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An examination of the use of Geotechnical BIM to provide value engineering solutions for coastal infrastructure.

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Abstract–the digitisation of construction is taking root as Building Information Modelling is becoming more prevalent across the industry. From an Irish context, the adoption rate of BIM has been slow; nationally its advantages and merits have been welcomed and the appropriate government support is either available, soon to be implemented or in the early conceptual stage. Within the Irish governments Project Ireland 2040 framework there are significant infrastructure developments looming ahead, in particular regarding ports and harbours. The importance of this type of infrastructure is only further compounded due to the UK's departure from the EU and the need for creating robust trade infrastructure. This research explores Geotechnical BIM as a crucial tool to be utilised but yet to be recognised in the development of coastal infrastructure. Suffice to say Coastal Infrastructure such as Harbours or Tidal Defences have long projected lifespans. Due to their function, they have to endure severe environmental loading as well as the geological complexities at where they interface with the natural environment. The primary purpose of this research is to offer guidance and awareness to the wider AEC industry through an investigation of current literature, emphasising the importance of Geotechnical BIM as a value engineering tool for coastal infrastructure. The findings in this section point to an urgent need of a national mandate to propel BIM in Ireland and examines the current status of Geotechnical BIM. Secondly it aims to explore the application of Geotechnical BIM through a case study where BIM in principle has been applied to the geotechnical design. The findings in this section examined significant capital savings in the range of 40%. Finally a survey was then carried out to gather data from industry providing insight on how other disciplines find Geotechnical BIM within the wider BIM process and derive recommendations as to better integrate Geotechnical BIM. The results indicate that Geotechnical BIM is welcomed however there are concerns related to cost and risk. The Author concludes that the advantages outweigh the concerns shared in addition to the limitations of the traditional process and suggests the need for a specific level of model detail identifier for Geotechnical models to improve communication and reduce risk.

Keywords– Building Information Modelling, Geotechnical BIM, Geology, Geohazard, Coastal Infrastructure, Value Engineering.

I INTRODUCTION

The British Standards Institute (BSI) defines that Building Information Modelling "(BIM) is the management of information through the whole life cycle of a built asset" [1] where it utilises digital processes to enhance collaboration and increase efficiency over the various stages of an assets lifecycle. The Architecture, Engineering and Construction (AEC) industry over the last number of years has been moving towards digital transformation in a move to close the gap regarding the delay of innovation within the sector [2]–[4]. In 2017 the Irish Governments Contracts Committee for Construction (GCCC) reaffirmed the national shift towards addressing this gap through the adoption of BIM after consultation with leaders from industry. It was identified that countries such as The United Kingdom (UK), The Netherlands, and other Scandinavian States had already been paving the way for BIM in Europe through exemplar public projects [5] such as the E4 Stockholm Bypass and the UK's Crossrail London Project. This introduction to digital collaboration and shared modelling enshrined in documented standards and processes is being investigated, recognised, and adopted at governance level and is becoming more prevalent on the international stage especially in the UK [6]. For example, in April of 2016 the UK outlined that all projects funded by central government have been mandated to be delivered through BIM Level 2 framework [7] and in 2019 governing institutions collaborated to align the latest UK BIM Framework providing a singular joined up approach across UK industry [8]

From the context of the Irish perspective; the Irish government has been promoting the uptake of digital design for many years by identifying the requirement for BIM [9] and in 2017 released a new framework in the form of the "roadmap to digital transition" in order to outline the national journey to adoption and engage with industry [10]. Although this was a positive step towards modernising the industry domestically and it ensures Ireland can compete with levels of international interests and investment, there are still many obstacles to overcome [11]. A common theme established not only nationally but internationally is that there is a need for greater levels of promotion from public clients as the industry is primarily being led by market orientated innovation rather than public leadership [12]. In a recent study addressing the "states readiness for BIM" it was found that although Ireland demonstrates maturity in modelling process and workflows (market led); it lacks the collaborative and policy leadership needed to drive BIM at a national level and a government mandate is required (public leadership) [13].

This would suggest that there is an opportunity for the Irish government and national bodies to champion BIM implementation and accelerate the national programme. It would appear that the Irish government is currently in the early stages of addressing this leadership gap. In September 2020 the Irish government set up the "Construction Sector Group-Subgroup for Innovation and Adoption", in order to implement priority actions which were recommended from a report on the "Economic analysis of productivity in the Irish Construction Sector" [14]. It has also launched the Digital Build Project challenge 2021 to SME's in industry to foster innovation within the sector [15]. Both are examples of promising developments but none the less are not direct mandates. However, the Irish government could already have a vehicle to deliver a mandate and become the example of digital build in Ireland if implemented correctly by utilising the Project Ireland 2040 Framework [16]. Project Ireland 2040 is an ambitious investment into the national infrastructure, while creating jobs and opportunities across sectors. Within this framework there is a strong emphasis on the expansion and upgrade of ports and harbours [17]. This thesis explores the hypothesis that the implementation of Geotechnical BIM can provide an excellent opportunity for greater holistic design and value engineering for coastal Infrastructure.

II Objectives & Methodologies

This research aims to address "An examination of the use of Geotechnical BIM to provide value-engineering solutions for coastal infrastructure". To address this hypothesis, a literature review has been carried out on traditional geotechnical Processes, Geotechnical BIM for Value Engineering and BIM for Coastal Infrastructure. A domestic coastal infrastructure case study was then identified to analyse the application of BIM in Principle in order to determine if Geotechnical BIM could be applied in providing value engineering solutions. A survey was then carried out across various disciplines of the AEC industry to identify if therein lies a disconnect with geotechnical BIM and that of the wider BIM process with the aim to identify opportunities for its inclusion.

Objective 1: To critically appraise the current traditional Geotechnical Design process and risk considerations.

Methodology: A literature review on traditional geotechnical design and risk considerations was undertaken. This identified the importance of Geotechnical Design and the impact it has on projects within the construction industry.

Objective 2: To extensively examine Geotechnical BIM and how it can be utilised as a value engineering tool for coastal infrastructure.

Methodology: A literature review was undertaken to investigate the application of Geotechnical BIM in a coastal infrastructure setting as a value engineering tool, identify the barriers to its adoption and highlight the merits of its inclusion.

Objective 3: To extensively examine a coastal infrastructure project in Ireland and identify how Geotechnical BIM in Principle provided value engineering solutions.

