\frac{\delta C}{\delta t} = k_{La}(C_0 - C_{equ}) \quad \text{Equation 1}$$

Where:

$\frac{\delta C}{\delta t}$  = Rate of mass transfer ( $\text{mol}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ ) – i.e. mass transfer is inherently time dependent

$k_{La}$  = Volumetric Mass Transfer Coefficient, which depends on the Diffusion Coefficient and the Diffusion Layer Thickness ( $k_{La}$ ) and the Gas-Liquid Surface Area to Water Volume Ratio ( $a$ ). As done here, these are often treated as a single lumped parameter due to the difficulty in measuring them independently.  $(C_0 - C_{equ})$  = Concentration Gradient where  $C_0$  is the concentration of gas dissolved within the bulk water, and  $C_{equ}$  is the equilibrium concentration of gas dissolved within the water governed by Henry's law.

Equation 1 can also be equated to Fick's first law for one-dimensional diffusion (J); this allows for better granularity of the terms that affect mass transfer. This is shown below:

Fick's Law for one-dimensional diffusion [2]:

$$J = D * \frac{(C_0 - C_{equ})}{\delta x} \quad \text{Equation 2}$$

Fick's law units [2]:

$$J = \frac{mol}{m^2 * s}$$

To equate Fick's law with Equation 1, Fick's law is multiplied by the surface area to volume ratio, a. This step is required because Fick's law describes the molar flux, J, which represents mass transfer per unit area per unit time. To express this flux as a rate of concentration change comparable to Equation 1, it is first multiplied by the gas-liquid interfacial area, representing the total area available for diffusion, and then normalised to a concentration by dividing by the liquid volume. This conversion yields a volumetric mass transfer rate, and all units are consistent after applying these transformations.

This allows Equation 3 to be produced which enables each parameter that affects  $k_{La}$  to be understood.

$$\frac{\delta c}{\delta t} = k_{La}(C_0 - C_{equ}) = D * \frac{SA}{V_{sw}} * \frac{(C_0 - C_{equ})}{\delta x} \quad \text{Equation 3}$$

$$\therefore k_{La} = \frac{D}{\delta x} * \frac{SA}{V_{sw}}$$

Where:

$D$  = Diffusion Coefficient ( $m^2/s$ )

$SA$  = Gas-Liquid Surface Area ( $m^2$ )

$V_{sw}$  = Volume of Sample Water ( $m^3$ )

$\delta x$  = Diffusion Layer Thickness ( $m$ )

$(C_0 - C_{equ})$  = Concentration Gradient ( $mol/m^3$ )

$k_{La}$  = Volumetric Mass Transfer Coefficient ( $1/s$ )

Within the constraints of the project's requirements and context, the following variables were highlighted as having potential to be exploited to optimise mass transfer performance (each relate to the bullets below Equation 1 discussed earlier):

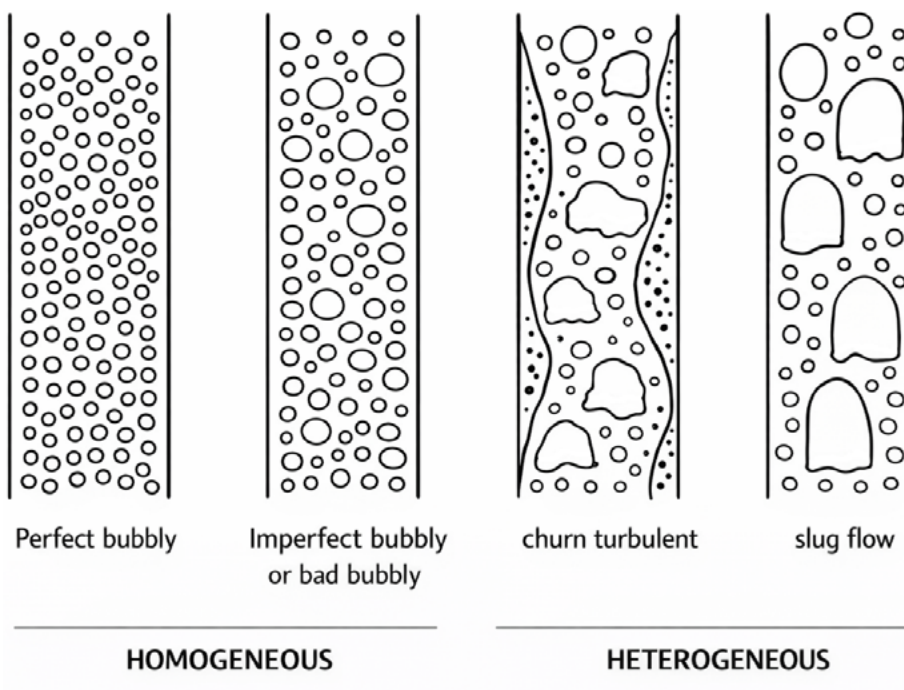
1. The **time** the sparging gas is in contact with the sample water is very influential on performance and is governed by the bubble rise time and the column height. These variables may be maximised by the production of small bubbles that have a low-rise velocity and the implementation of re-circulation which increases the effective column height.
2. Heating the sample acts to increase the **diffusion coefficient** of the gases in water [3]. Whilst this is beneficial, it was prohibited for this project since it would spoil the sample for subsequent laboratory analysis.
3. The **gas-liquid interface area** can be maximised during sparging by (again) reducing bubble size and increasing bubble density within the column, known as 'Gas Hold Up'.
4. The **concentration gradient** can also be maximised, by reducing  $C_{equ}$  as much as possible. This can be achieved through the use of high purity sparge gas (with respect to the gases you are trying to remove from the sample), and through the use of a vacuum (a technique known as 'Vacuum Degassing'). A consideration for both approaches is the head-space above the sample water in the Sampling Rig. A small head-space will reduce the concentration gradient more rapidly as degassing progresses, unless fresh sparge gas is used or the vacuum pressure is restored. Hence a large head space is desirable.

### 3.2 GAS HOLD UP

Gas hold up is defined as the volume of gas in the liquid divided by the total volume of liquid and gas in a reaction vessel [4]. Calculation of Gas Hold Up first requires an assumption about the flow regime, geometry and orientation of the system. In this case, the vessel is cylindrical and in a vertical orientation, and the pressure and flowrate from the nitrogen supply is understood. By following manufacturer guidance to size an appropriate sparger for the flow conditions, it was determined that a 'perfect bubbly' flow regime would be achieved (per Figure 1).

FIGURE 1

Different flow regimes experienced in bubble columns. Adapted from [5]



Bubble velocity can be calculated by assuming that the bubble reaches terminal upwards velocity immediately upon bubble creation and making an informed assumption about bubble size (see Section 3.3). It is possible to determine the bubble rise velocity by equating the buoyancy force with the drag force acting on the bubble as it rises. An extract of this method is shown below, with the last equation from the extract being solved to find bubble rise velocity ( $U_g$ ) [6]:

<p>Equate the buoyancy force to the drag force acting on the bubble (assuming terminal velocity and the density of nitrogen is significantly less than water)</p>	$\rho_w \cdot V_B \cdot g = \frac{1}{2} \cdot C_d \cdot \rho_w \cdot A \cdot U_g^2$
<p>Define the drag coefficient relationship for spheres (Schiller &amp; Naumann drag correlation)</p>	$C_d = \frac{24}{Re} (1 + 0.15 \cdot Re^{0.687})$
<p>Substitute the drag coefficient relationship into drag force equation</p>	$\rho_w \cdot V_B \cdot g = \frac{1}{2} \cdot \left( \frac{24}{Re} (1 + 0.15 \cdot Re^{0.687}) \right) \cdot \rho_w \cdot A \cdot U_g^2$
<p>Simplify equation (expand both brackets and cancel out <math>\rho_w</math>)</p>	$V_B \cdot g = \left( \frac{12}{Re} + \frac{(1.8 \cdot Re^{0.687})}{Re} \right) \cdot A \cdot U_g^2$
<p>Define Reynolds number</p>	$Re = \frac{U_g \cdot D \cdot \rho_w}{\mu_w}$
<p>Substitute in Re</p>	$V_B \cdot g = \left( \frac{12 \cdot \mu_w}{U_g \cdot D \cdot \rho_w} + \frac{1.8 \cdot \left( \frac{U_g \cdot D \cdot \rho_w}{\mu_w} \right)^{0.687} \cdot \mu_w}{U_g \cdot D \cdot \rho_w} \right) \cdot A \cdot U_g^2$
<p>Simplify equation (cancel velocities and factorise D, <math>\rho_w</math> and <math>\mu_w</math>)</p>	$V_B \cdot g = \left( 12 + 1.8 \cdot \left( \frac{U_g \cdot D \cdot \rho_w}{\mu_w} \right)^{0.687} \right) \cdot \frac{A \cdot U_g \cdot \mu_w}{D \cdot \rho_w}$

Using this bubble rise velocity and the height of the sample water in the Sampling Rig, the gas hold up can be calculated as follows:

Height of the water in the column: 
$$H_L = \frac{V_{sw}}{\pi \left(\frac{D_c}{2}\right)^2}$$

Bubble rise time: 
$$T_R = \frac{H_L}{U_g}$$

Volume of gas in the sample water at any given moment: 
$$V_G = Q * T_R$$

Gas Hold Up within the system [4]: 
$$\varepsilon_g = \frac{V_G}{V_G + V_{sw}}$$

Where:

$H_L$  = Height of sample water in the Sampling Rig (m).

$V_{sw}$  = Volume of sample water in the Sampling Rig ( $m^3$ ).

$D_c$  = Diameter of Sampling Rig that contains the sample water (m).

$T_R$  = Bubble rise time (s).

$U_g$  = Bubble rise velocity (m/s).

$V_G$  = Volume of gas in the sample water at any given time (assuming a fully utilised column) ( $m^3$ ).

$Q$  = Flow rate of nitrogen gas into the Sampling Rig (L/min).

$\varepsilon_g$  = Gas Hold Up (dimensionless number).

Provided the water column is fully utilised (as in this case), the transient partial filling of the column at sparging initiation is equivalent to the transient emptying that occurs

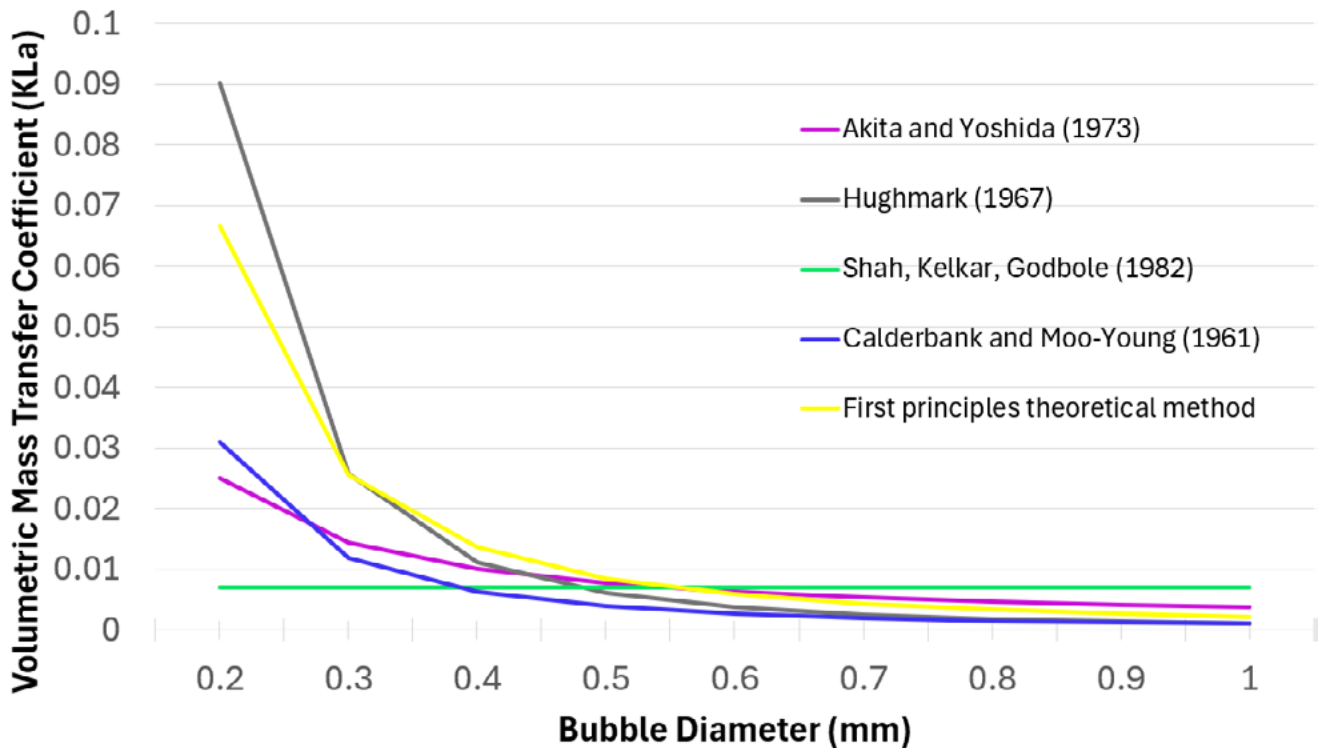
### 3.3 BUBBLE SIZE AND VOLUMETRIC MASS TRANSFER COEFFICIENT

In addition to bubble size affecting bubble rise velocity and thus Gas Hold Up, bubble size also strongly affects the gas-liquid interface area and therefore the Volumetric Mass Transfer Coefficient (VMTC) ( $k_{La}$ ). These two factors make bubble size a very important variable in sparging performance.

There is a range of published experimental correlations that can be used to approximate the Volumetric Mass Transfer Coefficient for a given system, of which four were considered in this project and compared against a theoretical method to improve confidence in the results [7, 8, 9, 10]. These results are plotted in Figure 2 and show how the Volumetric Mass Transfer Coefficient changes with bubble size.

FIGURE 2

How Volumetric Mass Transfer Coefficient varies with Bubble Size [7, 8, 9, 10]



When plotting VMTC against Bubble Diameter for the different correlations and the theoretical method, the following is observed:

1. VMTC exponentially decays as bubble size increases. This demonstrates how critical small bubbles are to mass transfer and therefore sparging performance.
2. That there is reasonable agreement between the experimental correlations that were dependant on bubble size.
3. That one correlation, Shah *et al*, is independent of bubble size.

The Shah, Kelkar, Godbole (1982) correlation (green line) was plotted using experimental data for a sintered sparger, meaning that bubble size was implicit. The only sparging variable considered in this correlation was Gas Hold Up within the system. Due to this correlation having a similar test set up as the other bubble size dependant correlations, an estimate for bubble size could be approximated by observing where this correlation intersects the others. This gives an approximate bubble size of 0.4–0.55mm for sintered spargers, as seen in Figure 2.

A further cross comparison was made using published experimental data from a sparger manufacturer. After correcting for the difference in gas diffusivity of the published experiment, the calculated bubble size was at the lower end of the 0.4-0.55mm range, giving further confidence in the findings and the robustness of the calculation.

Overall, this allowed an approximate bubble size to be determined for sintered spargers, defined as 0.4mm for onward calculations. This correlated to a Volumetric Mass Transfer Coefficient of approximately 0.01/s for a flow rate of gas of 0.7L/min. However, after reviewing manufacture guidance for maximum flow rates that avoid coalescence of bubbles, this flow rate could be increased to 1.7L/min, increasing the Volumetric Mass Transfer Coefficient to approximately 0.025/s. This increase is attributed to the flow rate increasing Gas Hold Up within the system and therefore the gas/liquid interface area (a).

### 3.4 SPARGING EFFECTIVENESS

To complete the calculation, sparging effectiveness was evaluated by determining the concentration of active gas in the sample water after the sparging process was complete, and expressing this as percentage reduction of active gas concentration. The mathematics below show how the Mass Transfer Equation (Equation 1) can be developed to from a time-dependent formula for active gas concentration. The VMTC calculated from the experimental correlations and the total sparge time were input to this equation to find the concentration of active gas after a given time. The equilibrium concentration was initially set to zero during the initial sparging stage where pure nitrogen is used. However, this value was then increased according to Henry's law to reflect the contamination of sparging gas as it starts the re-circulation phase.

