Advancing Geotechnical Practice with Design for Manufacture and Assembly (DfMA) Retaining Wall Construction

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doi: https://doi.org/10.21467/proceedings.7.7.14

ABSTRACT

This paper presents the application of Design for Manufacture and Assembly (DfMA) in the construction of a 52m long L-shaped retaining wall with a maximum height of 4.8m, founded on Completely Decomposed Granite, as part of the Relocation of Sha Tin Sewage Treatment Works into Caverns project. This initiative not only enhances sewage infrastructure but also mitigates environmental impact and frees up valuable land for sustainable urban development. The retaining wall supports a 500m access road to the Site Explosives Magazine, strategically designed for the supply of explosives for multiple blasts daily. By favoring DfMA over conventional in-situ methods, the project implemented an innovative design featuring precast steel beams encased in concrete, which were assembled on-site. This approach dramatically reduced construction time from 147 days to approximate 10 days, streamlined on-site activities from 70 to 21, and completely eliminated working-at-height risks, significantly enhancing safety and efficiency. A key to this success was collaboration among the RSS, contractors, subcontractors, and strong client support. Active engagement enabled the collective development of the DfMA strategy, leveraging on-site experience in design optimization and risk management. This approach facilitated early risk identification, ensuring DfMA strategies were well-resourced and successfully implemented.

1 INTRODUCTION

The construction industry is undergoing a transformative shift toward innovative methodologies that not only enhance efficiency but also deliver improvements in safety and sustainability. In an era where rapid urban development and environmental stewardship are paramount, DfMA emerges as a pioneering approach. While traditionally leveraged in building construction and bridge engineering, DfMA is now breaking into geotechnical applications, promising substantial benefits in complex site conditions. This paper presents a case study of the DfMA retaining wall implemented in the project ‘Relocation of Shatin Sewage Treatment Works to Caverns’ (STC).

Urban environments, particularly high-density metropolises like Hong Kong, pose a unique set of challenges. Geotechnical projects here encounter constraints such as steep or irregular terrain, in close proximity to the site boundary, limited working space, and heightened safety concerns. The STC project exemplifies these challenges. It demands a solution that minimized on-site activities while delivering structural robustness. By integrating DfMA into the retaining wall designthe project team was able to transition key construction activities from congested and risky site environments to controlled, off-site manufacturing settings. The

Proceedings DOI: 10.21467/proceedings.7.7; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-989164-3-3

integration of DfMA into retaining wall construction is the first of its kind being adopted in Hong Kong. This shift not only streamlined operations but also opened the door to enhanced precision and quality control. This paper will discuss the DfMA considerations involved in the design and construction of the retaining wall, including casting yard, transportation, and lifting strategies. Additionally, it will highlight the benefits of DfMA in addressing common challenges faced in geotechnical projects, ultimately contributing to improved project outcomes. Through this case study, we aim to demonstrate the effectiveness of DfMA in modern geotechnical practice and encourage its adoption in future projects within Hong Kong and beyond.

1.1 Design of DfMA

DfMA is often misperceived by some contractors and subcontractors as merely an enhanced form of precast construction. However, its philosophy extends well beyond off-site fabrication. Boothroyd (2005) noted that DfMA evaluate and improve product design by considering the downstream manufacturing and assembly processes – a view of that, while partly accurate, does not reveal the full scope of the approach. At its core, DfMA embodies the principle of "starting with the end in mind," meaning every design decision is intrinsically linked to the entire DfMA cycle. This cycle encompasses ensuring adequate space for a casting yard and storage area of the precast unit, transportation of precast unit from precast yard to the installation location, the maximum capacity of lifting cranes. Designers must also address external constraints, including steep or narrow access roads that could impede delivery and installation. Collectively, these factors dictate the maximum dimensions of precast units, compelling designers to thoughtfully divide the structure into sensible, manageable segments that not only optimize assembly but also enhance overall efficiency. In addition, ensuring that the design units are repetitive and standardized is crucial. If units are not designed to be uniform for ease of manufacture, contractors will face increased costs due to the necessity of developing additional types of molds during fabrication. In the case of retaining walls, which often exhibit variations in retaining height, it is advisable to incorporate at least two identical units in terms of dimensions or to design the molds with the flexibility to accommodate minor adjustments for slight variations. Finally, the design of the connections between units is paramount. Standardized, robust connections ensure proper alignment, structural integrity, and efficient on-site assembly while minimizing the need for custom joint solutions that could further inflate costs.