Methodology: This was examined through a combination of action research and case studies.

Objective 4: To critically appraise the perception of Geotechnical Design and its inclusion within the wider BIM process.

Methodology: Through mixed Quantitative and Qualitative research approaches; a series of structured questions was developed and posed in a survey which was delivered to various designers in the AEC industry. Its purpose was to analyse and identify whether the inclusion of geotechnical BIM is useful to the wider BIM process. A large sample size was sought across various stakeholders to gather all types of themes, bias or subjective views. The results of this survey will assist in the delivery of objective 5.

Objective 5: To Identify and validate how geotechnical BIM can be better integrated into the wider BIM Process.

Methodology: Through using the results from the questionnaire and findings from the case studies, the author proposed how the geotechnical component of a BIM project can be more effectively integrated and utilised for value engineering in coastal infrastructure.

III A Brief Introduction to Geotechnical Design

Geotechnical Engineering (or geotechnics) is a branch of civil engineering that directly deals with the analysis, behaviour and application of soil and rock mechanics [18]. Geotechnics has an intrinsic role in engineering as all assets interface with the natural environment and considerations need to be made given the variable and uncertain nature of the subsurface in conjunction with the constructability of the asset [19]. In addition; other considerations include the assessment of natural geotechnical hazards (Geohazards) such as landslides, Slope failures, flooding and erosion. These geohazard types amongst others are prevalent to Ireland and have an array of event triggers such as adverse weather or failure due to natural material degradation, this is particularly true in the case of coastal infrastructure such as ports and harbours [20], [21].

The exemplar traditional process defined as "good practice" by J.R Greenwood is captured in Table 1 and shows a simplification of the various actions carried out in the role of a Geotechnical Designer during an investigation process across a projects design & construction cycle. It is a very involved role where design decisions have significant implications on a project, it is also to be acknowledged that when dealing with geology; hazards or risks can be revealed over time which may have not been a factor at the time of the investigation, thus good geotechnical design relies heavily on quality data to make sound design decisions.

Table 1: Stages of Investigation [22]

Phase	Investigation Work
Definition of Project	Appointment of Geotechnical Advisor on likely design issues
Site Selection	Preliminary Study
Conceptual Design	Detailed preliminary sources study, site inspections (SI) and recommendations
Detailed Design	Full Ground investigation, Geotechnical Design and additional SI if necessary
Construction	Comparison of actual and anticipated conditions. Assessment of new risks.
Performance/ Maintenance	Monitoring, Instrumentation and feedback reporting

Traditional Geotechnical investigative processes if provided with sufficient investment have the potential to provide lower project costs across design and construction by identifying risks and utilising the existing conditions to the advantage of the overarching project [23]. Unfortunately geotechnical conditions are complex and in reality the process can be prone to issues from miscommunication of risks and misinterpretation through incomplete data which can also lead to conservative designs to mitigate the unknown [24]. Many variables need to be taken into account when implementing a geotechnical design. Unknown or misinterpreted geotechnical conditions can cause significant risk to life, budget, project resources and the assets lifespan [25].

The practice of ascertaining information below the ground alone can be a costly upfront exercise and although it is mandated in standards and regulations, Geotechnical Investigation is also commonly perceived as a cost item by clients. Communicating the worthiness and cost significance of sufficient ground investigation information over minimal requirements can be a challenge [26]. In contrast the cost of such services for infrastructure projects tend to be in the realm of 1% of total project budget and if inadequately resourced have the potential to cost between 15-50% of the project budget to correct when issues arise [25]. With such a broad scope for potential risk it is crucial that geotechnical design is properly considered and communicated. This thesis recognises that most geotechnical engineering projects require innovation for more effective and inclusive processes. Innovation within Geotechnical processes would have an obvious benefit to project execution, implementation and asset operation, thus in principle providing significant value engineering potential.

IV Geotechnical BIM & Value Engineering

There are many successfully examples of BIM in last decade (such as Stockholm's yellow line subway extension [27]) with different learning moments on application and execution. In a study by Berdigylyjov & Popa [28] the authors identified that a common theme related to the application of BIM is that projects are typically designed "from the ground upwards" where the least attention is paid towards the subsurface. The emphasis has been primarily related to the obvious stakeholders such as Clients, mainstream designers, contractors and facility managers; and this is evident in some of the most popular publications relating to BIM [29],[30]. The apparent solution is to incorporate the geotechnical component of a design within the BIM Process to ensure no aspect of the project is omitted/ overlooked just because it can't be directly seen or observed [31].

Geotechnical BIM is an additional discipline within the BIM process and is an extension of the civil engineering design which utilises digital data and workflows to create detailed models of ground conditions in order to collaborate with other stakeholders; this information is then used to communicate any constructability issues and geotechnical design recommendations the same way other designers operate in the context of a BIM project [32], [6]. Combining all available geotechnical datasets together into a single source of information can help geotechnical consultants make more informed decisions and expose areas where information is irregular or incomplete; this is in addition to standard Geotech outputs such as the Ground Investigation Report (GIR) and the Ground Design Report (GDR) [33].

Whether it be a traditional or BIM orientated process; it is not unusual for the geotechnical component to be deprioritised due to cost [26]. In some cases, geotechnical design responsibility is pushed down the supply chain or is vaguely scoped and as a result falls to the way side because it's seen as a secondary issue [34], [35]. Anecdotally there is also concern within the industry that Geotechnical BIM will leave designers open to risks, fearing any model produced will be misused or misinterpreted; however the reality is that irrespective of the type of delivery path, geotechnical models/ interpretations are only as good as the information used to create them. Since ground investigations (GI) can be costly there can be substantial gaps in GI data leading to a heavily interpreted understanding of the subsurface, thus any tool that can aid in creating a clearer picture of subsurface conditions is an advantage [33].

It is often not considered that even if the ground model is sparsely populated with GI that as long as the model is maintained it can be further iterated and developed during construction or in the operations stage to help make a more refined model to assist in future decisions [36] [6]. Much like cartography such models are developed with improvements over time and regularly updated as information becomes available. Digitising GI data into a holistic database and modelling the ground conditions as closely as possible will inform a greater appreciation of the geo complexities of the subsurface, assist as a communication tool to convey potential risk items and just like the MacLeamy principle in Figure 1 help front end the projects design so there are less surprises when resources are mobilised to site and ground is broken [37].