Define the rate of change of concentration equation [1]	$\frac{\delta C}{\delta t} = K_{La} \cdot (C_0 - C_{equ})$
Re-arrange equation above	$\frac{\delta C}{(C_0 - C_{equ})} = K_{La} \cdot \delta t$
Integrate the above equation to determine the concentration over time	$\ln \left( \frac{(C_0 - C_{equ})}{(C(t) - C_{equ})} \right) = K_{La} \cdot t$
Raise the right-hand side of the equation above to the exponential	$\frac{(C_0 - C_{equ})}{(C(t) - C_{equ})} = e^{K_{La} \cdot t}$
Re-arrange the above equation to make the time dependant concentration the subject	$C(t) = C_{equ} + (C_0 - C_{equ}) \cdot e^{-K_{La} \cdot t}$

## 4. Results

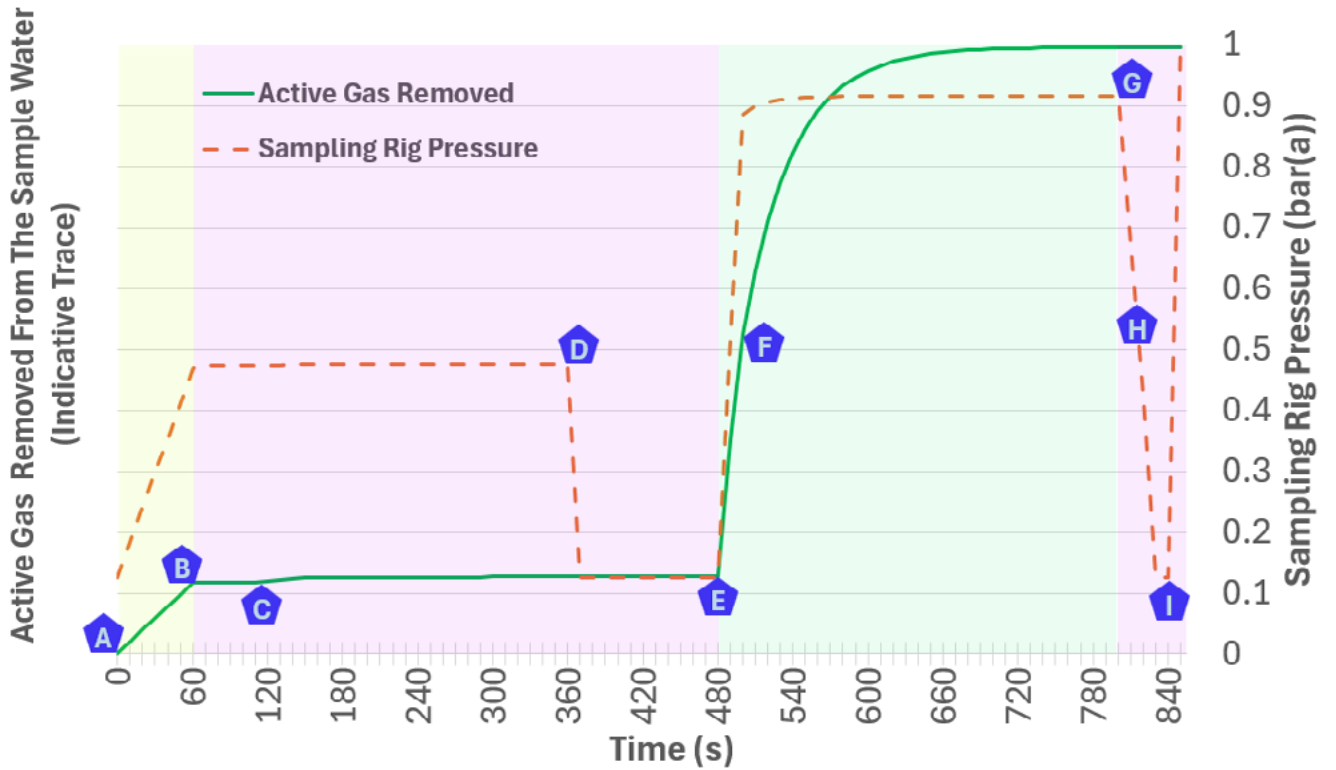
This paper has thus far only discussed the benefit that the sparging process brings in terms of degassing performance. As part of work to assess any extra benefit inherent in the procedure and to assess alternative design variants, calculations were produced to understand vacuum degassing effectiveness during both static and turbulent events. These employed Fick's second law of diffusion to understand how the diffusion layer thickness changes with respect to time and agitation [11]. Additionally, consideration was given to the effect of bubble nucleation during initial depressurisation, which was achieved by relating field experience of a closely related system. System variables including materials, likely surface finishes, temperatures, pipe-run lengths, and flow conditions were analysed, which concluded that the amount of off gassing through initial depressurisation could be conservatively read across.

To characterise the performance of the proposed degassing system in full Figure 3 was produced which describes the cumulative degassing benefit (left vertical axis) against time. For this publication the gas removal performance is normalised to illustrate the method and relative contribution of considered degassing phenomena to system performance. Included is a pressure trace (right vertical axis) that was determined through application of the ideal gas law. The key procedural steps are marked A through I, with commentary below the figure that aligns to the Sampling and Degassing Sequence in Section 2.3 to aid interpretation.

Figure 3 is separated into three colour coded sections. The yellow section refers to the gas expansion out of the sample water during the initial depressurisation of the sample water from primary circuit pressure. The pink sections refer to the mass transfer of dissolved gas out of the sample water through vacuum degassing (of varying vacuum). The green section refers to the mass transfer of dissolved gas out of the sample water due to sparging.

FIGURE 3

Sampling Rig Degassing  
Performance (Indicative)



Commentary on Key Steps (A through I):

- A. The sample starts to be drawn.
- B. The sampling complete.
- C. Sampling Rig begins transportation to new location.
- D. Headspace pressure reduction prior to sparging.
- E. Sparging process starts.
- F. Sparging recirculation starts.
- G. Sparging ends due to time constraints.
- H. Sparging and active gas mix sent storage via vacuum.
- I. Sampling Rig is vented to atmosphere, and the sample water is drained.

## 5. Discussion

**Sparging (green region in Figure 3)** provides the dominant contribution to de-gassing performance, justifying the additional procedural effort and system complexity associated with a recirculating sparging concept. The initial phase exhibits a high de-gassing rate as bubbles are introduced, followed by a gradual decay as the system approaches equilibrium – this trend is common to one-shot nitrogen sparging and recirculating systems.

A disadvantage of gas recirculation is that it results in progressive contamination of the sparging gas, weakening the concentration gradient and reducing the mass transfer rate on subsequent passes. However, in this application the effect is small: the volume of active gas released from the sample is low relative to the system headspace, resulting in only a minor reduction in overall removal performance. This is fortunate for this system as the small quantity of nitrogen permitted on account of gas storage constraints would provide insufficient contact time and thus unacceptably poor performance without recirculation. Recirculation has enabled the system to reach equilibrium rapidly while maximising the effectiveness of the available sparge gas.

Figure 3 shows that, within the defined time constraints, the final 100 seconds of sparging delivers negligible additional benefit, indicating that equilibrium has been reached. In subsequent design phases, this margin could be traded for improved robustness, for example by adopting a coarser sparger to reduce fouling risk.

**Vacuum degassing (pink regions)** was assessed and found to contribute negligibly to overall performance. This is attributed to the limited gas-liquid interfacial area inherent to the vessel geometry and orientation in use. A small increase in de-gassing rate is observed during vessel transportation, where agitation is assumed to reduce diffusion layer thickness and enhance mass transfer.

Alternative concepts aimed at reducing gas storage requirements were considered, including vacuum only degassing and COTS membrane contactors. Vacuum only designs were found to require a large footprint, precise levelling, and to deliver inferior performance, while membrane contactors were rejected due to material compatibility constraints.

**Initial depressurisation (yellow region)** contributes to gas removal through bubble nucleation, but this contribution is an order of magnitude lower than that obtained from sparging, representing a useful but secondary effect. As nucleation may also occur at other stages, the performance shown in Figure 3 is considered conservative.

Not all removed gas is captured within the storage vessels. Limits on achievable vacuum, imposed by pump capability and the need to avoid boiling, result in a small residual fraction remaining in the Sampling Rig headspace and subsequently vented during sample discharge. Opportunities to reduce this residual, including higher-vacuum pump specification, can be addressed during detailed design.

## 6. Conclusions

The combination of first principles modelling, published correlations, and cross comparison with manufacturer data has shown that the analytical approach provides a reliable framework for early stage process design within a unique requirement set.

The study clearly identifies bubble diameter, effective interfacial area, and available mass-transfer time as the primary drivers of sparging performance. This provides useful design guidance for future system iterations and for other applications involving rapid batch degassing.

The analysis highlights the relative contribution of each mechanism to degassing performance (sparging, vacuum degassing and bubble nucleation) for this specific system.

Sufficient confidence in the degassing performance of the proposed system was achieved through these and similar calculations commensurate with the project's position in the design lifecycle. Some performance headroom is carried forward that may be traded to improve reliability, reduce clogging risk, or simplify operation without compromising overall degassing performance.

Considering operator doses associated with the postulated fault event are already within statutory limits, the proposed system reduces personnel exposure further to levels that are as low as reasonably practicable (ALARP).

## **Acknowledgements**

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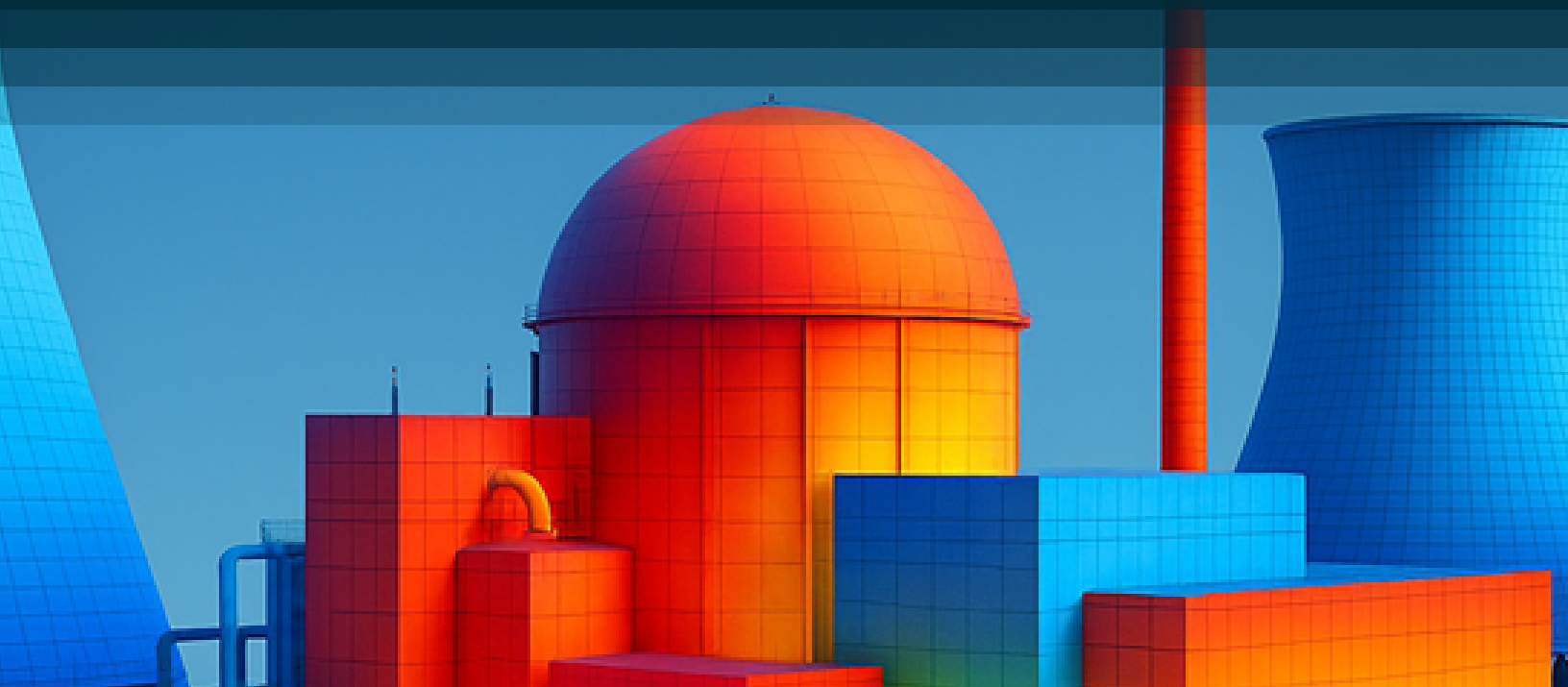
# 06: 3D Analysis and Visualisation of Reinforced Concrete Design Data

### Significance Statement

Designing reinforced concrete structures for nuclear projects has traditionally involved slow, manual interpretation of complex engineering data buried in specialist software. Our work transforms this process by converting complex analysis results for reinforced concrete structures into useful design output including calculated reinforcement requirements, design margin and densities. These are presented in accessible, interactive 3D models that all stakeholders can interrogate, supporting faster, clearer decision making. Through visual and intuitive design data we improve quality, reduce rework, and give stakeholders immediate insight helping deliver safer, more efficient nuclear infrastructure.

### Énoncé d'importance

La conception de structures en béton armé pour les projets d'énergie nucléaire a toujours nécessité une interprétation manuelle et fastidieuse de données techniques complexes cachées dans des logiciels spécialisés. Notre travail transforme ce processus en convertissant les résultats d'analyses complexes des structures en béton armé en résultats de conception exploitables, notamment les besoins en armature calculés, les marges de sécurité et les masses volumiques. Ces informations sont présentées sous forme de modèles 3D accessibles et interactifs que toutes les parties prenantes peuvent interroger, ce qui favorise une prise de décision plus rapide et plus claire. Grâce à des données de conception visuelles et intuitives, nous améliorons la qualité, réduisons les révisions et offrons aux parties prenantes une visibilité immédiate, contribuant ainsi à la mise en place d'infrastructures d'énergie nucléaire plus sûres et plus efficaces.





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## Abstract

Traditionally, reinforced-concrete nuclear design teams had to navigate vast quantities of analysis data locked inside specialist tools or static reports. This slowed engineering workflows, limited transparency, and created delays for clients seeking clarification or design assurance. AtkinsRéalis has replaced and improved this process by converting finite element model (FEM) outputs into interactive, data rich 3D models, with a fully accessible 3D environment which embeds design data directly into the model. This shift enables first-hand interrogation of results by designers, clients and contractors, improving quality, reducing rework, and enabling significantly faster, more informed responses to change and technical queries.

ContourRC was developed internally by AtkinsRéalis to determine the reinforcement provision for reinforced concrete slabs and walls based on a full suite of ultimate limit state (ULS) and serviceability limit state (SLS) design checks. These checks use extracted force and moment results of FEMs using the sandwich panel method presented in Eurocode 2. ContourRC has been tailored to multiple design codes including Eurocodes, American Concrete Institute and nuclear industry specific design codes, and calculates the optimised reinforcement required for each finite element. This design requirement is interrogated by the engineer to determine suitable and efficient reinforcement intents across the walls and slabs. ContourRC enables bulk structural analysis for high volume analytical outputs without the limitations of many proprietary design software. This ensures enveloping is performed at the latest stage possible to create both an optimised design and a rich design data set to enable informed decision-making in both the design phase and future project phases.

This data formed the foundation for creating data-rich 3D models in the industry foundation classes (IFC) format. These models integrate design data and can be reviewed within any building information modelling (BIM) environment, enabling spatial context and cross-disciplinary collaboration. To further enhance interrogation of the design results and improve intuitive understanding, AtkinsRéalis developed custom plug-ins for Autodesk Navisworks. These tools focus on colour coding and data accessibility to improve understanding of the design results, streamline the review process and consider results from adjacent panels.

The conversion of FEM and analysis data into IFC format was achieved using bespoke Python scripts. These scripts interpret the spatial structure of the building from the input model, translate FEM finite elements into IFC schema objects, and embed design data as object metadata. This ensures consistency and significantly accelerates the delivery of results compared to traditional documentation methods. This enables rapid, informed iteration of design, as well as enabling faster responses to design changes.

These tools are currently being deployed on new-build nuclear projects throughout Europe (including Sizewell C and Penly nuclear power stations), transitioning design data delivery from cumbersome documentation to BIM-compatible, data-rich 3D models. The models have demonstrated improved design efficiency, facilitated spatial reviews, and enhanced quality assurance. They are also being used by contractors to support collaborative decision-making around reinforcement arrangements. With all the design information immediately accessible, this reduces the response-time to technical queries from multiple days to immediate feedback.