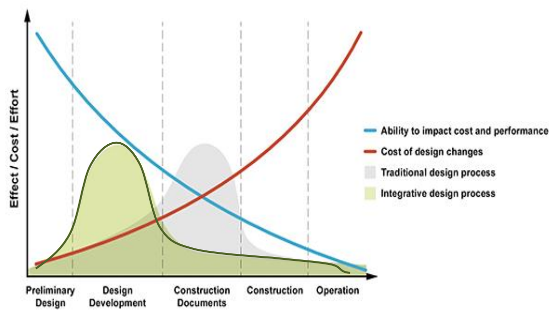

Fig. 1: Macleamy Principle [38]

Leading experts within the field have responded to concerns relating to risk by identifying the benefits of Geotechnical BIM and are elevating the confidence in industry [39], [33]. We must remember that the goal of BIM is to increase efficiency in the construction process and ensure smarter delivery and maintenance of projects across their lifecycle to reduce capital costs [40] to that end it is imperative that the industry embraces geotechnical BIM for a holistic design approach [36]. As outlined in Figure 2 which captures in grey the BIM related effort expended over the Project Lifecycle it is clear to see that model information extraction is most important in the operations to end of life stages [41] and this emphasises the case for quality data later in an assets lifecycle.

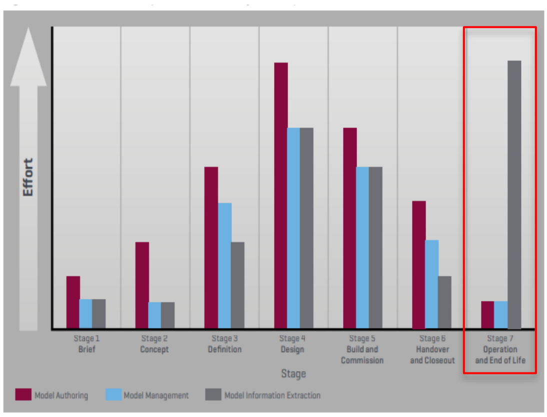

Fig. 2: Related effort expended over the projects lifecycle [41]

The inclusion of Geotechnical Information within a BIM process has the ability to benefit all stakeholders through the integration of this information at an early engagement stage. The understanding of the subsurface conditions in an integrated project delivery process (so that risk is shared) can assist designers in realising issues related to their own design and can save the project considerable time and budget [42], [43]. For example the ability to quantify sub surface material and its composition/reusability provides considerable capability for assessing material quantities, the appropriate interfacing design and inform value engineering options where designs may have been conservative [44]. In a study by Adam et al [45] which identified trends and implications of cost overruns and time delays in large public infrastructure, it was found that the most common issues causing delays came from poor communication, poor quantity surveying, slow reaction to issues and inadequate designs to name a few of the findings . Geotechnical BIM helps mitigate these issues with holistic design and communication allowing for less surprises, especially once resources are committed to site; Lean design options can only be provided if the base design information is accurate. It is for this reason that Geotechnical BIM is useful as a Value Engineering tool and is best suited to high capital infrastructure (such as coastal infrastructure or roads and bridges) where isolated levels of traditional human interpretation can be open to higher levels of risks if improperly communicated or documented [46]. We also need to account for the long lifespan of such infrastructure projects; for example in the UK there are over 150,000 bridges where the majority were built in the last 200 years [47].

a) Geotechnical Testing and Data Management

Geotechnical data is a tremendously valuable resource not only because it can be costly to acquire but rather in how it can maintain its value throughout a projects lifecycle. Most geotechnical deliverables are summarised by reports and drawings such as the GIR or GDR and are stored in electronic format such as pdf's or by paper based physical copies [48]. This means the developed ground models and raw data tend to sit on company servers never to be reused thus this information has to be relearned or reacquired at a later time [28]. This was a common theme echoing throughout the AEC industry pre BIM [29] but still exists today. BIM offers a means to carry this information forward over time in a cumulative manner by adding to the repository which defines the ground conditions. Organisations such as the Geological Survey Ireland (GSI) have created large databases of publicly available historical GI information; however the quality of this information varies, it can be extremely sparse depending on the geographical location and it is suitable more so for mapping geology over large areas [49]. If Geotechnical information is really to be useful for an assets lifecycle, then the subsurface conditions need to be recorded in a manner that is useful to all stakeholders so informed decisions can be made into the assets future and not only during the early inception, design and construction phases.

As shown in Figure 3 the European Environmental Agency (EEA) measured the average cost of Site Investigation (SI) across 10 central European countries and recorded that 60% had spent between €5,000-50,000 on site investigation. [50]. Based on this study the Author suggests that the majority of SI acquired for most projects is disproportionate to what is needed when we consider project scale. Comparing this information to another study by Statista regarding the average cost per square meter of internal area for buildings in selected EU cities; it shows that the city of Dublin has an average cost of €2581.80 per $m^2$and the city of Belfast has an average cost of €1950.32 per m^2. Considering a building with a 400m^2 (20m x 20m) footprint, then based of these average costings it can be assumed if the GI should be in the realm of 1% [25] of the projects budget then an average cost of GI per similar sized building would be €10,327.30 for the city of Dublin and an average cost of €7801.35 for the city of Belfast. This seems proportional at first, when compared to Figure 3, however in reality other factors need to be taken into consideration which can affect the cost such as the type of investigation, access of equipment, the size of the area under investigation and what is already known. As these factors grow so does the disproportionate nature regarding GI and the projects overall cost typically resulting in allocations of budget less than 1%. Although this is applied to buildings in cities it offers insight to sub optimal investment for GI data regarding onshore investigations. Experts in industry advise that at least 3% of project cost should be allocated to SI [51].

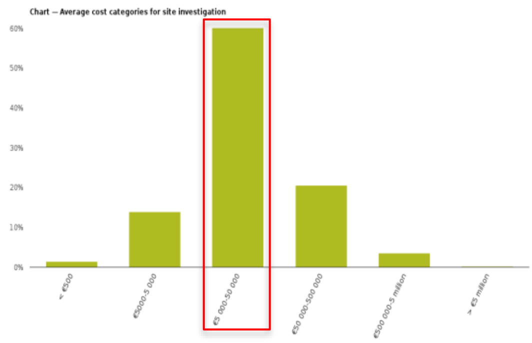

Fig. 3: Average cost categories for SI [50].