Together, these developments demonstrate a robust, scalable framework for delivering reinforced concrete design data in a BIM-compatible 3D environment, improving design efficiency, enhancing transparency, and enabling more informed decisionmaking for designers, clients and contractors across nuclear newbuild projects.

#### **KEYWORDS**

Reinforced Concrete Design; Finite Element Analysis (FEA); 3D BIM Visualisation; IFC Data Integration; Automated Reinforcement Optimisation

# 1. Introduction

Emerging digital tools are improving quality, sustainability and safety across construction. AtkinsRéalis developed ContourRC to support reinforcement design for concrete slabs and walls modelled in Finite Element Analysis (FEA) packages. The software improves quality through reduction in manual processes, reduces unnecessary material use through reduced design conservatism, and enhances collaboration through improved access to information and spatial understanding. Initially developed for nuclear new-build projects, the approach aligns with AtkinsRéalis' 2035 nuclear vision for cost, quality and health-and-safety gains through digital adoption (AtkinsRéalis 2024).

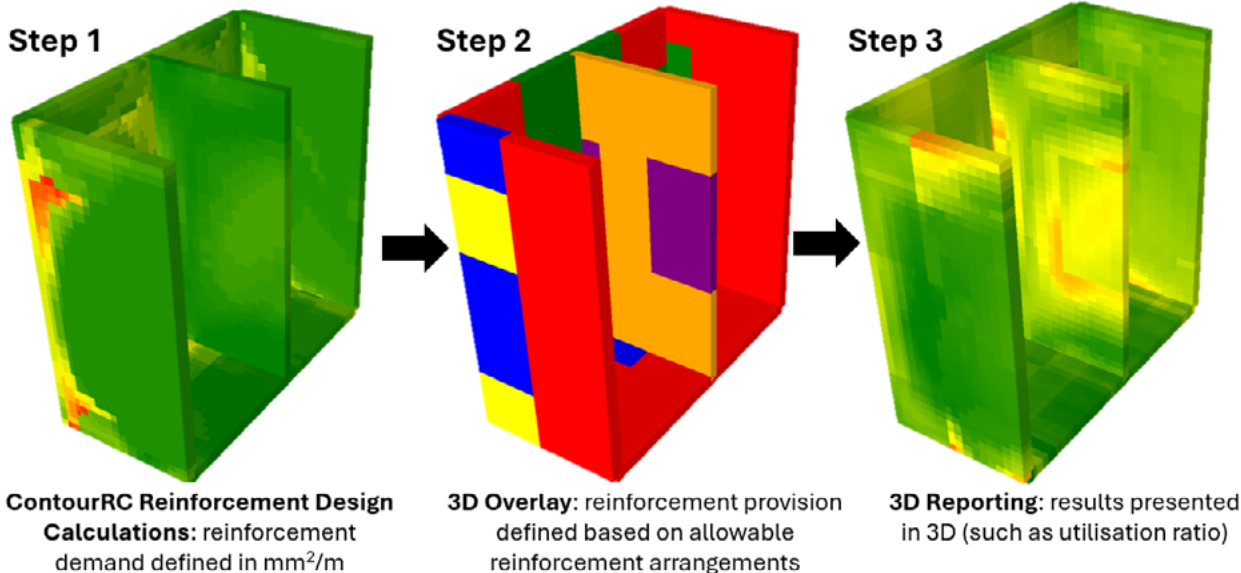
## 1.1. WORKFLOW OVERVIEW

ContourRC provides the foundations for a robust and clear end-to-end reinforcement design pathway through providing the following functionality (Figure 1).

The following sections describe each stage in sequence, highlighting both the technical process and its contribution to design efficiency.

FIGURE 1

ContourRC  
Process Diagram



- **Step 1 – ContourRC Reinforcement Design Calculations:** Perform reinforcement design calculations based on the FEA force and moment results, presenting a theoretical reinforcement demand.
- **Step 2 – 3D Overlay:** Enable the engineer to define the reinforcement provision within a 3D environment.
- **Step 3 – 3D Reporting:** Calculates the densities, utilisation ratios and design margin for this provided reinforcement which are presented graphically within data-rich 3D models and reported in excel summary tables.

## **2. Step 1 - Reinforcement Design Calculations**

### **2.1. OVERVIEW**

Within the reinforcement design of nuclear structures, safety-critical structure requires detailed analysis to fulfil its safety case and achieve regulatory approval. In cases where dynamic, seismic or non-linear analysis is necessary, this process is often beyond the capability of dedicated structural analysis packages and, to ensure sufficient rigour, requires the use of specialised general-purpose FEA software such as Abaqus. Additionally, these projects generate extremely large datasets and typically have project specific requirements and design codes. This led AtkinsRéalis to develop a flexible tool capable of handling large datasets, accommodating multiple design codes, and producing refined design outputs.

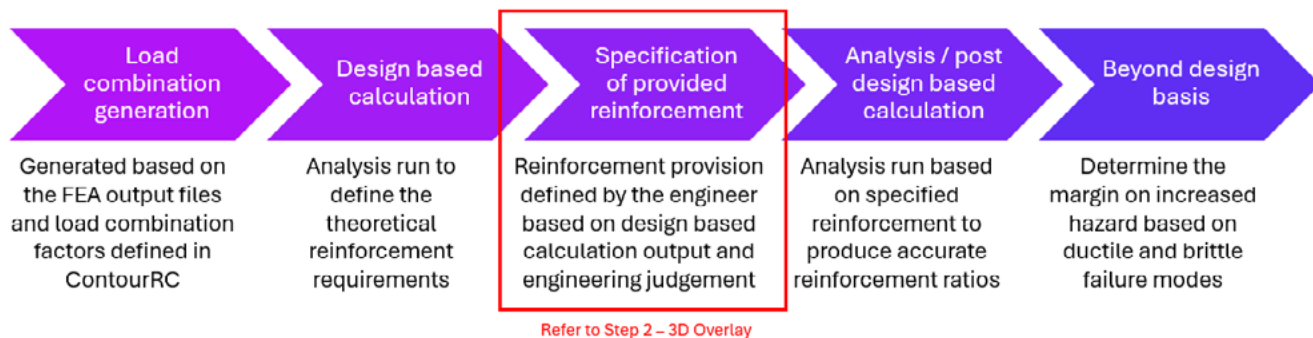
Any FEA package can be used to generate section forces and moments for the shell elements for the reinforcement design calculations. Engineers define the load combination table based on code requirements and loading conditions which ContourRC uses to calculate the section forces and moments for each load combination at each shell element. Through the graphical user interface (GUI), the user can adjust section properties and calculation options as required. These include reinforcement spacer size, cover to reinforcement, concrete cylinder strength and aggregate type for section properties, and calculation of minimum and maximum reinforcement requirements, restraint, allowable utilisation ratios and inclusion of shear effects for calculation options.

## 2.2. TECHNICAL APPLICATION

The reinforcement and concrete stresses are determined in accordance with the sandwich model approach detailed in Annex LL of Eurocode BS EN 1992-2 (2010), a mechanical-based approach which allows for compatibility with all design modules used within ContourRC. The design checks are carried out in accordance with the design code module selected for Ultimate Limit State (ULS) and Serviceability Limit State (SLS) checks to provide, dependent on the analysis option, the required reinforcement area, design utilisation ratios and margin. Finally, the results are enveloped to present the governing requirements. Enveloping at the end of the design process reduces conservatism whilst also allowing for interrogation of information for each load combination. The overall approach is shown in Figure 2.

FIGURE 2

ContourRC  
Analysis Approach



ContourRC provides the following analysis options (typically run in series):

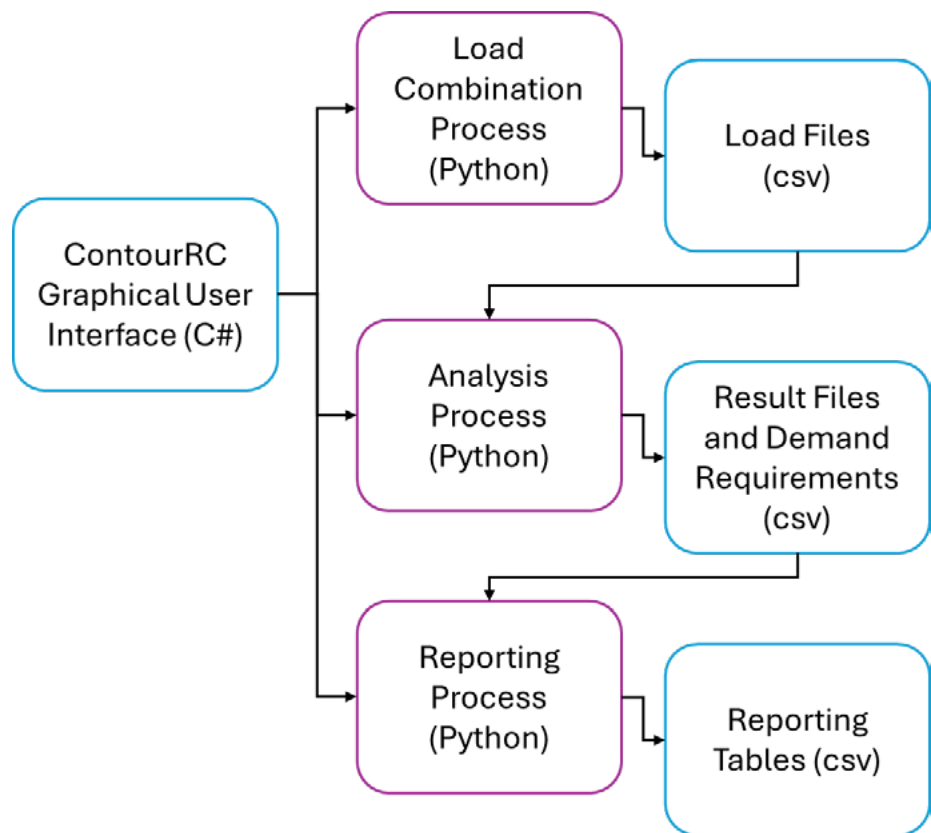
- **Design-based calculation:** An iterative calculation which will calculate an optimised reinforcement provision for each load combination, based on stepping through a user defined table of potential reinforcement arrangements.
- **Analysis / post design-based calculation:** Analyses a fixed reinforcement provision to calculate 'actual' utilisation ratios and governing cases for each defined load combination. This analysis uses files of reinforcement provision for each element which may be user defined or outputted from the 3D Overlay Tool (refer to Section 3) after rationalisation of results from the design-based calculations.
- **Beyond design basis:** Re-run final design reinforcement against additionally factored accidental load combinations to return design margins against increased hazard/seismic events for use in design justification.

### 2.3. DIGITAL DEVELOPMENT

The two most important considerations when developing ContourRC were creating a software package that was able to efficiently deal with the large number of analysis cases required while still ensuring consistent quality in the results. Considering these two factors all the analysis aspects of ContourRC were developed in Python, a programming language that can deal with the significant quantities of numerical analysis while remaining concise and understandable to engineers. This process is shown in Figure 3.

FIGURE 3

ContourRC  
Computational Process



To provide engineers with a clear and intuitive way of performing analysis, a GUI was developed outlining all options and inputs required in a simple and intuitive form. This allows ContourRC to be fully packaged as a standalone and locked application (with no other required software installation) which can be used across a range of projects with confidence. Utilising Python's wide range of data processing modules allows the calculation to process quickly and reliably, allowing engineers to process tens of thousands of load combinations across large FEMs within tight delivery schedules.

#### **2.4. BENEFITS**

ContourRC reinforcement design calculations were developed in collaboration between project engineers, digital developers and clients to produce a package that is clear to use, interrogable and continuously improving. Recent developments include major upgrades to the software to capture changes to reinforced concrete design codes, migration to a new programming code base, incorporating additional design checks (such as construction joint verification) and capturing lessons learnt previous projects to improve functionality and user understanding.

### 3. Step 2 - 3D Overlay Markup

#### 3.1. OVERVIEW

In the next stage, engineers review the optimised reinforcement demands and define the actual reinforcement layout. These activities include reviewing loading and utilisation results from ContourRC, defining element assumptions such as averaging zones to mitigate reinforcement singularities, carrying out model reviews, and assigning reinforcement demand. This process uses a mix of technical reinforcement design knowledge and consideration for construction methods to produce a suitable, efficient and buildable design. Traditionally, reinforcement mark-up was carried out on 2D drawings, a slow process that has limited visibility of global structural behaviour. Engineers were required to navigate multiple drawings and files, limiting their ability to understand how local design decisions interact with the wider structure.

By transitioning these activities into a fully 3D environment, the plug in allows engineers to interrogate the model and design data directly, assessing the entire building simultaneously to develop a clearer understanding of structural behaviour. A 3D design package was developed, allowing engineers to interrogate the model and results, apply assumptions, and defining the required reinforcement provision. This involved the creation of a 3D industry foundation class (IFC) model created from the input FEM. The results of the calculations are then imported into Navisworks using a custom-built ContourRC 3D Overlay tool, for interrogation and investigation by the engineer. Design outputs such as governing limit state and required reinforcement area are displayed visually in 3D within Navisworks to provide a holistic understanding of the design requirements. The tool also provides the section forces and moments for the governing load combinations for specific elements, allowing for interrogation into unexpected or unusual results. Informed by the design output, the engineer then assigns reinforcement, considering constructability and practical detailing.

### 3.2. CONVERSION OF THE FINITE ELEMENT MODEL TO IFC

To enable effective 3D interrogation, the FE model must first be converted into a BIM-compatible format. A key challenge in structural and nuclear design projects is that FEMs are typically confined within proprietary FEA software environments. These platforms are often expensive, require specialist expertise and licences, and are not optimised for integration with construction-focused digital workflows. As a result, valuable analysis data is difficult to share beyond the core analysis team, limiting cross-disciplinary understanding and slowing decision making.

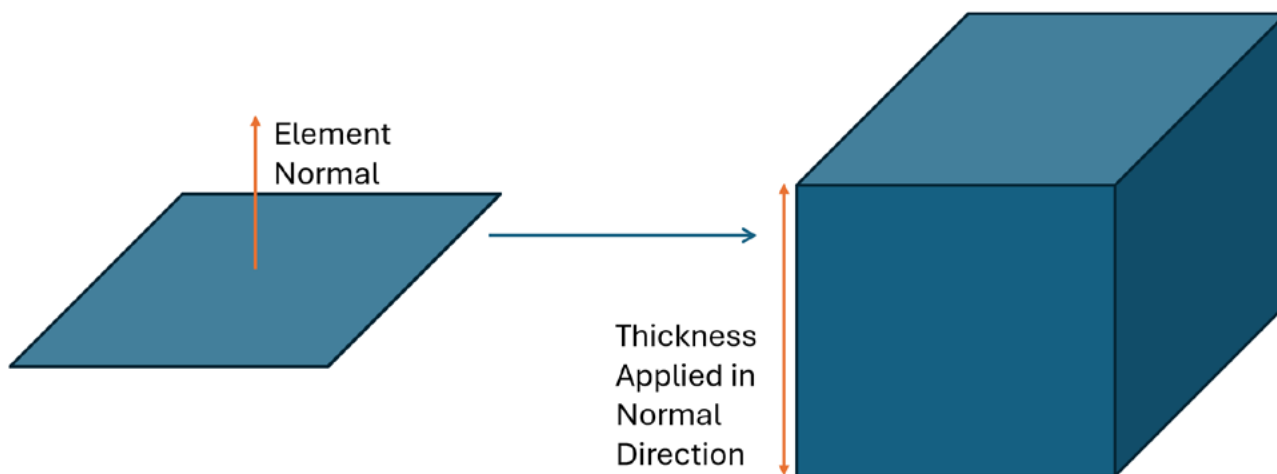
To overcome this constraint, a standalone tool was developed to translate FEMs from multiple analysis packages (including Abaqus, ANSYS, and Robot Structural FEMs) into an IFC model. The IFC schema was selected because it is the established open standard for BIM interoperability, enabling software-agnostic model exchange across the full design and construction lifecycle. Its open specification allows developers to embed additional metadata and create tailored digital workflows without dependence on any single vendor.

Python was chosen as the development language due to its accessibility for engineering teams, its suitability for large-scale numerical processing, and its extensive ecosystem of geometry and data-handling libraries. Within the conversion process, each FE shell element is treated individually and converted into a corresponding 3D IFC object. The geometric thickness is derived directly from the input element properties, extruded along the element's local normal direction to form a solid representation. Reinforcement primary and secondary directions are then assigned according to project conventions and tool preferences (e.g., vertical secondary direction for walls). Element offsets defined within the FEM are respected to ensure correct alignment of inner and outer concrete surfaces in the resulting geometry. A simplification of this step is shown in Figure 4.