Ground investigations involve a series of ground sampling tests which can be invasive/destructive such as Boreholes, Trial Pits and Cone Penetration Tests [52]. GI can also involve non-destructive means of investigation by using technologies such as Ground Penetrating Radar (GPR) [53] or Seismic Refraction Testing (SRT) [54]. Ground investigation techniques will vary depending on what is already known about the subsurface mechanics and the size/type of asset to be constructed. When trying to understand the subsurface it's suffice to say that the greater number of samples acquired will give Geotechnical Designers more information to correctly interpret the ground conditions. However the cost of this testing and other factors such as accessibility can be barriers to capturing a detailed sample source. Geotechnical Designers usually have to interpret geology between samples and make assumptions based on isolated sample data.

The combination of multiple datasets such as Geophysics, Borehole logs, probing etc. into a single digital surface/stratigraphical model or database, lends to a holistic understanding of the subsurface conditions, which is unmatched by traditional interpretation [33]. This data can be refined once construction has commenced and any variations recorded to update the model. Having a dependable geotechnical model can support better decision making across the design team and allow for additional value engineering options over conservative decisions due to poor quality of data.

b) AGS Data & Keynetix Holebase

A very useful file format for creating holistic ground models is .AGS. Similar to the well-established "industry foundation class" or .IFC as it's better known in the BIM industry; .AGS was created to facilitate the transferring of data between industry organisations' and created a multiplatform file type that could be utilised regardless of the authoring tool utilised. It was first developed in 1991, however has undergone various improvements over the years. It was created by the Association of Geotechnical & Geo-environmental Specialists in the UK and utilises the testing samples processed by laboratories which are compiled into this format and shared with the geotechnical specialists or other project team experts to interpolate the geology [55]. Specialist geotechnical database software such as Holebase [56] or gINT [57] can then import lab data in .AGS format and compile this information in database form. This repository of meta data from ground investigations can contain geotechnical parameters from multiple sources which can then either be interrogated within the database or exported into 3d geometry representing the stratigraphy for use in BIM authoring software such as Autodesk's Civil 3D (C3D) [58]. This model can then be interrogated live through the extrapolation of dynamic sections and metadata while juxtaposed with other developed models of the asset, allowing for more informed decisions to be made. This in turn enables the designer to reduce conservative design and produce value engineering options.

V BIM FOR COASTAL INFRASTRUCTURE

Significant developments in the last few years regarding Geotechnical BIM have primarily been focused on large scale infrastructure such as Roads, Rail and Tunnelling [44], [59], [60]–[62]. Coastal Infrastructure such as Ports & Harbours and Coastal Protection Systems can also benefit from BIM; especially where a holistic approach is taken and the Geotechnical component is included [63]. However research regarding the application of Geotechnical BIM in the coastal environment is quite novel and most of the research in this area extends from China with some other studies originating from the Nordic countries and Russia.

Coastal Structures usually have long lifespans exceeding well beyond 50years and due to their geographical locations have to endure a variety of environmental and operational conditions such as, coastal erosion, accretion, siltation, adverse weather and corrosion to name a few [64]–[66].

Considering the EU's 329 key seaports alone, the European Commission identified the importance of the marine transport sector by highlighting in 2015 that 400 million passenger's travelled through these seaports of which employs 1.5 million workers and where 74% of goods entering or leaving the EU go by sea [67]. With regulatory support such as the EU Commissions "Ports 2030" initiative [67] and various infrastructure support plans through national schemes such as Project Ireland 2040 [17]; there should a clear demand in the immediate future to deliver vital coastal infrastructure projects in a smarter way utilising technology and digital workflows similar to how BIM has been utilised elsewhere on inland infrastructure [12].

Projects such as Dublin Ports Masterplan Project 2 which entails a capital investment of €1Bn into the port over the next 10 years [68] will require complex collaboration between the various stakeholders at the different stages of its delivery and BIM/Digital Build processes could offer many advantages in its delivery [41]. Unfortunately this has not been recognised and instead the Client has requested .PDF and CAD drawings to form the design documentation [69]. This is also in contrast to the governments Contracts Committee for Constructions Paper of intent "a public sectors BIM adoption strategy" [5]. In the context of geotechnical design the port will also depend on properly investigated geotechnical data to inform stakeholders on reusability of materials, dredging operations and the interfacing conditions of newly proposed structures [63], [70].

The potential for BIM & Geotechnical BIM in the application of coastal infrastructure is promising based on the success of other infrastructure based work however, further research is required in this field regarding its application.

VI Port of Rossaveel Deep-Water Quay Conceptual Design Review

a) Introduction

This case study focuses on Geotechnical modelling techniques and workflows where BIM in Principle has been applied to provide value engineering options to the Department of Agriculture, Food and the Marine (DAFM). Gavin & Doherty Geosolutions Ltd (GDG) was commissioned by DAFM to conduct a peer review of the planning design of a deep-water quay (DWQ) completed by a fellow consultant. Recommendations were presented with the aim to reduce the projects capital cost and improve the viability of DWQ's implementation. No requirement for BIM was stipulated by DAFM from the outset of this desktop study however, BIM principles and BIM authoring tools would prove as a catalyst to achieving the client's goal of a viable DWQ design and reducing capital costs. The proposed DWQ was to be located at the Rossaveel Fishery Harbour Centre (FHC) in the Connemara area of Co. Galway Ireland (See Figure 4).

Fig. 4: Location of Proposed DWQ at Rossaveel FHC [71].

The original design brought through planning entailed the use of caisson structures to facilitate the newly proposed 200m berthing point for the DWQ; other works included dredging in the navigation & berthing zones to ensure adequate clearance for a series of larger draught vessels. It was found that the original design was conservatively sufficient and held a high degree of safety; however upon initial observation, GDG had provided recommendations regarding the structures size and configuration in addition to reducing the required dredging and rock blasting. The proposed structure required extensive re-profiling of the bedrock layer at the site and so in order to facilitate any improved design recommendations a detailed ground model needed to be constructed from various data sources to understand the interfacing conditions and constraints of the proposed DWQ.

Various surveys were conducted between 2001 & 2019 which included intrusive and non-intrusive GI techniques. This information was difficult to ascertain in addition to being costly to acquire considering that the samples needed to make design recommendations lay beneath the seabed; this information has tremendous value and if properly maintained could assist with future developments or the operational needs for the harbour. Ground Investigations Ireland (GII) were contracted in 2019 to conduct a ground investigation of 13nr Cable Percussion Boreholes via a jack-up barge in the bay area as seen in Figure 5. These works had to be carefully coordinated with the harbour master to ensure the harbour stayed operational during the various stages of mobilising and demobilising the Barge [52].

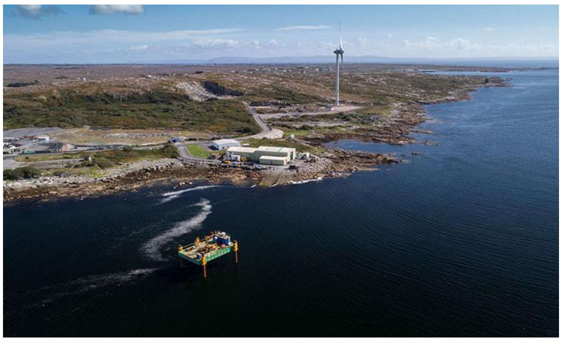

Fig. 5: Near shore GI by jack-up barge [52].

b) Geotechnical Model

Once all the data was collated it was then used to develop the ground model, where the various datasets included were:

- Historical Ground Investigation Data – source date 2001.
- Bathymetric data of the seabed – source date 2018.
- Geophysical data of the subsurface – source date 2018.
- New Ground Investigation data – source date 2019.

Keynetix Holebase SI Professional (HBSI) was used as a Geotechnical database in order to compile the intrusive ground investigation data where both the historical and newly captured GI information was combined via .ags import. Where .ags was unavailable the historical data was manually added and digitised from paper records creating a repository of Geotechnical Meta data that could be both visualised and interrogated. Designers now had a tool which would display detailed BH logs, create live sections, combine geotechnical data with external inputs such as .dwg and filter information for transparent interpretation of the subsurface (See example in Figure 6).

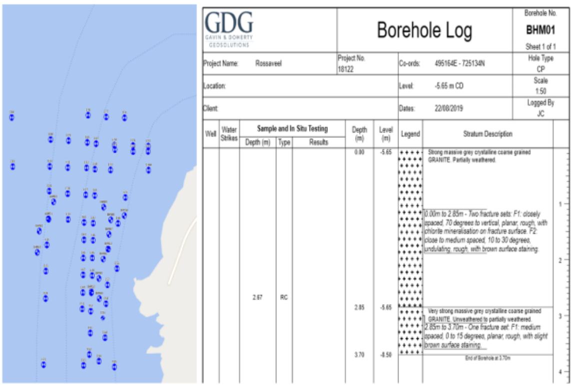

Fig. 6: Typical outputs from Keynetix Holebase SI – Location Plan & BH Logs [71].

Once correctly compiled and interpreted in HBSI the geotechnical information was then exported using the Keynetix Holebase Civils Extension to Autodesk's Civil 3D. The imported GI was extrapolated without effort and compiled into both 2D & 3D representations of the GI. The various levels of stratigraphy could then be interpolated between investigations to create TIN surfaces representing each subsurface layer as can be seen in Figure 7 depicting the bedrock level.

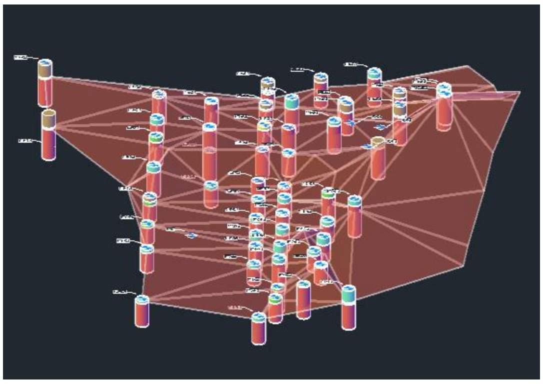

Fig. 7: Compiled historical & newly surveyed GI imported to C3D from HBSI Professional [71]

The ground model was further complimented with comparative layers of data in the form of the geophysical surveys (in particular the bedrock profile). This information was imported in the form of .XYZ data directly into civil 3D to create a series of 3D point's forming a point group and this point group was then triangulated into an additional Triangular Irregular Network (TIN) surface which further informed the depth of bedrock and assisted with filling gaps between the intrusive GI locations. Having redundant forms of geotechnical data provided a solid basis for the proposed engineering solutions and helped verify bedrock levels in addition to other important stratigraphy and measure overburden above bedrock. (See Figure 8)

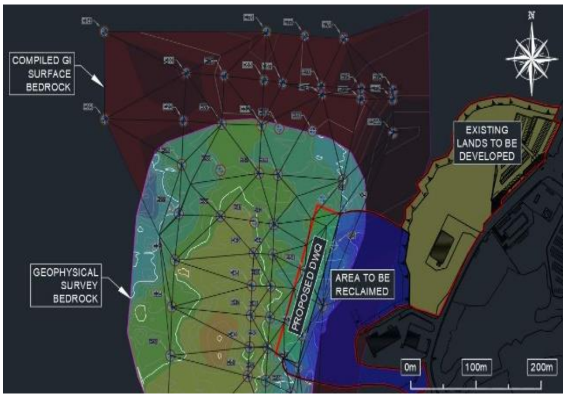

Fig. 8: C3D Bedrock surface data derived from geophysical survey and compiled GI imported from HSBI Professional [71].

The ability to interact and interrogate the bathymetry and bedrock profiles enabled GDG to provide 5 alternative designs on the basis of the conceptual design provided for planning. The first two options maintained the use of the caisson design with variations; a third option was presented using an "L" shaped retaining wall configuration; a fourth involving a mass concrete retaining wall and the final option explored utilising a "Ruukki" tubular pile wall system.

The main costing issues recognised by GDG with the original design stemmed from the depth of the proposed structure as the planning design assumed the structure required to extend beyond the full depth of the berthing pocket at -13.5mCD (meters Chart Datum). With a cost of circa €80 per $m^3$to drill or blast the bedrock and a cost of circa €25 per m^3 to process the soft dredging material; it was clear that the reduction of cutting where possible would provide significant savings. GDG were also well placed to perform volumetric analysis options of the Navigational channel and berthing slots in addition to reconfiguring and reducing the turning area required for vessels. From performing various volumetric analysis of the geotechnical surfaces and incorporating the new structure design options, GDG were able to assess the level of cost reduction as opposed to the original design (see table 2 & 3).