Once generated, the IFC elements are assembled into the appropriate hierarchical structure required by the IFC schema, maintaining consistency between the source FE model, the resulting 3D model, and the associated analysis results. This automated process allows large and complex FEMs to be converted into IFC models within minutes, enabling rapid sharing with the wider project team, including clients, designers, and contractors.

FIGURE 4

FE to IFC Element  
Translation Process

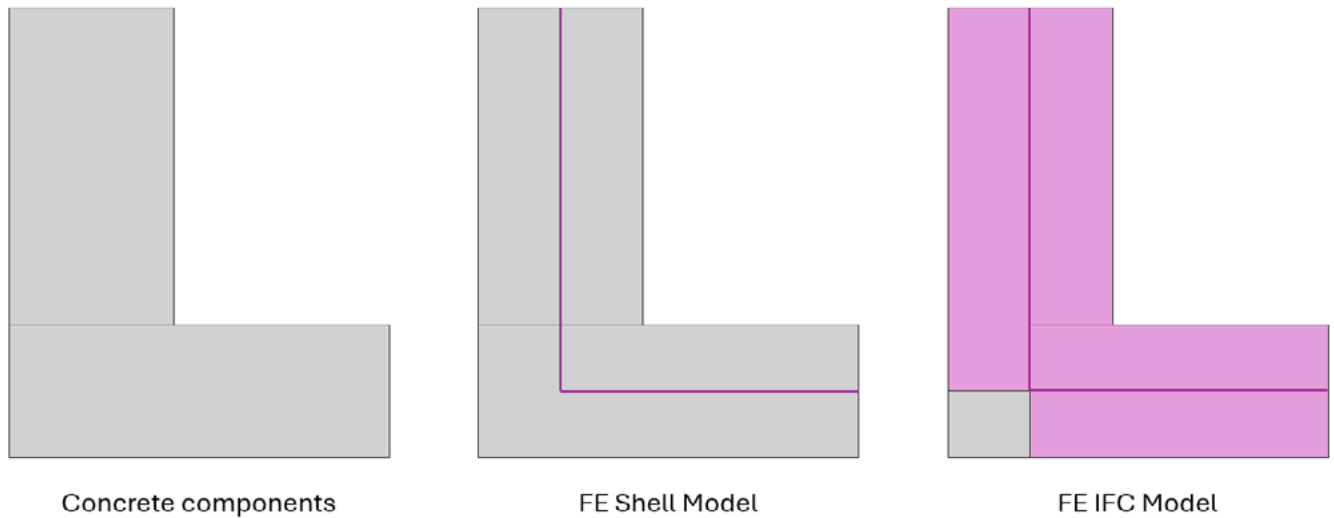


The conversion approach intentionally preserves the FE modelling assumptions rather than idealising the geometry to match the “real” concrete structure. By scaling each element directly based on its FE thickness, the resulting model reflects any simplifications present in the analysis model, such as mesh offsets, simplified connectivity and idealised junctions. For example, at 90-degree connections between components, small geometric gaps may be present where FE offsets, or mesh assumptions do not exactly reproduce the physical concrete volume as shown in Figure 5. Altering the geometry to match a detailed BIM model would risk creating inconsistencies between the analysis data and the 3D representation interrogated by engineers. Retaining the FE assumptions in the IFC model ensures full traceability, supports engineering understanding of model behaviour, and avoids potential misinterpretation of design results.

FIGURE 5

FE to IFC

Connection Behaviours



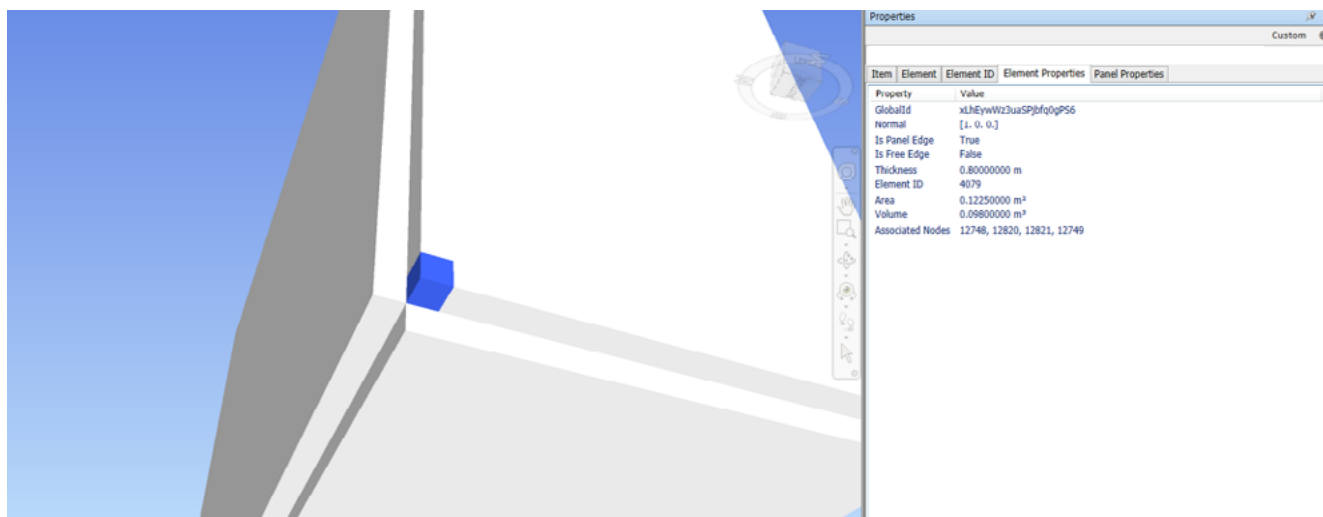
In addition to geometric creation, the IFC elements are populated with metadata required for design interrogation and downstream workflows. This includes fundamental geometric properties such as thickness and area but also enriched engineering information generated during the conversion process. Examples include:

- Primary and secondary reinforcement directions based on axis conventions
- Identified connecting elements
- Distances to panel edges and structural joints
- Relationships between adjoining walls and slabs

These modelling behaviours and view of the applied metadata are shown in Figure 6.

FIGURE 6

Modelling Assumptions and  
Applied Element Metadata



### 3.3. DEVELOPMENT OF 3D OVERLAY TOOL

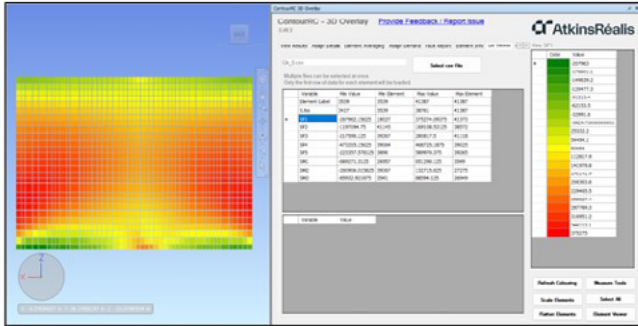
A new in house C# Navisworks Manage plug in was developed to streamline the reinforcement mark-up and design activities that were previously carried out in 2D drawing software. Projects are loaded from a single directory consistent with the ContourRC folder structure, automatically populating the tool with analysis stage results, demands, load information and design assumptions. Once reinforcement has been rationalised and applied, the updated design can be exported back into ContourRC for full post analysis, enabling verification of utilisation factors and compliance checks using the detailed design reinforcement.

The move to 3D also enabled the development of additional design-oriented tools that were impractical in 2D environments. These include the ability to edit individual reinforcement sub-layers, improved measurement tools within the 3D space, and options to visualise load case data across the structure. Together, these capabilities provide a more efficient and informed design workflow, with the principal benefit being the ability to view structural information directly within the spatial context of the 3D model, assisting engineering review and decision-making.

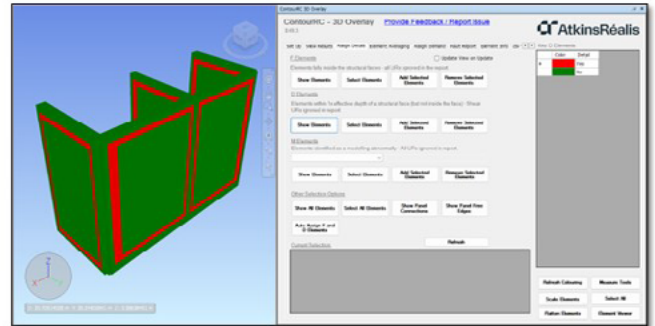
A selection of steps from the 3D Overlay Tool are shown in Figure 7.

FIGURE 7

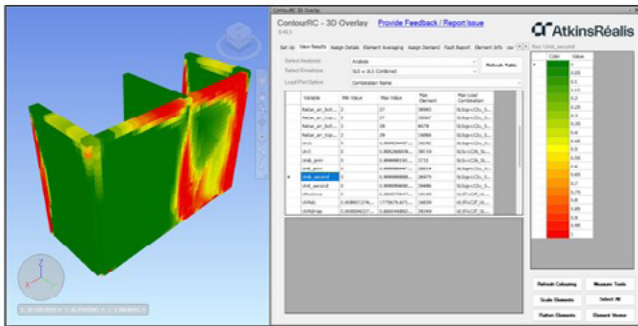
Examples of 3D  
Overlay Functionality



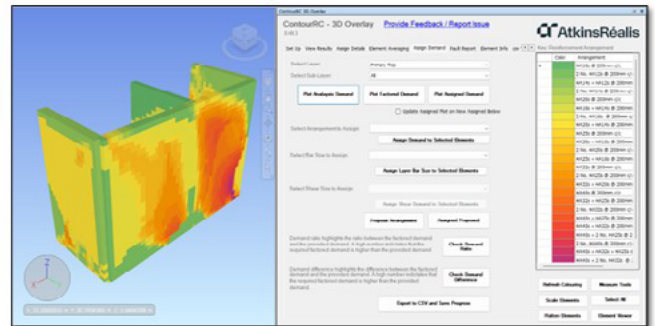
Review input forces and moments



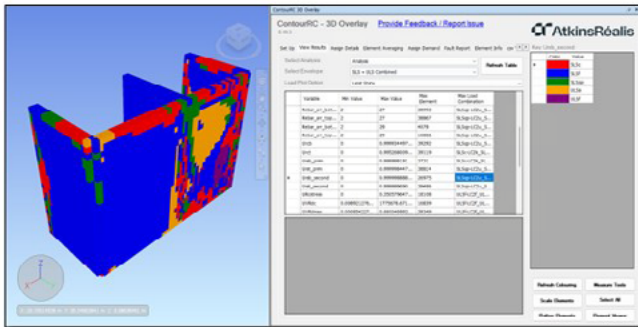
Application of modelling assumptions



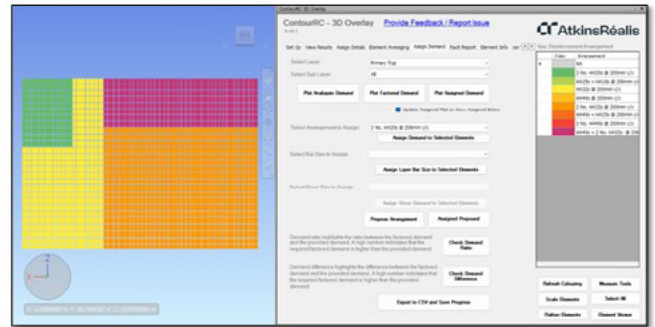
Review analysis utilisation factors



Review initial reinforcement demand



Review governing load combinations



Apply provided reinforcement demand

### 3.4. BENEFITS

The 3D overlay model was developed to enhance and modernise the reinforcement design process that had previously been carried out within 2D environments. The introduction of the 3D overlay provides a single, integrated spatial environment in which all relevant information; analysis results, loading data, demand requirements, and engineering assumptions, can be viewed concurrently. This consolidation eliminates the need to navigate between numerous files and enables engineers to visualise reinforcement behaviour in context with the overall structural model. The resulting workflow not only reduces the manual effort required to perform markup but also enhances design quality by enabling engineers to observe interactions between structural components, identify potential issues earlier, and make decisions with improved confidence and clarity.

## **4. Step 3 - 3D Reporting**

### **4.1. OVERVIEW**

Once the structural design is finalised, it is processed back through ContourRC to generate the as-designed utilisation factors. These results form the basis of the final design information issued to the client and contractor. Traditionally, this information would have been communicated through extensive drawing packages or detailed reports, often requiring a full page of output for every attribute for each individual structural component. Considering the need to present four reinforcement layer demands, shear demand, multiple design checks and utilisation measures, even a small element could easily exceed ten pages of documentation. For larger structures, the resulting design outputs could span thousands of pages. Such documentation is not only time-consuming to produce and interpret but also offers limited insight into global structural behaviour, as each element is presented in isolation.

A custom Navisworks plug-in now presents these results in an interactive 3D environment for the design team, clients and contractors. This model displays information which can include reinforcement provision, utilisation ratios, calculated crack-widths and reinforcement densities shown on an editable colour scale. The reinforcement provision can either be viewed as the requirement across the panel, or where multiple reinforcement layers are used, as the reinforcement bar size and spacing per layer. This has significantly improved understanding of reinforcement arrangements by enabling clearer communication and more intuitive visualisation of bar layouts.

#### 4.2. DEVELOPMENT OF THE 3D VISUALISATION TOOLS

A second Navisworks plug-in was developed to present ContourRC results directly within a BIM-compatible 3D environment. This tool allows designers, reinforcement modellers, clients and contractors to interrogate the final design results spatially rather than through isolated documentation. The plug-in enables colour-coded visualisation of reinforcement demand, utilisation ratios, crack-width outputs and reinforcement densities using adjustable colour scales. Reinforcement can be displayed either as overall panel requirements or, where multiple reinforcement layers exist, as bar size and spacing for each layer, improving clarity for construction planning and detailing.

Unlike native Navisworks functionality, which has limited ability to colour code elements based on element metadata, the custom Colour Mapping Tool enables complex plotting options including continuous ranges, discrete bands and project-specific colour schemes such as reinforcement visualisation. Metadata for each element is indexed internally to ensure fast performance, even for models containing tens of thousands of objects. Although designed for ContourRC output, the tool is model agnostic and can colour code any Navisworks model with appropriate information.

The final IFC model is delivered with embedded analysis data including reinforcement demands, utilisations, design assumptions and governing load combinations. This allows all stakeholders to review the structural design within a single BIM environment without requiring access to ContourRC. This approach significantly increases the amount of information that can be shared compared to conventional drawing based workflows, enabling richer review, clearer communication and improved understanding of structural behaviour across the full project team.

Examples of the Colour Mapping Tool to review an example 3D model are shown in Figure 8 and Figure 9.