Table 2: Saving estimates for all 2019 design options [71].

Design Option	Description	Cost Saving from original planning design
1	Steepening rock profile based on original design.	-€82,335.00 (cost increase)
2A	Rock ledge profile & smaller Caisson	€7,907,054.60
2B	Rock ledge Profile & "L" wall structure	€8,120,517.00
2C	Rock ledge profile & mass concrete retaining wall	€10,238,017.00
3	Ruuki Pile type retaining wall	€8,204,532.00

Table 3: Cost estimates from cost reduction exercise Q1 2020 [71].

Design Option	A	B	C
1	€29.293m	N/A	N/A
2A	€21.304m	€20.398m	€19.022m
2B	€21.090m	€20.185m	€18.809m
2C	€18.973	€18.067m	€16.691m
3	€21.006	N/A	N/A

A. 200mØ turning circle at -12mCD
B. 150mØ turning circle at -12mCD
C. 150mØ turning circle at -10mCD

c) Discussion

GDG analysed the original planning design determining it as a feasible design with an appropriate safety factor. GDG were also successful in the delivery of additional design options of the DWQ providing significant viable cost reductions in the range of 40% of the proposed planning design. Each design option was carefully analysed and designed by expert geotechnical and marine engineers however it was clear that high quality geotechnical data and BIM in principle acted as a catalyst to enhance the value engineering options presented even without BIM being required from the client.

The ability to compile multiple datasets in graphical and non-graphical capacities and query them in a GI database (HBSI) provided a powerful holistic tool to derive geotechnical and marine engineering designs. With historical, newly captured GI and geophysical investigations a robust understanding of the subsurface suitable for conceptual design was realised and this allowed for dependable quantification of materials, in particular the bedrock where any cut bared significant cost implications.

The BIM principles employed in this process were as follows;

- The Digitisation of Geotechnical Information into a clear understanding of the conceptual stratigraphic layers to allow for 3D visualisation and appreciation from all internal designer's involved.
- The digitisation of various datasets so that information could be shared through a Common Data Environment (CDE).
- Reduction of waste and increase of efficiency in the process through the interoperability of authoring tools. HBSI & C3D etc.
- Prepared conceptual models for future graphical and non-graphical use.
- Front ending the design with a highly detailed geotechnical model.
- Optioneering & Value Engineering.
- Measurement of Quantities [72]

The points outlined below are possible extensions of this BIM in principle process with the further possibility to transition into a Level 2 BIM process if the funding is awarded, there is buy in from the client and the design progresses to a Pre-Tender state and beyond;
.
- Development of the Asset Information Requirements (AIR).
- BIM documentation such as the Exchange Information Requirements, BIM Execution Plan & BIM Protocol.
- Integrated Project Delivery
- Creation of roles & management of people
- Coordination mechanisms between various stakeholders.
- Further optimization amongst BIM authors & authoring tools.

- Further reduction of waste, risks, Health & Safety issues and unknown's before works on site.
- An agreeable format for facilities Management in this case the Harbour Master and DAFM and development of an asset information model (AIM).[72]

Figure 9 identifies the process workflow for the inclusion of geotechnical data in a BIM processes based on the authoring tools, Geotechnical information and lessons learned from this case study. This workflow would allow for further optimisation and savings via quality data management, maintenance of the geotechnical data that has significant value and allow for future enrichment of completed work if and when Rossaveel FHC DWQ progresses.

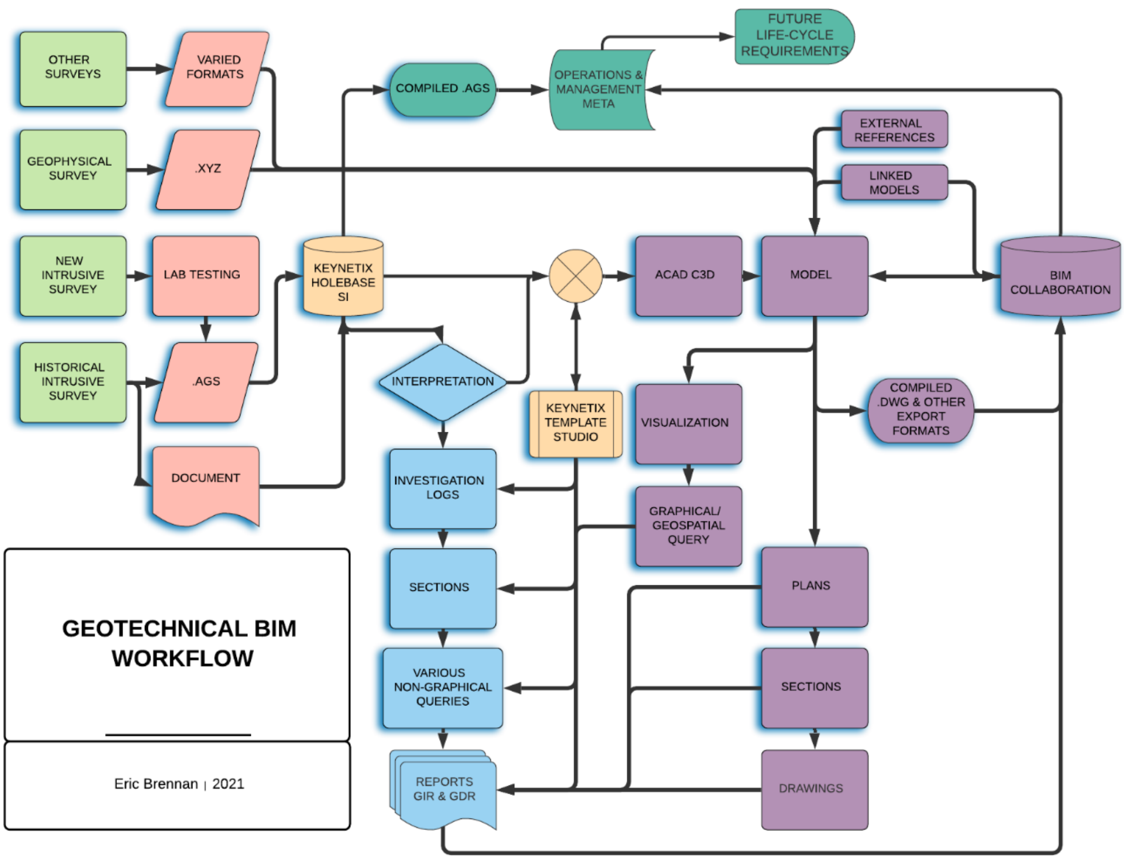

Fig. 9: Geotechnical BIM Workflow based on HBSI & Civil 3D

VII SURVEY RESULTS

a) Respondent Profile

Multiple points of view were sought from industry to help identify how Geotechnical BIM is perceived by the various stake holders across the AEC industry. A series of open and closed questions were posed in a survey to measure statistical analytics and to gauge any subjectivity or bias regarding Geotechnical BIM. Questions were also posed to respondents to help identify any perceived barriers as well as to measure their understanding of the research topic which will inform a thematic analysis.