FIGURE 8

3D Visualisation of  
Reinforcement Demand

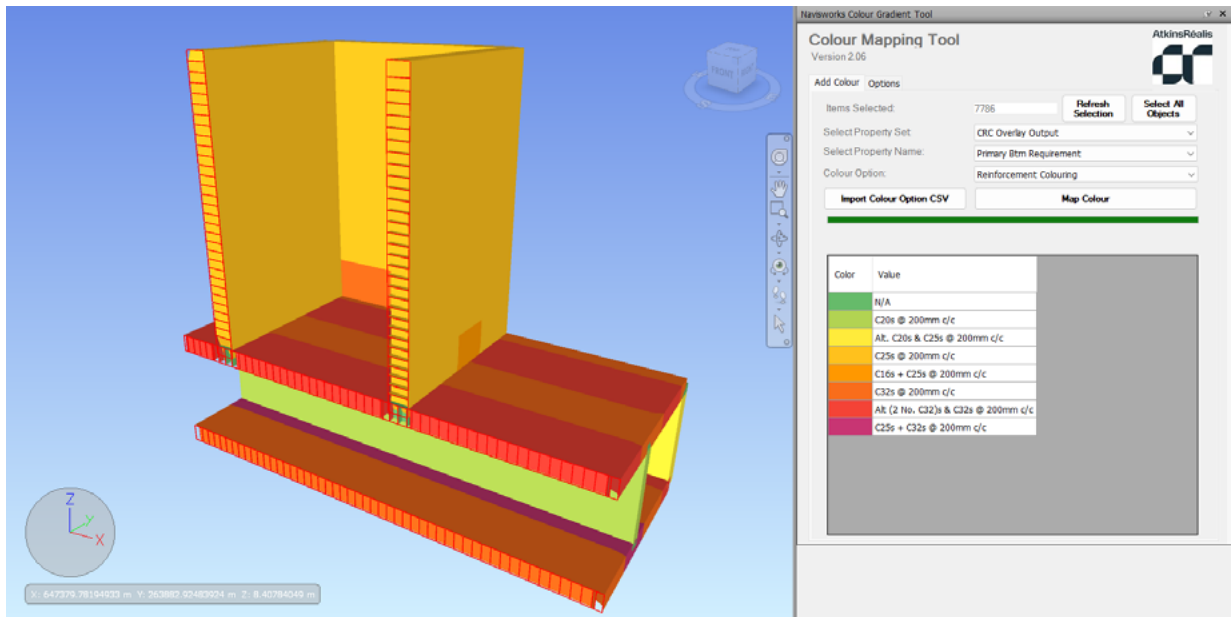
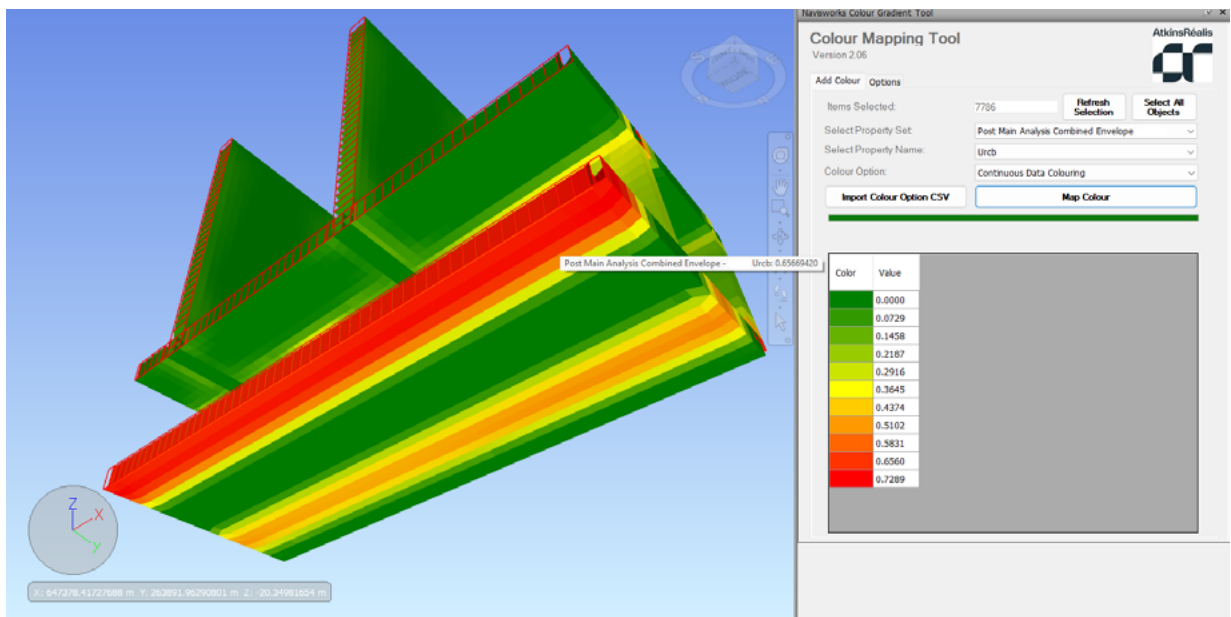


FIGURE 9

3D Visualisation of  
Utilisation Factors



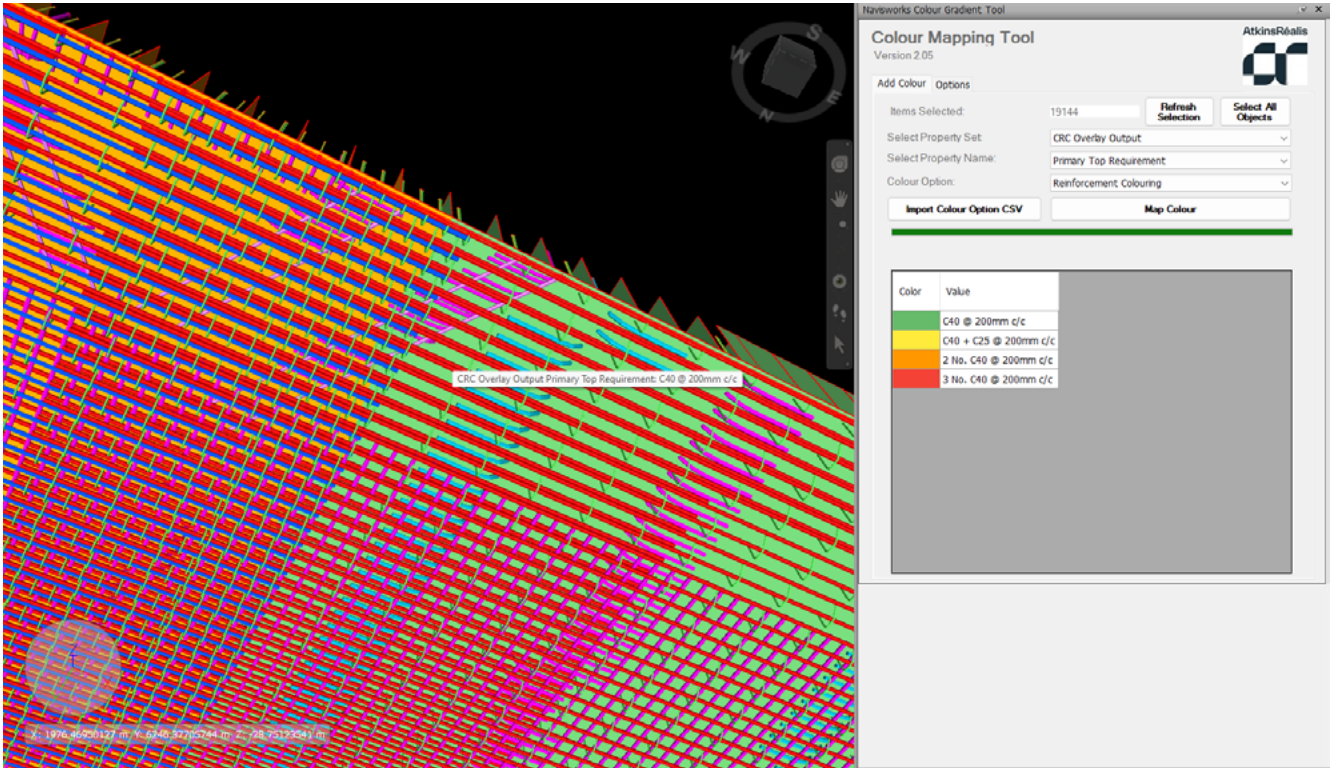
### 4.3. BENEFITS

Integrating design results into a 3D IFC model enables all stakeholders to access structural information in a single, shared environment, providing a unified source of truth. By embedding results directly within an IFC model, engineers and non engineers alike can access the information through multiple software platforms without needing the analysis tool.

The bespoke Navisworks plug in further enhances result interrogation through editable colour coded and tailored views. Performing reinforcement design directly within the 3D model has also strengthened the design process by improving clarity, reducing manual interpretation and integrating contractor preferences into the visualisation environment. This has supported more efficient communication of construction requirements and improved understanding of reinforcement layouts during design development and delivery. Furthermore, the 3D reinforcement can be integrated into the same modelling space to improve quality assurance through direct comparison between the required and modelled reinforcement as shown in Figure 10.

FIGURE 10

Use of the 3D Visualisation  
Tool for Comparison to 3D  
Reinforcement Model



## 5. Quality Assurance and Validation

A rigorous Verification and Validation (V&V) process has been adopted, which ensures that ContourRC performs accurate design calculations in line with evolving engineering codes. This process is critical: under design risks structural failure, while over-design leads to unnecessary costs and carbon emissions. The V&V framework developed by the team is a model of quality assurance, combining engineering precision with digital innovation. A strong quality culture is adopted that prioritises continuous improvement, cross-functional collaboration, and knowledge sharing. The team's efforts culminated in the release of a validated software package, complete with a user guide and V&V report, ensuring confidence and consistency in its application.

Each software update undergoes a comprehensive V&V cycle, anchored by a reference calculation template tailored to each design code. These templates, available to all users, provide transparency and foster a deeper understanding of the software's engineering principles. The team meticulously selected load cases, including edge cases, to stimulate all relevant behaviours in the design code. Co-located engineering and digital teams collaborated in real time to resolve discrepancies, supported by subject matter experts who ensured alignment with engineering intent.

The members of the ContourRC development team are integrated into the project delivery using ContourRC. This enables integration of important quality control processes into the project delivery. Each package release of the software includes a summary of the update, which is briefed to the project team. A log file is produced and automatically saved with the design results which includes information including the ContourRC version number, calculation input settings, and file paths to input and output files. Project checklists focus on ensuring processes has been correctly followed, input/outputs are correct, and engineering judgement has been correctly applied.

## 6. Unlocking Potential

The ContourRC suite of tools provides numerous benefits, including:

- **Reduction in manual post-processing:** The automation of the process reduces the effort required for post-processing compared to existing spreadsheet-based methods.
- **Improved quality assurance:** Software can be rigorously checked once, then re-used without need for changes to the code. Input parameters can be adjusted independently of the software itself. Moreover, fewer manual data handling steps reduce the scope for human error in the input/output process.
- **Reduction of conservatisms:** To allow the post-processing of FE output by a spreadsheet method, the volume of data must be reduced to a practical level. This is typically done by enveloping section forces and moments across all load combinations prior to calculation of the reinforcement requirements. This leads to conservatism, as the maximum force and moment components in all directions across the full set of load combinations do not necessarily occur concurrently. The method adopted for ContourRC calculates the required area of reinforcement individually for each load combination, then envelopes the actual reinforcement demand across all load combinations, which leads to a more efficient design.

- **Improved contextual understanding:** The presentation of results within a single 3D environment improves data management and interpretation, as well as improved spatial understanding. For example, viewing results for adjacent wall and slab panels simultaneously allows for an improved understanding of the structural behaviour across the joints between panels. This enables a more constructible and robust reinforcement provision to be developed.
- **Interrogation:** Enveloping at the last stage of the analysis allows for improved interrogation into the design results. Additional functionality has been incorporated into the tool to identify the governing limit state, load combination number, section forces and moments, and governing load to be identified. This enables further examination to be conducted into the results where required.
- **Flexibility:** With drop-down options, free-field value boxes and toggles, the ContourRC GUI enables amendment of panel properties and calculation settings. Information boxes for each amendable input provide contextual understanding of the option. This enables a large range of structures to be analysed using ContourRC. Additionally, the direct communication between developers, engineers and clients enables continuous improvement.

## **7. Conclusion**

This work demonstrates how a digital, data-led approach can unlock meaningful improvements in quality, efficiency and assurance for the design of complex nuclear infrastructure. By combining advanced reinforcement design calculations with accessible 3D models, AtkinsRéalis has created a robust framework that enhances understanding, accelerates delivery and supports better decision-making at every stage of the project. As nuclear new-build programmes continue to grow in scale and complexity, approaches such as ContourRC highlight the value of integrating engineering rigour with digital innovation to deliver safer, more sustainable and more collaborative outcomes.

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# 07: Leveraging AI to Enhance Project Management Tasks

## Significance Statement

Generative AI is changing how project managers handle everyday tasks, but until now there has been little guidance on how to use these tools responsibly within recognised professional frameworks. Our work shows how AI, when aligned to the APM Competence Framework, can reduce routine effort, improve clarity, and strengthen decision-making. This helps our clients and teams by enabling more consistent, efficient, and transparent project delivery using practical, digitally enabled workflows.

## Énoncé d'importance

L'IA générative transforme la manière dont les gestionnaires de projet gèrent leurs tâches quotidiennes, mais jusqu'à présent, il existait peu de recommandations sur la manière d'utiliser ces outils de manière responsable dans des cadres professionnels reconnus. Nos travaux montrent comment l'IA, lorsqu'elle est alignée sur le cadre de compétences pour un APM, peut réduire les tâches routinières, améliorer la clarté et renforcer la prise de décision. Cela aide nos clients et nos équipes en permettant une exécution de projet plus cohérente, plus efficace et plus transparente grâce à des flux de travail pratiques et numériques.





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## Abstract

Artificial Intelligence (AI) is increasingly being adopted across project delivery environments, yet guidance on how AI should be integrated into recognised project management practice remains limited. Existing discourse often focuses on technological capability rather than professional application, leaving project managers uncertain about how AI tools align with established competence frameworks. This paper addresses that gap by presenting a practitioner-led exploration of how generative AI tools, specifically Microsoft Copilot, can be aligned to the Association for Project Management (APM) Competence Framework to support everyday project management activities.

The study adopts an exploratory qualitative approach involving four practising project managers working in engineering and infrastructure delivery contexts. A structured prompt library was developed and mapped to selected APM competencies, with participants testing AI-enabled workflows within real project tasks. Data was collected through focus groups and individual interviews, capturing perceived time savings, workflow effectiveness, and impacts on confidence and decision support.

The findings indicate that AI-enabled prompts can reduce administrative effort, improve the structure and consistency of outputs, and enhance support for information-intensive activities such as reporting, risk management, stakeholder communication, and lessons learned. Importantly, AI was consistently viewed as augmenting rather than replacing professional judgement. The paper concludes that competence-aligned AI offers a practical and responsible pathway for integrating AI into project management practice, providing a foundation for future capability development as both technology and practitioner understanding evolve.

## KEYWORDS

AI-Enabled Project Management; APM Competence Framework; Generative AI Workflows; Decision Support; Digital Project Delivery

## 1. Introduction

Artificial Intelligence (AI) is no longer an emerging curiosity within project management (PM); it is rapidly becoming integral to how projects are planned, delivered, and governed. Across multiple reviews and empirical field studies, researchers report that AI adoption is associated with improvements in schedule and cost forecasting, decision support, and measurable productivity gains on knowledge-work tasks, especially for routine and administrative activities [1,2,3]. These developments signal a fundamental shift: AI is moving from a peripheral support tool to a strategic enabler capable of reshaping core project management practices [4].

Yet despite this momentum, practical guidance on how AI should be integrated into established PM frameworks remains limited. Recent systematic reviews consistently describe a fragmented discourse that catalogues AI capabilities (e.g., Natural language processing (NLP), predictive analytics, optimisation) but offers little on how these map onto professional PM standards and competencies [4,2]. This gap is particularly evident with respect to the Association for Project Management (APM) Competence Framework (3rd ed.), which sets out 29 competence areas for project professionals; while widely used, there is no published, systematic mapping that connects specific AI capabilities to the APM competence areas [5,6,7].

This absence of structured alignment is more than a theoretical gap; it presents practical risks for organisations seeking to adopt AI responsibly. Without a clear framework, AI may improve efficiency in isolated tasks while inadvertently undermining governance, creating inconsistency across teams, or weakening assurance processes. Scholarly work in AI governance underscores the need for transparent, auditable, and accountable integration to avoid such pitfalls [8,9]. Likewise, without understanding how AI supports competence development, organisations may struggle to design training, assess skills progression, or assure that AI-enabled PM practice continues to meet professional standards, an issue echoed in broader literature on AI governance and public-sector decision-making [8]. As digital transformation accelerates, the profession requires a principled, structured, and competence-aligned approach to AI [9].

This paper responds directly to that need. It presents a practical, structured exploration of how AI, specifically generative AI tools such as Microsoft Copilot, can support project managers across multiple areas of the APM Competence Framework. Unlike purely conceptual treatments, this work is grounded in practitioner-led experimentation. Our early testing aligns with peer-reviewed and academically-led findings that generative AI can reduce time spent on routine PM tasks, increase the clarity and consistency of reporting, and support competencies such as risk management, stakeholder engagement, and lessons-learned synthesis [10,11,12,13,14].

The overarching aim of this paper is therefore threefold. First, it provides a conceptual and practical mapping between AI capabilities and selected APM competencies, enabling project managers to understand which AI functions support which aspects of professional practice. Second, it demonstrates through concrete examples—supported by prompt libraries, workflow illustrations, and early practitioner testing—how AI can enhance performance in targeted PM areas, consistent with evidence of productivity and quality gains in comparable knowledge-work settings [3,11]. Third, it establishes a foundation for future AI-enabled capability development by offering a structured model that can evolve as both technology and practitioner understanding mature, reflecting research agendas that call for precisely this kind of competence-aligned, socio-technical approach [6,7].