The representation of AEC disciplines for the survey respondents is identified in Fig 10 where the majority of respondents stated they belonged to Architecture or Civil, Structural and Mechanical & Electrical Engineering fields.

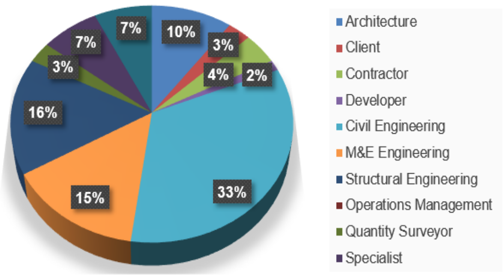

Fig. 10: Survey Respondents Discipline

81% of Survey participants stated that most of their relevant experience came from domestic projects in Ireland which would inform that the majority of these opinions are from an Irish market context. As can be seen in Fig 11 the respondents extent of experience in industry was best represented in the 5-10years range accounting for 30% of respondents followed by >20 years at 29%.

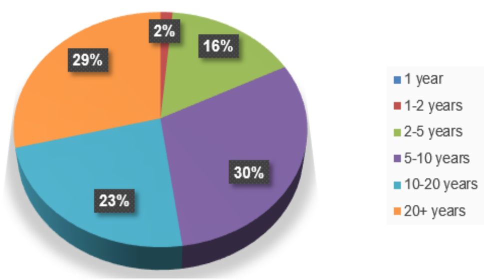

Fig. 11: Range of Experience

Respondents were asked to state on a scale of 1-10 their level of awareness regarding BIM where the average score measured 6.09 (above intermediate levels of awareness); the same was also asked of their level of awareness regarding geotechnical design which measured at 4.75 (below intermediate levels of awareness). 74% of respondents represented the Private sector and 26 represented the public sector.

b) Geotechnical Design & BIM

Participants were canvassed to identify what percentage of projects in their respective organisation is delivered through BIM. The results suggest that BIM is practiced in some capacity by most firms in Ireland where 19% of respondents even stated that 75-100% of the work they conduct is facilitated through BIM as seen in Fig 12. This is interesting when compared against findings from McCauley et al [13] which identified that the sector is mostly being led by market influence and not by governance or state leadership. This would suggest that a mandate for BIM in Ireland would greatly inflate these figures since the skills and practices are already in place to a degree; public and private clients could be availing of increased efficiencies and workflows that would benefit their assets. From a public perspective Project Ireland 2040 [16] could prove as a catalyst for the adoption of BIM, and although digital build is supported by the state [9] these findings would suggest better awareness is needed amongst clients and not the workforce.

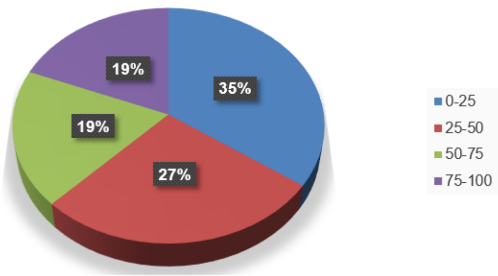

Fig. 12: Percentage range of Projects delivered by BIM

Regarding Geotechnical experiences from respondents an interesting discovery was that 62% stated Geotechnical Engineering had a bearing on their designs. However when asked if geotechnical data was available in the implementation of their respective designs 71% stated that this would have been of a benefit to them. 62% recognised that poorly communicated geotechnical designs led to delays in project delivery and 26% stated that geotechnical conditions posed as a possible risk to life. This is a very significant point of view as it clearly suggests that this information is crucial for successful project delivery and health and safety. It's clear that a more efficient means of communicating geotechnical design for holistic delivery processes needs to be explored. This was further reinforced as 90% of respondents agreed that geotechnical models would provide as a useful information tool to base decisions from indicating Geotechnical BIM is very much welcomed by other AEC professionals.

c) Barriers to Geotechnical BIM

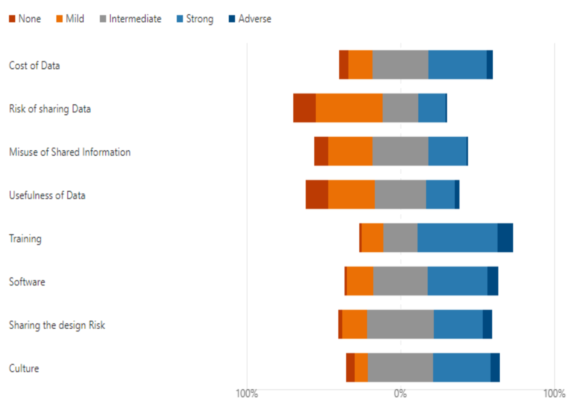

Fig. 13: Barriers to Geotechnical BIM

Attitudes and opinions were measured from participants regarding how they identified barriers to Geotechnical BIM. Responses were measured on a scale from None, Mild, Intermediate, Strong and Adverse. Interestingly cost related issues were at the forefront of most concerns where 37.7% identified the cost of data to be a significant barrier and where 52.2% identified training as a barrier in addition to 39.1% who identified software as a barrier. This would suggest that this process is welcomed but further cost awareness may be required to encourage the incorporation of Geotechnical BIM irrespective of the fact that this process can be used to explore value engineering solutions for clients in order to reduce costs.