Importantly, this paper does not present AI as a replacement for human judgement or professional expertise. Rather, we argue—consistent with AI governance scholarship—that AI can strengthen these qualities by reducing administrative burdens, accelerating access to information, and improving the quality of inputs into human decision-making, provided deployments meet standards of transparency, accountability, and oversight [8,9]. In doing so, AI has the potential to enhance governance, improve assurance processes, and reinforce the competence expectations that underpin the PM profession [9].

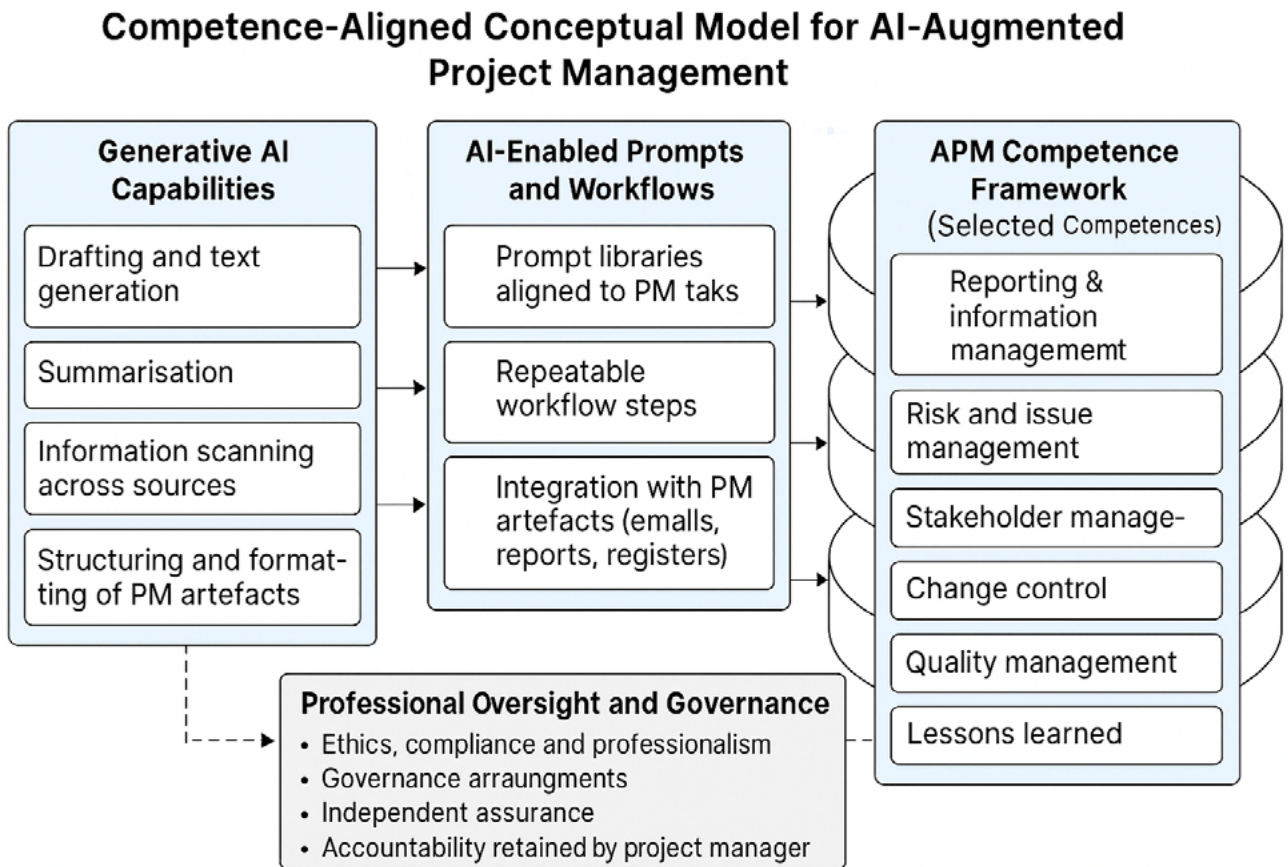
The work presented here reflects the state of practice at this point in time. AI technologies—and their potential applications in PM—are evolving rapidly. The mapping and use cases developed by our team should therefore be viewed as a foundational model, offering immediate value while allowing for future refinement as organisational experience, practitioner confidence, and technology capability continue to grow [4]. By articulating a clear link between AI tools and established PM competencies, this paper provides project managers with a structured, principled, and practically tested pathway for integrating AI into their ways of working [5].

As organisations progress further into digital delivery models, the core question is no longer whether AI will influence project management, but how effectively it can be integrated into competence frameworks that ensure professionalism, governance, and value creation. This paper offers a confident, structured contribution toward that integration [9].

To address the lack of structured guidance for integrating AI into recognised project management practice, this study developed a competence-aligned conceptual model that links generative AI capabilities to selected competences within the APM Competence Framework. The model focuses on core delivery and control competences, while explicitly recognising reporting and lessons learned as cross-cutting elements that span multiple areas of practice.

FIGURE 1

Competence-Aligned  
Conceptual Model  
for AI-Augmented  
Project Management



The conceptual model shown in Figure 1 underpins both the development of the AI-enabled prompt library and the organisation of the testing and results presented later in this paper. By anchoring AI use within clearly defined APM competences and explicitly recognising cross-cutting practices, the model supports responsible and professionally aligned adoption rather than isolated tool experimentation.

## 2. Hypotheses

Building on the evidence reviewed in the introduction—specifically the documented productivity gains from generative AI, its demonstrated ability to enhance forecasting and decision support, and the current absence of structured alignment within project management frameworks—the following hypotheses guide this study:

### HYPOTHESIS 1

**AI-driven tools such as Microsoft Copilot significantly reduce the time required to complete routine project management tasks compared to traditional methods.** This hypothesis is grounded in empirical findings showing that generative AI tools can substantially reduce task duration for knowledge-work activities, particularly those involving drafting, summarisation, and information synthesis. Controlled experiments report large time reductions—e.g., a ~40% decrease in completion time for professional writing tasks with generative AI assistance [11]—and significant speed gains across multiple enterprise tasks in early Copilot studies<sup>15</sup>. Results from developer experiments also show substantial acceleration (up to 56% faster on a programming task when using an AI assistant), illustrating the mechanism by which assistance on text- and code-intensive tasks can translate to routine PM activities such as reporting, risk log updates, stakeholder summaries, and lessons-learned preparation [16]. Complementary field evidence with consultants indicates meaningful productivity and quality improvements when generative AI supports complex knowledge work [3].

## HYPOTHESIS 2

**Integrating AI into project management practice improves decision making accuracy and enhances risk identification compared to teams using conventional processes.** Research in project management and AI-supported decision systems shows that AI can strengthen risk identification, predictive capability, and analytical accuracy across project scenarios. Studies highlight improved schedule/cost foresight and impacts on risk-related knowledge areas [9,10], and reviews synthesise cross-phase forecasting and decision-support benefits while noting current integration gaps that structured approaches can address [4]. In parallel, AI governance scholarship emphasises transparent, auditable decision support to reduce human error and make judgement-based processes more consistent, particularly where documentation, traceability, and oversight are required in project governance [12,8,9].

### **3. Methodology / Testing Approach**

#### **3.1 STUDY DESIGN**

This study adopted a practitioner-led, exploratory methodology designed to evaluate how generative AI tools, specifically Microsoft Copilot, can support project management activities when structured through an APM-aligned prompt library. The intention was not to create a controlled experimental environment, but to understand whether AI-assisted workflows could reduce effort, improve clarity, and support the practical realities of project delivery. The approach emphasised real-world usability, practitioner perspectives, and alignment with the APM Competence Framework to ensure that testing reflected both professional standards and authentic project contexts.

The study followed a qualitative design rooted in environments typical of engineering and infrastructure delivery. Rather than seeking statistical generalisation, the focus was on examining how AI tools could be integrated into day-to-day tasks performed by practising project managers. Testing centred on a curated set of AI prompts and workflows mapped to selected APM competencies. These workflows reflected common project activities such as preparing stakeholder updates, drafting reports, synthesising lessons learned, and structuring risk information. This enabled the evaluation of both practical functionality and the user experience of interacting with AI tools, particularly for individuals with limited prior exposure to generative AI.

#### **3.2 PARTICIPANTS**

Four practising project managers participated in the testing phase. Each PM works primarily on engineering and infrastructure projects and was selected to reflect typical project delivery responsibilities within the organisation. None of the participants were AI specialists, and their previous experience with AI tools was minimal. This was intentional: the aim was to assess whether AI-enabled prompts could provide meaningful support to practitioners who mirror the real skill profile, time pressures, and operational context of project delivery teams. Testing was conducted alongside the participants' standard duties, ensuring that insights were based on realistic project conditions rather than artificial scenarios.

### **3.3 PROMPT LIBRARY AND WORKFLOW DEVELOPMENT**

A structured prompt library was developed to support the testing process. Each prompt group was explicitly mapped to its corresponding APM competency area to ensure coherence with professional expectations. The prompts were designed to be clear, repeatable, and directly applicable to core project tasks such as reporting, risk review, stakeholder communication, and lessons learned synthesis. Supporting workflows were developed to demonstrate how prompts could be applied consistently and where AI assistance could be integrated within typical project management processes. This combination of prompts and workflows formed the foundation of the testing activities.

### **3.4 TESTING PROCEDURE**

The participants were provided with access to the prompt library and attended a short onboarding session explaining the purpose, structure, and intended use of the prompts. They were encouraged to apply the prompts naturally when undertaking tasks aligned with each competency area, rather than being directed to use them at set times. This flexible approach enabled the study to capture how AI might be voluntarily integrated into workflows within a busy project environment. Prompts were applied across a variety of project management activities, including reporting cycles, risk updates, stakeholder communications, and general coordination tasks.

### **3.5 DATA COLLECTION**

Data was collected through a combination of individual interviews and a focus group discussion. The interviews enabled participants to reflect on their personal experiences, describe the usefulness of the prompts, identify challenges, and provide qualitative estimates of time savings achieved using AI. The focus group provided a collective perspective, enabling participants to compare experiences, discuss workflow integration, consider potential improvements, and identify opportunities for broader adoption. Although the time savings reported were subjective, they offered early insight into where AI might reduce effort or streamline specific project management activities.

### 3.6 ANALYSIS APPROACH

Thematic analysis was used to interpret the data. Notes from interviews and the focus group were reviewed and grouped according to the APM competencies explored in testing. This allowed the research team to identify common themes and patterns relating to efficiency, clarity, consistency, and overall practitioner confidence. Particular attention was given to identifying areas in which prompts appeared to streamline repetitive tasks, accelerate document preparation, or enhance the quality of project outputs. These themes form the basis of the findings presented in the Results section.

To support the testing process, a structured prompt library was developed and aligned explicitly to selected competences within the APM Competence Framework. Each set of prompts was designed to support typical project management activities associated with those competences rather than isolated or generic AI functionality.

**TABLE 1**

Overview of AI-Enabled Prompt Library Aligned to APM Competences

<b>APM Competence</b>	<b>Typical Project Management Activity</b>	<b>AI-Enabled Support Provided</b>
Budgeting & Cost Control	Reviewing cost information and updating cost registers	Scanning emails and documents; summarising cost-related actions; structuring register entries
Change Control	Identifying, recording and summarising change events	Scanning communications; populating change logs; generating change summaries
Quality Management	Monitoring quality issues and actions	Identifying quality-related communications; summarising non conformances and actions
Risk and Issue Management	Identifying and maintaining risks and issues	Extracting risks from meeting notes and emails; structuring risk and issue registers
Stakeholder Management	Preparing stakeholder communications and updates	Drafting tailored communications; summarising engagement outcomes
Reporting & Information Management*	Preparing routine project reports	Drafting progress reports; consolidating information from multiple sources
Lessons Learned*	Capturing and synthesising lessons	Summarising discussions; structuring lessons learned records

The prompt library focused on core delivery and control competences, while recognising reporting and lessons learned as cross-cutting practices that span multiple areas of project management. This alignment ensured that testing remained grounded in recognised professional practice and reflected the realities of day-to-day project delivery.

## 4. Results

### 4.1 OVERVIEW OF RESULTS

The testing programme produced a consistent and coherent set of findings across all four participating project managers. While the scale of the study was intentionally limited and exploratory in nature, the results indicate clear early-stage benefits associated with the use of AI-enabled prompt libraries aligned to the APM Competence Framework. Across all competencies tested, participants reported perceived reductions in time spent on routine project management activities, improvements in the clarity and consistency of outputs, and enhanced confidence when dealing with information-intensive tasks.

Importantly, the results suggest that AI was most effective when used as an augmentation tool—supporting drafting, synthesis, and preparation—rather than as a substitute for professional judgement or decision-making. Participants consistently described AI as enabling them to work “faster with more structure,” allowing greater focus on assurance, stakeholder engagement, and leadership activities. The findings below are presented by APM competency area to reflect the structure of the prompt library and to reinforce alignment with professional standards.

### 4.2 REPORTING AND INFORMATION MANAGEMENT

Reporting and information management emerged as the competency area where AI enabled prompts delivered the most immediate and visible benefits. All four project managers used prompts for tasks designed to generate items such as draft progress reports, summarise recent communications, and consolidate information from emails, meeting transcripts, and project documentation.

Participants reported that AI-generated drafts significantly reduced the effort required to prepare routine reports, particularly weekly and monthly updates. Rather than starting from a blank document, PMs described using AI outputs as a structured first draft that could be quickly reviewed and refined.

Beyond speed, participants highlighted improvements in consistency and completeness. AI prompts helped ensure that key sections—such as risks, actions, and progress against milestones—were consistently addressed, reducing the likelihood of omissions. Several PMs noted that this consistency was particularly valuable when managing multiple reporting cycles or when handing over responsibilities.

Overall, AI support in reporting was perceived as reducing administrative burden while improving the quality of outputs, enabling project managers to allocate more time to interpreting information rather than compiling it.

### **4.3 RISK AND ISSUE MANAGEMENT**

The application of AI prompts within risk and issue management workflows was perceived to enhance both efficiency and analytical rigour. Participants used prompts designed to scan recent emails, meeting notes, and project documents to identify potential risks and issues and to support the maintenance of risk registers.

PMs reported that AI assistance was particularly valuable in surfacing early signals—such as repeated concerns in communications or emerging patterns in meeting discussions—that might otherwise be missed during periods of high workload.

While all participants emphasised that final judgement and validation remained a human responsibility, AI was seen as accelerating the identification and structuring of risk information. The ability to rapidly generate well-structured risk descriptions and summaries improved the quality of subsequent risk discussions and reviews.

These findings suggest that AI can strengthen risk management practice by improving early visibility and documentation quality, while preserving professional oversight and accountability.

#### 4.4 STAKEHOLDER ENGAGEMENT AND COMMUNICATION

AI-enabled prompts were widely adopted to support stakeholder communications, particularly for drafting updates, tailoring messages for different audiences, and summarising meetings. Participants reported that AI reduced the cognitive effort associated with producing professional communications, especially when similar messages needed to be adapted for multiple stakeholders.

Several PMs noted that AI assistance improved confidence in tone and clarity, particularly when communicating with senior stakeholders or external parties. The ability to quickly generate concise, well-structured updates was seen as enabling more timely and proactive engagement.

Despite these benefits, participants consistently retained ownership of final outputs, reviewing and refining AI-generated content before distribution. This reinforces the role of AI as a support mechanism rather than a replacement for professional communication skills.

#### 4.5 CHANGE CONTROL

In the context of change control, AI-enabled workflows were primarily perceived as supporting improved organisation, traceability, and governance rather than direct decision-making. Participants used prompts to scan communications for potential changes, populate change logs, and generate summary reports.

PMs reported that AI assistance reduced the manual effort associated with maintaining change registers and helped improve completeness, particularly for smaller or incremental changes that might otherwise be poorly documented.

While AI did not replace formal impact assessments or approval processes, participants noted that better-structured documentation supported clearer decision-making and improved auditability.

These findings suggest that AI can enhance change control by strengthening documentation and visibility, supporting governance without undermining established control mechanisms.

#### **4.6 LESSONS LEARNED**

The use of AI to support lessons learned activities was viewed positively, particularly in addressing long-standing challenges associated with time pressure and unstructured capture. Participants used prompts to summarise meeting transcripts, extract lessons from discussions, and review historical project information.

PMs reported that AI reduced the effort required to synthesise lessons and helped structure outputs in a more consistent and actionable format.

Several participants noted that AI support made lessons learned exercises feel more achievable within normal project constraints, increasing the likelihood that they would be completed rather than deferred or omitted.

These results indicate that AI has the potential to improve organisational learning by lowering the barriers to capturing and reusing experiential knowledge.

#### **4.7 QUALITY MANAGEMENT**

AI prompts supporting quality management were used to scan communications for quality related issues, update quality registers, and summarise outstanding actions. Participants reported that AI assistance helped improve visibility of quality concerns and reduced the effort required to prepare quality summaries for reviews.

While professional judgement remained central to quality assurance activities, AI was perceived as supporting consistency and completeness in documentation.

#### **4.8 CROSS-CUTTING THEMES**

Across all competency areas tested, several cross-cutting themes emerged. First, perceived time savings were primarily driven by reduced drafting effort and fewer iterations required to achieve acceptable outputs. Second, AI was consistently viewed as enhancing structure and clarity rather than replacing thinking. Third, participant confidence in using AI increased over the course of testing, particularly as prompts became familiar and aligned with existing workflows.

In addition to the qualitative findings described above, participants comments were taken to provide indicative assessments of the relative benefits observed when using AI-enabled prompts across the competences tested.

TABLE 2

Perceived impact and confidence across APM competencies

APM Competence	Perceived Time Saving	Perceived Quality / Clarity Impact	Practitioner Confidence in Use
Budgeting & Cost Control	Low-Medium	Low-Medium	Low-Medium
Change Control	Medium (project-dependent)	Medium	Medium
Quality Management	Medium	Medium	Medium
Risk and Issue Management	Medium	Medium	Medium
Stakeholder Management	Medium-High	High	Medium-High
Reporting & Information Management*	High	High	Medium-High
Lessons Learned*	Medium-High	Medium-High	Medium

While these assessments are qualitative rather than quantitative, they provide a consolidated overview of where AI-enabled support was perceived to deliver the greatest value and where benefits were more limited or context-dependent

### SUMMARY OF RESULTS

In summary, the results provide early but compelling evidence that AI-enabled prompt libraries, when aligned to professional project management competencies, can deliver meaningful benefits for practising project managers. The findings indicate perceived reductions in administrative effort, improvements in output quality, and enhanced support for information-intensive tasks. While exploratory in nature, these results suggest that AI can act as a practical enabler for project professionals at the early stages of their AI journey, supporting more efficient and structured practice while preserving professional judgement and governance. These findings are discussed further in the following section.

## 5. Discussion

### 5.1 INTERPRETATION OF KEY FINDINGS

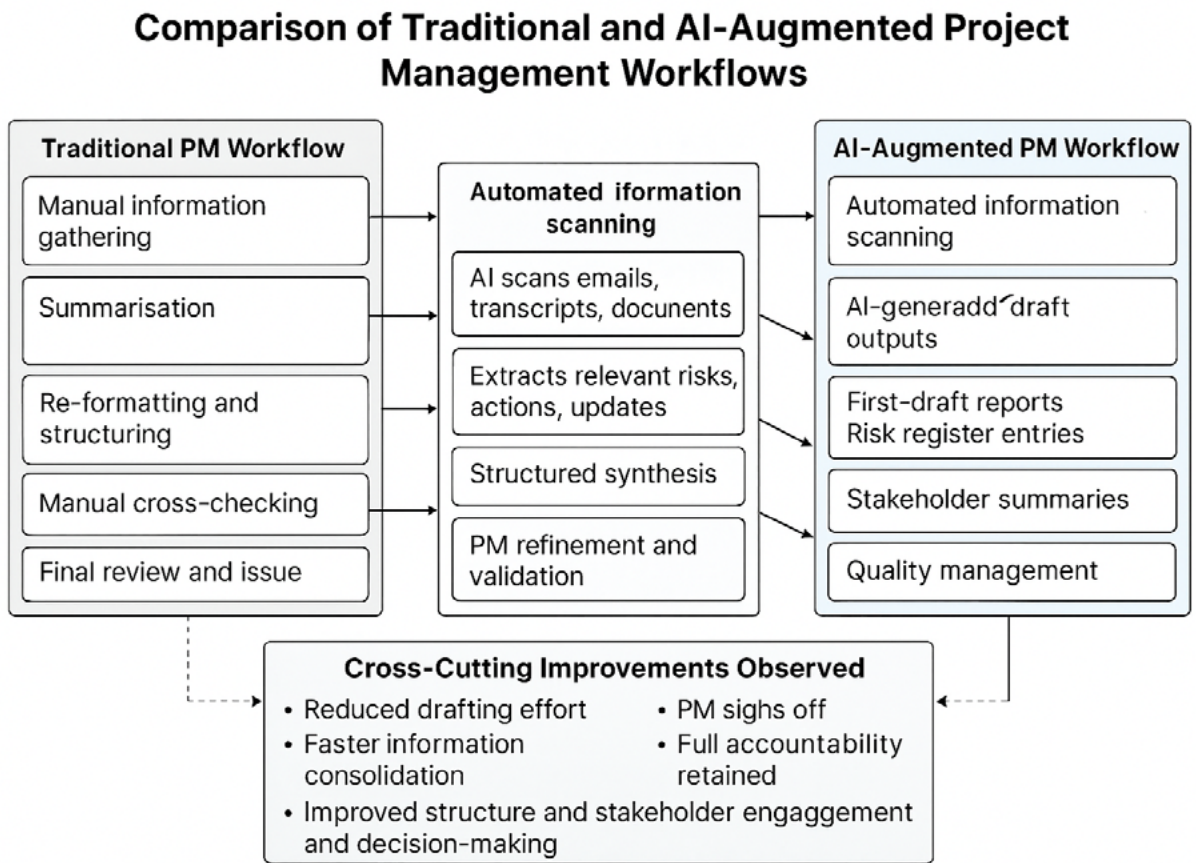
The results of this exploratory study suggest that AI-enabled prompt libraries, when deliberately aligned to recognise project management competencies, can deliver meaningful early-stage benefits for practising project professionals. Across all competency areas tested, participants reported perceived reductions in time spent on routine administrative tasks, improved clarity and consistency of outputs, and enhanced confidence when dealing with information-intensive activities. These findings support the study's hypotheses and align with emerging literature on the role of generative AI as a productivity and decision support tool in knowledge based work.

Importantly, the benefits observed were not associated with the replacement of professional judgement. Instead, AI was consistently described as an augmentation mechanism—supporting drafting, synthesis, and preparation—while leaving interpretation, validation, and decision making firmly with the project manager. This distinction is critical. It reinforces the view that AI's value in project management lies not in automation of responsibility, but in reducing cognitive and administrative load so that practitioners can focus on leadership, assurance, and stakeholder engagement.

The findings indicate that AI-enabled prompts and workflows reshaped how project managers undertake information-intensive tasks. While decision-making authority remained firmly with the project professional, the sequence of activities and the effort distribution changed significantly when AI support was introduced

FIGURE 2

Comparison of Traditional and AI-Augmented Project Management Workflows



As shown in Figure 2, AI support primarily affects preparatory and synthesis activities, reducing manual data handling while preserving professional judgement. This shift explains why participants reported both efficiency gains and increased confidence in the quality and consistency of project outputs.

## 5.2 IMPLICATIONS FOR PROJECT MANAGEMENT PRACTICE

For practising project managers, the findings indicate that AI can provide immediate, practical value without requiring advanced technical expertise. All participants in this study were experienced delivery professionals working in engineering and infrastructure contexts, yet none were AI specialists. Despite this, they were able to integrate AI tools effectively into their workflows when supported by clear prompts and structured guidance.

This has important implications for how organisations approach AI capability development. Rather than positioning AI as a specialist or centralised function, the results suggest that value can be realised through targeted, role-specific enablement embedded within existing professional frameworks. Prompt libraries aligned to recognised competencies offer a practical mechanism for lowering the barrier to entry, enabling PMs to experiment with AI in a controlled and professionally coherent manner.

The benefits observed in reporting, risk management, and stakeholder communication are particularly relevant to project environments characterised by high information volume and time pressure. By reducing the effort required to produce structured outputs, AI support may help project managers maintain quality and consistency even as delivery complexity increases. This is especially pertinent in large infrastructure programmes, where reporting and assurance demands can consume significant proportions of PM time.

### 5.3 AI AS AN ENABLER OF PROFESSIONAL JUDGEMENT, NOT A SUBSTITUTE

A consistent theme across the results was the importance of maintaining professional judgement and accountability. Participants repeatedly emphasised that AI outputs required review, refinement, and contextual understanding before being relied upon. This reinforces the view that AI should be positioned as a decision-support and preparation tool rather than a decision-making authority.

From a professional standards perspective, this distinction is crucial. Project managers remain accountable for the accuracy, appropriateness, and ethical implications of their decisions. AI can support this responsibility by improving the quality of inputs—through clearer summaries, more complete registers, and better structured information—but it cannot replace the contextual awareness and ethical judgement required of a project professional.

The findings therefore support a socio-technical view of AI adoption, in which technology and human expertise are complementary rather than competing. This aligns with broader concerns around AI governance and reinforces the importance of transparency, traceability, and human oversight in AI-enabled project management practice.

### 5.4 COMPETENCE-ALIGNED AI AS A GOVERNANCE MECHANISM

One of the most significant contributions of this work lies in its demonstration of competence-aligned AI as a governance mechanism. By explicitly mapping prompts and workflows to APM competencies, the study provides a structured way of embedding AI into professional practice without undermining standards or assurance processes.

Participants reported greater confidence in using AI outputs when they could clearly see how those outputs supported recognised PM activities. This suggests that competence frameworks can serve not only as professional development tools, but also as design principles for AI integration. In doing so, they offer a way to manage risk, ensure consistency, and support ethical use of AI across project environments.

This has implications for organisational governance. Rather than attempting to control AI use through restrictive policies alone, organisations may benefit from embedding AI within professional frameworks that practitioners already understand and trust. Such an approach may support more sustainable adoption while reducing the risk of fragmented or inappropriate use.

## **5.5 LIMITATIONS OF THE STUDY**

As an exploratory, practitioner-led study, several limitations should be acknowledged. First, the sample size was small, comprising four project managers within a single organisational context. While this limits generalisability, the aim of the study was to generate early insights into practical usability rather than statistically representative findings.

Second, time savings and effectiveness were assessed qualitatively through participant perceptions rather than objective measurement. While subjective estimates provide valuable insight into perceived value, future studies could benefit from more formal measurement approaches, such as time-tracking or comparative task analysis.

Third, the testing period was relatively short. Longer-term use may reveal additional benefits, challenges, or changes in trust and reliance that were not captured in this study. As AI tools and user familiarity evolve, patterns of use may also change.

These limitations are not weaknesses of the approach, but reflections of the study's exploratory intent. They highlight areas for further research rather than undermining the validity of the findings presented.

## 5.6 IMPLICATIONS FOR ORGANISATIONAL AI ADOPTION

For organisations considering wider AI adoption in project delivery, the findings suggest that early value can be achieved through small-scale, practitioner focused experimentation. Rather than pursuing large scale transformation initiatives, organisations may benefit from piloting AI within clearly defined roles and competency areas.

The prompt-library approach demonstrated here offers a scalable model. As prompts are refined and validated, they can be shared across teams, embedded into training programmes, and adapted for different project contexts. Over time, this could support the development of an organisational “AI capability baseline” aligned to professional standards.

Importantly, this approach also supports learning and adaptation. By treating AI adoption as an iterative process rather than a one-off deployment, organisations can evolve their use of AI alongside changes in technology, governance expectations, and practitioner confidence.

## 5.7 DIRECTIONS FOR FUTURE RESEARCH

This study opens several avenues for future research. Larger-scale studies could examine the impact of competence-aligned AI across multiple organisations, sectors, or project types. Quantitative measurement of time savings, error reduction, or decision quality could strengthen the evidence base.

Further research could also explore how AI adoption influences project manager skill development over time. For example, does reduced administrative burden enable greater focus on leadership and strategic thinking? How does sustained AI use affect confidence, judgement, or professional identity?

Finally, future work could examine the governance implications of AI at programme and portfolio levels, where aggregation of AI-Supported outputs may introduce new opportunities and risks.

## **SUMMARY OF DISCUSSION**

In summary, the findings suggest that AI-enabled prompt libraries, when aligned to recognised project management competencies, can deliver meaningful early-stage benefits for project professionals. The results support the view of AI as a practical enabler of efficiency, clarity, and consistency rather than a replacement for professional judgement. By grounding AI adoption within established competence frameworks, this study offers a structured and responsible pathway for integrating AI into project management practice. The implications extend beyond individual productivity, pointing towards new models of capability development, governance, and professional practice in an increasingly AI-enabled delivery environment.

## 6. Conclusion

This paper set out to explore how generative AI can be integrated into project management practice in a manner that is both practical and professionally grounded. Rather than focusing on AI capabilities in isolation, the study adopted a competence-aligned approach, mapping AI-enabled prompts and workflows to the Association for Project Management (APM) Competence Framework. In doing so, it sought to provide project professionals with a structured pathway for adopting AI that reinforces, rather than undermines, recognised standards of practice.

The findings from the exploratory testing indicate that AI can deliver meaningful early-stage benefits for practising project managers. Participants reported perceived reductions in time spent on routine administrative tasks, improvements in the clarity and consistency of key outputs, and enhanced confidence when dealing with information-heavy activities. These benefits were most evident in areas such as reporting, risk and issue management, stakeholder communication, and lessons learned, where AI support helped structure information and accelerate drafting and synthesis activities.

Crucially, the results demonstrate that AI was not viewed as a substitute for professional judgement. Across all competency areas, project managers retained responsibility for interpretation, validation, and decision-making. AI was consistently described as an augmentation tool—supporting preparation and analysis while allowing practitioners to focus their expertise on leadership, assurance, and stakeholder engagement. This distinction is central to responsible AI adoption in project management and aligns with broader expectations around governance, accountability, and ethical use.

One of the key contributions of this paper lies in its demonstration of competence aligned AI as both an adoption and governance mechanism. By explicitly linking AI prompts to familiar professional competencies, the approach reduced uncertainty and increased practitioner confidence. This suggests that competence frameworks such as the APM Competence Framework can play a dual role: not only defining professional expectations, but also providing a structure through which emerging technologies can be safely and consistently integrated into practice.

The study is not without limitations. The testing was conducted with a small number of participants within a single organisational context, and findings are based on qualitative perceptions rather than objective measurement. However, these limitations reflect the exploratory intent of the work rather than a lack of rigour. The aim was to generate practical insight into usability and value at an early stage, providing a foundation for further refinement and future research rather than definitive conclusions.

Looking ahead, the findings suggest several opportunities for future development. Larger-scale studies could explore the impact of competence-aligned AI across different sectors, project types, and organisational contexts. Quantitative measurement of time savings and quality improvements could strengthen the evidence base, while longer-term studies could examine how sustained AI use influences professional capability development and confidence. At an organisational level, prompt libraries and workflows could be refined, governed, and embedded within training and assurance processes, supporting more consistent and responsible AI adoption at scale.

In conclusion, this paper demonstrates that AI-enabled prompt libraries, when aligned to recognised project management competencies, offer a practical and credible pathway for integrating AI into project delivery environments. By grounding AI adoption in professional standards and real-world workflows, the approach supports project professionals at the early stages of their AI journey while preserving the judgement, accountability, and integrity that underpin the project management profession.

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# 08: Digital Work Permits in Rail Transit: Operational Challenges, Cost-Benefit Evaluation Framework, and Change Implementation

## Significance Statement

Rail systems depend on work permits to keep workers safe while maintenance and construction occur alongside live operations. This paper shows how many rail organizations still rely on PDFs and email to manage these permits, creating delays, hidden costs, and gaps in oversight in a safety-critical environment. Using real survey data from Canadian rail operators, the study explains why digitizing work permits matters and introduces a practical way to measure total process delay cost (TPDC) and Return on Investment (ROI). By linking safety, efficiency, and financial impact, the paper offers decision-makers a clear, evidence-based case for modernization and a realistic roadmap for implementing change.