Surprisingly only mild concerns at 42.3% of respondents were measured regarding the risk of sharing data, however in contrast an intermediate concern was identified at 42.3% for sharing the design risk. Respondents also acknowledged that misuse of shared information and the usefulness of Geotech data was of less concern. These opinions would point again to a cost related barrier as respondents stated they have no issue with using the data for design purposes but were uncomfortable with possible exposure via sharing the design risk.

c) Thematic Analysis

Respondents were also presented with two open ended questions to identify the general group think and feelings towards the research topic while validating the statistical data taken from the closed questions.

When asked if Geotechnical BIM could be utilised as an effective value engineering tool 5 main categories arose.

- Agree
- Agree Conditional
- Disagree
- Disagree Conditional
- Unsure

From these categories a series of themes were identified. The majority of respondents agreed that Geotechnical BIM would be best placed for Value Engineering solutions. In particular the 15.94% of respondents identified opportunity to reduce risk and uncertainty from projects, where 11.59% identified Geotechnical BIM as a tool to reduce construction related operational costs. 21.7% directly stated that Geotechnical BIM would be an effective value engineering process.

Other respondents agreed however provided some conditional concerns such as cultural barriers at 7.24% and interoperability concerns at 8.68%. In regard to the negative categories the main themes identified seemed to be related to unfamiliarity at 8.6% or based on niche activities measuring at 2.89%.

Given the variety of respondent disciplines it would suggest that from a multidisciplinary perspective the consensus recognises the potential in Geotechnical BIM and is open to its integration within the BIM process for value engineering.

When the respondents were pressed then to identify the most suitable use case for Geotechnical BIM the following 7 categories arose.

- Urban
- Transport Infrastructure
- Large structures
- Marine
- Subsurface
- Unsure
- Not Applicable

At the forefront of these categories 33.33% of respondents identified transport infrastructure as the main use case for Geotechnical BIM. This encompassed themes such as of Roads & Highways, Drainage and Earthworks.

13.02% identified Urban use as the next popular use case for Geotechnical BIM where themes such as deep foundations & housing were predominant in this category range.

Surprisingly Marine works and Tunnelling combined only accounted for 14.49% of responses, where themes such as Mining, Tunnelling, Coastal Infrastructure and Offshore works were identified. It is the author's hypothesis that the niche nature of these use cases are the reasoning behind the low levels of representation for coastal infrastructure from the thematic analysis. Secondly the author identifies that transport infrastructure and urban development are predominant within the industry in Ireland and a high degree of the workforce has direct experience which is reflected in the analysis. Suffice to say a wide variety of mainstream and non-mainstream project types were extrapolated from the survey data informing a wide range of potential application for geotechnical BIM.

VIII Recommendations

As indicated by the results from the survey there are concerns relating to the cost and successful integration of Geotechnical BIM, specifically in regard to the sharing of the design risk and managing costs for the required data. 90% of respondents however still stated that the inclusion of this information would prove as a useful tool in design considerations. The author identifies that one of the main issues relating to the successful integration of geotechnical ground models so that they can be better used for value engineering purposes is the absence of ground model definition in a BIM process. Currently if a ground model is shared it is difficult for other stakeholders to understand how developed a ground model is and how dependable that information may be for basing any design considerations. A useful tool to help address this lack of definition could take the form of a definition table akin to the Level of Detail Principles outlined by the NBS [73] See Fig 14. This table and others like it define the required amount of information per stage of the project identifying clear criteria needed from each design team stakeholder at a given time during the projects main milestones. Such a mechanism would be very powerful to reduce risk in geotechnical models and minimise costs through identifying the exact richness of model information needed.

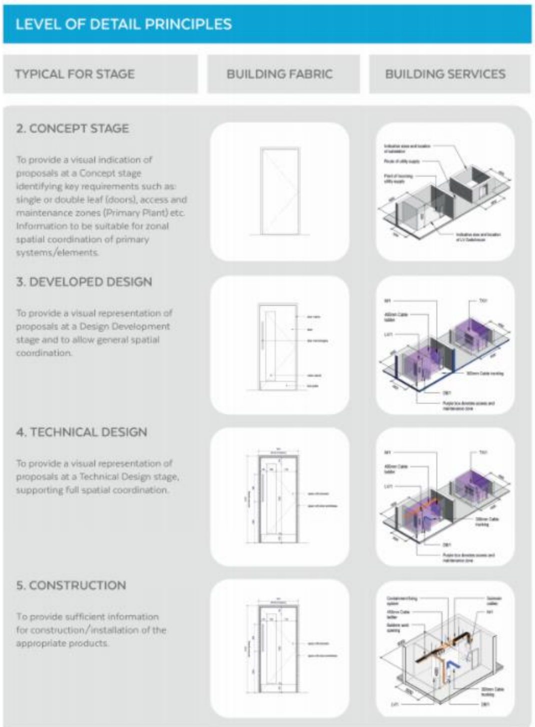

Fig. 14: Level of Detail Principles – NBS BIM Toolkit [73]

Further research would be required to identify the correct amount of graphical and non-graphical definition to implement such a table, which may need to be specialised to regions due to the varying nature of the subsurface and depending on geographical location. However geotechnical requirements for BIM have been touched on indirectly in the past when defining levels of definition in specifications [74] and also in tunnelling projects across central and northern Europe [27]. This would suggest that the concept is not entirely novel and there is a semi developed basis for further research.

IX Conclusion

It is acknowledged that the quality of data and how it's communicated historically has led to issues regarding successful geotechnical design [25]. The same has been true of the construction industry where over the past 10 years or so it has been transitioning into a digital space to reduce delays, costs and communicate more effective designs concepts [2]–[5]. These lessons were observed from the manufacturing and aviation industry and were slowly adopted in the form of BIM but only amongst mainstream design disciplines[75]. It's suffice to say that the incorporation of geotechnical BIM is only part of this elongated transition of BIM across the AEC Industry. With the development of geotechnical tools such as HBSI and the interconnectivity between HSBI, Civil 3D and BIM collaborate Pro just as an example; it is a reality that geotechnical designs can now be included into the BIM process in a sufficient way. Case studies such as the Rossaveel FHC DWQ concept design provide evidence that Geotechnical BIM can be applied and can further empower collaborative design. Savings provided through the modelling of the geotechnical elements were crucial in significant capital cost reduction[71] and provided insight for how this process in principle was used as an effective value engineering tool.

Clients in the form of National Bodies such as the Department of Agriculture, Food and Marine have an opportunity to promote the inclusion of Geotechnical BIM and simultaneous be at the forefront of this area in Europe as it is still a niche market and area of research.

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