## Énoncé d'importance

Les réseaux ferroviaires s'appuient sur des permis de travail pour assurer la sécurité des travailleurs lorsque des travaux d'entretien ou de construction sont effectués parallèlement à l'exploitation en service. Cet article montre que de nombreuses entreprises ferroviaires continuent de recourir aux fichiers PDF et aux courriels pour gérer ces permis, ce qui entraîne des retards, des coûts cachés et des lacunes en matière de surveillance dans un environnement où la sécurité est primordiale. À partir de données d'enquête réelles provenant d'exploitants ferroviaires canadiens, l'étude explique pourquoi la numérisation des permis de travail est importante et présente une méthode pratique pour mesurer le coût total des retards de processus (TPDC) et le rendement du capital investi (RCI). En établissant un lien entre la sécurité, l'efficacité et l'impact financier, cet article offre aux décideurs des arguments clairs et fondés sur des données factuelles en faveur de la modernisation, ainsi qu'une feuille de route réaliste pour la mise en œuvre du changement.





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## Abstract

This paper evaluates the need for digital work permits in rail transit through survey findings and a cost-benefit model used to estimate annual savings, return on investment (ROI), and implementation strategies. The study uses survey inputs from AtkinsRéalis O&M rail transit operations subsidiaries—Pro-Trans BC, the operator of the Canada Line, and Rideau Transit Maintenance (RTM)—to characterize existing processes and identify key delay drivers, including bottlenecks and manual follow-up requirements across multiple stakeholders (maintenance, operations, safety/EHS, projects, and finance) within the current work permit processing system. A quantitative model is developed to enable organizations to evaluate delay costs, annual cost savings, and ROI. Given that rail operations and maintenance are safety-critical, the paper additionally operationalizes Kotter’s eight-step change model as a structured implementation blueprint for managing change in such an environment. Overall, this study helps organizations understand the need to transition to a software-based work permit system, provides a formula for determining cost-benefit outcomes, and outlines a methodology for implementing change in an organization.

## KEYWORDS

Digital Work Permit System; Rail Transit Operations; Operations & Maintenance (O&M); Total Process Delay Cost (TPDC); Cost-Benefit Evaluation Framework

## **1. Introduction**

Rail transit operations and maintenance (O&M) demand rigorous control over activities that could potentially compromise train movements, endanger passenger safety, or damage critical infrastructure. The work permit system serves as the foundational governance instrument for authorizing, scheduling, coordinating resources, and ensuring safety compliance for all activities within an active rail operating territory.

Within the broader engineering sector, large-scale construction and infrastructure projects, such as railway construction and site improvements, are continually undertaken to deliver essential community facilities. The successful execution of these projects depends heavily on robust planning and implementation stages (Remi, 2017). This execution involves multiple departments within transit O&M. However, despite their importance to development, railway infrastructure projects are frequently hampered by implementation challenges like safety, scheduling, budget, manpower etc., often resulting in significant delays (Effendi et al., 2021). These delays and challenges can be substantially mitigated through the implementation of robust data storage solutions and systematic analysis of historical data.

In some rail transit O&M centers, the reliance on manual, paper-based processes specifically using Portable Document Format (PDF) for managing complex work permits creates significant operational latency, increasing data loss risks, leading to compliance gaps, and resulting in analytic blind spots. This mirrors challenges identified in general infrastructure project/facilities management, where issues like poor planning, frequent rescheduling, overlap, safety concerns, and manual data handling predominantly lead to suboptimal control during the work plan execution phase (Fahmi, 2017). The traditional "bring hard copies of documents for assistance" approach in technical planning and field supervision has been proven inefficient (Effendi et al., 2021).

To address these persistent inefficiencies and delays, a transformative approach is required. Digitization offers a solution to shift permits from static to dynamic, living data objects, enabling the use of data for analysis and decision-making objectives. Studies have shown that the implementation of digital technology in maintenance processes can improve efficiency and effectiveness, leading to enhanced infrastructure availability and improved performance data to make better decisions (Riess, 2021). By digitizing the work permit system, rail operators can enable real-time visibility, implement advanced safety controls, and leverage historical operational intelligence to mitigate risks and improve project delivery outcomes. The research will discuss in detail the cost-benefit analysis and change implementation process to support the introduction of, digitized work process.

## 2. Literature Review

Work permit issuance is a systematic process for approving specific controlled work in potentially hazardous conditions to prevent workplace injuries (Victorica, 2023). Legal regulations across the globe emphasize the issuance of permits by the operator before commencing work at heights, at depth, in confined spaces, in potentially explosive atmospheres, on energy facilities, when using hazardous chemical substances, and when working in areas where there is a serious, unavoidable, or immediate danger or harm that may endanger the health of employees and contractors. Since the employer/operator is required to establish the permit issuance procedure, the subject of this work is the procedure for implementing a system for issuing work permits for high-risk operations (Victorica, 2023).

Permit to work (PTW) software can provide organizations with greater visibility and control over their permit programs. Organizations can use the system to track all permit applications, approvals, and completions. They can also use the system to generate reports on permit activity. Additionally, stakeholders will be able to quickly generate and print site-specific permit documents with custom fields & prepopulated key work details, including those that adhere to standards like the Indian Standard: Work Permit System — Code of Practice (Victorica, 2023).

This improved visibility and control can help organizations identify and address problems within their permit program, from keeping track of completed permits and permit-related site activities to identifying associated hazards, control measures, and equipment. This visibility empowers organizations to prevent work from starting at locations where safety is compromised until those issues are resolved. Organizations will also have visibility into reports on in-progress and completed work (Victorica, 2023).

According to Husein Umar (2009), a “work plan” is the selection of a set of activities and the making of decisions about what to do, when, how, and by whom. Once the plan is established, the associated planning documents must be executed. In a work permit system, it is necessary to have a work plan, as the system includes scheduling, allocation of responsibilities, and an administrator who drives the entire process.

In the Canada Line O&M rail transportation territory, there are multiple stakeholders assigned responsibilities to manage and control the inflow of work permits. The process of managing and controlling the influx of work permits is a shared responsibility distributed among several key stakeholders; these groups include internal teams such as maintenance, operations, HSE (Health, Safety, and Environment), and project teams, as well as external vendors and contractors who submit work permits for processing.

There are multiple software solutions available in the market to address the need for digitized data collection and analysis for work permit processing. One such solution is Environmental, Health, and Safety (EHS) platforms. The report *Market Insight: 10 EHS Technologies With a Rapid Financial Return* by Verdantix emphasizes that economic uncertainty and regulatory pressures are driving organizations to adopt EHS technologies that deliver quick financial returns. Firms are prioritizing solutions that reduce compliance costs, mitigate accidents, and improve productivity within two years of implementation. The Verdantix study categorizes technologies into three phases: mature (EHS software, mobile apps, IoT sensors), growth (digital training, fleet safety telematics, process safety management software, UAVs), and launch (AI-enabled compliance, computer vision, industrial wearables). These technologies not only streamline compliance and operational processes but also generate tangible and intangible benefits, such as improved brand reputation and worker confidence, making EHS investments strategic rather than discretionary.

The financial returns of EHS technologies are compelling. For instance, EHS software can achieve a ROI of 239% over five years, saving \$7.8 million for a \$6-billion chemical manufacturer through IT cost reductions, fewer shutdowns, and lower non-compliance penalties (Chiang et al., 2022). Walmart’s adoption of digital EHS training reduced recordable incidents by 54% in six months (Chiang et al., 2022). Beyond immediate cost savings, EHS technologies deliver long-term strategic value. Consolidating EHS solutions into integrated platforms enhances data-driven decision-making and supports Environmental, Social, and Governance (ESG) and sustainability goals, creating indirect returns through improved brand perception and employee retention. As budgets tighten amid inflation, firms are focusing on technologies with proven ROI and scalability, ensuring compliance while optimizing resources (Chiang et al., 2022). Ultimately, EHS technology adoption is not merely a compliance exercise but a strategic investment that strengthens resilience, operational efficiency, and competitive advantage in an increasingly regulated and sustainability-driven market (Chiang et al., 2022). While these studies highlight the benefits of digitalization in general, traditional systems—such as PDF-based work permit systems—inherently prevent these outcomes, as data retrieval is difficult and manual follow-up is required at all times.

### **3. Methodology and Implementation Framework**

This study will explore the need for a digital work permit system based on survey responses from rail operations teams on the Canada Line in British Columbia and from Rideau Transit Maintenance (RTM) in Ontario, Canada. The paper will focus on developing formulas to evaluate total process delay costs in order to identify cost savings resulting from digital transformation. This will also help derive ROI for new software products that could serve as alternatives to, or replacements for, traditional work permit processing methods. Because rail operations and maintenance are safety-critical, the methodology will also incorporate a structured change management approach. This change methodology will follow Kotter's 8-step framework (Kotter, 1996) and will help explain how to practically implement change using tools such as stakeholder maps, communication and training plans, pilot success measures, and methods to reinforce change.

## 4. Results and Discussion

### 4.1 SURVEY FINDINGS

The survey was conducted with operating teams from the Canada Line and RTM in Canada. The survey results indicate that work permit processing is highly manual, inconsistent, and time-consuming across both organizations. Respondents process between 10 and 25 permits per week, with average completion times ranging from one to two days for straightforward requests to as long as three to five days when engineering review, external validation, or additional analysis is required. Delays are primarily caused by approval bottlenecks, engineering confirmation, billing steps, and the need to coordinate with multiple stakeholders, often involving engineers, operations teams, facility crews, subcontractors, and external agencies. Rework also appears to be common, although the frequency varies by permit complexity, with corrections typically involving dates, times, or incomplete technical details.

Challenges highlighted also include inefficient PDF-based forms, cumbersome email chains, and the amount of time spent “chasing” stakeholders to move permits forward or provide clarifications. Locating past permits is also inconsistent, ranging from quick retrieval to difficult searches, depending on how documents are stored. Data storage practices vary: some rely on folders of PDFs, while others use SharePoint; however, both note that analyzing permit data for KPIs, cost, or manpower insights is limited or still in progress. Overall, there is strong openness toward adopting a software-based work permit system, as respondents believe it could streamline processing, reduce rework, minimize error and improve data accessibility.

Digitizing the work permit process replaces PDFs and email chains with a structured, trackable workflow that improves turnaround times by automating routing and notifications and providing real-time status visibility. As a result, requests can move forward without manual email follow-ups, and delays become easier to identify and prevent. It also increases consistency and reduces rework by using standardized templates and built-in validation, ensuring permits are complete and accurate at submission rather than being returned for missing or incorrect information.

A digital solution strengthens governance and audit readiness by capturing a clear history of actions (who approved, what and when) and storing all records in a centralized, searchable repository. In addition, it enables continuous improvement through dashboards and reporting that highlight volumes, cycle times, bottlenecks, and overdue approvals, turning the permit process into a measurable and manageable performance function. Where permits are safety-related, digitization adds further value by enforcing checklists and prerequisites, improving oversight of active work, and helping ensure controls are applied consistently. It is also necessary to conduct a cost-benefit analysis (CBA) to determine the value added by implementing change within the system. This requires quantifying process delay costs, which can then be used to estimate annual savings and ROI.

## **4.2 COST-BENEFIT EVALUATION FRAMEWORK**

### **4.2.1 Rationale for Quantifying Process Delay Costs**

1. To quantify the dollar impact of waiting time in the process (includes queues, handoffs, approvals, and revisions).
2. To prioritize improvement opportunities so that resource conflicts and bottlenecks are addressed where they generate the highest delay costs.
3. To determine when to expedite activities by comparing the cost of delay versus the cost of intervention (e.g. additional reviewers, forwarding, automation, or re-routing).
4. To focus on improving overall process flow speed.
5. To assign a dollar value to queues and bottlenecks, enabling objective decisions about which issues to address first.

### 4.2.2 Total Process Delay Cost (TPDC)

#### Traditional Method

$$\text{TPDC manual} = N \times W \times [H_{\text{manual}} + (E_{\text{rate}} \times H_{\text{fix}})]$$

#### Digital method

$$\text{TPDC Digital} = [N \times W \times (H_{\text{manual}} \times (1 - \text{TRR})) + N \times W \times (E_{\text{rate}} \times (1 - \text{ERR})) \times H_{\text{fix}}]$$

$$\text{Annual Savings} = (\text{Manual TPDC} - \text{Digital TPDC}) \times 52$$

- $E_{\text{rate}}$  - Error Rate (percentage of permits that require correction)
- $H_{\text{fix}}$  - Average hours required to identify, track down and correct errors per week
- $H_{\text{manual}}$  - Total hours spent on manual PDF entry, filing, and chasing per permit per week
- $N$  - Average number of permits processed per week
- $W_h$  - Hourly wage of staff performing the correction

$$\text{Net Benefits} = \text{Annual Savings} - \text{Software Cost per year}$$

$$\text{Return of Investment (ROI \%)} = \frac{(\text{Net Benefits})}{(\text{Software Cost per year})} \times 100$$

Further research is needed on how to evaluate value-added benefits which also contribute to the overall ROI.

### 4.3 Kotter's 8-Step Process

Implementing an application-based work permit system across interdependent departments works best when organizations begin by aligning stakeholders around “why change is needed now” and “what good looks like.” Kotter’s 8-Step process (Kotter, 1996) can be used to create urgency through simple, relatable examples, such as permits stuck in inboxes, rework caused by missing information, and the lack of a single place to view permit status. A guiding coalition should then be formed with representatives from different departments, as each group touches a different part of the permit cycle and can either block or enable progress. This coalition defines a shared vision: one digital workflow, one source of truth, clear ownership, and faster approvals without sacrificing safety. A broader group of “power users” (requesters, approvers, and planners) should then be enlisted to test prototypes early and support adoption of the change. In multi-department environments, these steps are critical because resistance is often not to the tool itself, but to perceived loss of control, changes in habits, or added workload; therefore, visible leadership and a clear, shared purpose help reduce friction prior to rollout.

The biggest challenges in interdependent organizations are usually handoff breakdowns and competing priorities: one department prioritizes speed, another emphasizes compliance, and another seeks control. The next step in Kotter’s framework—removing barriers and enabling action—is critical, as it is often where change either succeeds or stalls. New workflows should be made easier to use or, where possible, designed to resemble the existing process to reduce resistance. Clarifying roles and responsibilities is also essential and can be achieved through the effective use of a RACI matrix—Responsible, Accountable, Consulted, and Informed—to define who requests, reviews, approves, performs, and closes work.

To build confidence and sustain momentum, organizations should focus on achieving short-term wins and then scaling adoption. Running a small pilot to test credibility and reliability, such as for one permit type, one site, or one crew, allows organizations to track outcomes that stakeholders care about, including turnaround time, the number of incomplete submissions, and how often approvals must be “chased.” Results should be shared widely and supported with real examples and stories. Acceleration can then be sustained through dashboards that show adoption rates and cycle-time trends, along with continuous improvement of templates and routing based on feedback from the pilot group. Once acceptable results are demonstrated, changes should be institutionalized through the development of standard operating procedures (SOPs) that can be followed and shared across the organization. Further research and analysis are necessary for organizations seeking to implement Kotter’s approach, as the framework may not be suitable for organizations of all sizes and must be adapted to fit the unique cultural and organizational context in which change is implemented.

FIGURE 1

Kotter’s 8-Step Process for Change Implementation



## 5. Conclusion

This paper demonstrates why rail transit O&M requires a digital work permit capability, presents a cost-benefit evaluation framework for introducing a new work permit processing system, and outlines how such a transformation can be implemented. Findings from the survey results reinforce that the work permit process is not merely administrative; it also includes critical components such as safety, control, and cost that must be continuously monitored and evaluated. In a rail environment where risk tolerance is low and operational coordination is high, continued reliance on manual PDFs, email-based routing, or other traditional work permit processing methods creates unavoidable delays, weakens real-time oversight, and fragments accountability across stakeholders. Overall, the survey respondents have expressed significant interest in transitioning to an online process. To move from qualitative concerns to measurable justification, this paper developed a Total Process Delay Cost (TPDC) model quantifying the cost impact of manual processing.

This approach strengthens decision-making in two ways. First, it monetizes delay by capturing not only direct effort, but also the hidden costs associated with rework loops and process friction. Second, it provides a standardized method for evaluating new EHS (Environmental, Health, and Safety) and ePTW (electronic Permit-to-Work) platforms, enabling direct, “apples-to-apples” comparisons of ROI by translating operational improvements into quantifiable annual cost savings and net financial benefits. While ROI will vary by platform and licensing model, the TPDC baseline offers a consistent reference for comparing options and justifying investment decisions. Finally, recognizing that digitization in a safety-critical rail environment is as much a people and process transformation as it is a technical deployment, this paper outlines an implementation approach based on Kotter’s 8-step change framework.

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