In order to achieve such a comprehensive DfMA approach, RSS can no longer rely solely on approving contractor proposals under the New Engineering Contract (NEC) and assume that the construction method is exclusively the contractor's responsibility. Instead, RSS must engage actively with both contractors and subcontractors to collectively develop and refine the DfMA construction strategy. This integrated approach leverages the invaluable on-site experience and resources of contractors while capitalizing on RSS's expertise in design optimization, risk management, and regulatory compliance. Lu (2020) suggests that the early collaboration of all contracting parties brings more detailed information to light compared to traditional design processes. This integrative approach, anchored in DfMA principles, not only enhances the understanding of project requirements from the onset but also facilitates the early identification of potential risks during manufacturing and construction. Perhaps most importantly, robust support from the client is critical to ensure that effective DfMA strategies are adequately resourced and successfully implemented.

1.2 Consideration of Casting Yard

Determination of the casting yard location and the associated logistics is critical. Ideally, if a project site can accommodate it, establishing an onsite casting yard is advantageous because it simplifies logistics and improves site supervision through direct oversight of fabrication activities. In such cases, the facility may either be provided as part of the contract or rented at the contractor's expense, each carrying its own implications. Conversely, when an offsite casting yard is used, which is often the case in Mainland China, additional factors come into play. Designers must carefully review the dimensional limitations imposed by border crossing facilities to ensure that oversized precast units can be transported without issue. Offsite production also demands that experienced engineers or supervisors be deployed to remotely manage fabrication, ensuring quality control and adherence to project specifications. Furthermore, a temporary stock area is essential for storing precast elements prior to installation. For smaller projects with limited onsite storage, renting additional space may further complicate the process and increase costs. All these factors form an interconnected mind map that must be carefully considered and balanced to optimize the DfMA approach and ensure successful project outcomes.

1.3 Consideration of Transportation

In Hong Kong's bustling urban landscape, transportation is the lifeblood of successful DfMA projects. Narrow streets, strict regulations, and precise load limits demand innovative planning and flawless execution. Designers must carefully consider truck capacity and traffic routing intricacies, such as road gradients, available turning space, and the challenges posed by steep terrain. Particularly, DfMA solutions for retaining walls often involve construction on steep terrain with narrow access roads, where accessibility is limited and U-turns can be extremely difficult. Moreover, all trailers and loads must comply with the local road traffic ordinance, which stipulates a maximum width of 2.5 meters, a maximum height of 4.6 meters, and a maximum length of 12 meters for rigid vehicles or 16 meters for articulated vehicles. Should any load exceed these dimensions, a special permit for wide or long loads becomes mandatory.

1.4 Consideration of Lifting

One of the key benefits of DfMA is mitigating the hazards associated with working at height by transferring the risk to controlled lifting operations. When implementing DfMA, the design of precast units should be optimized not only for their structural roles in a retaining wall but also for their weight, size, and lifting requirements. Typically, precast units weigh between 30 tonnes and 40 tonnes, based on the typical lifting capacity of the crane. Geotechnical engineers play a critical role in assessing the ground conditions at the site, particularly the bearing capacity of soil, to ensure that it can support both the lifting crane and the temporary loads imposed by the precast units during placement. This is especially important in areas near the edge of natural terrain, where soil stabilization or additional support may be necessary. In addition, the lifting capacity of the crane must be meticulously assessed to ensure that the maximum lifting radius for the intended load is not exceeded.

1.5 Effective Cost Assessment

The benefits of DfMA are widely promoted in Hong Kong for their potential to reduce costs, boost productivity, and enhance safety, quality, and sustainability (Devb, 2018). These outcomes however are not universal across all projects. Therefore, RSS and the contractors must conduct a thorough cost-effectiveness analysis to evaluate the financial viability of adopting DfMA principles. This analysis should consider key factors such as labor expenses, stockpiling area rentals, transportation, and lifting costs. Importantly, it must also assess whether any temporary works will be required, as these additional works can significantly increase overall project expenses. Regional cost differences further influence the cost-benefit equation. For instance, off-site casting yards in mainland China benefit from substantially lower labor costs and stockpiling rentals. Such variations can markedly affect the overall economics of DfMA implementation. In addition, not all project scopes are equally suited to DfMA. For example, water retaining structure designs are often irregular and non-uniform, leading to elevated labor costs and expensive manufacturing cost that may negate the expected cost savings and watertightness concern. In contrast, projects such as retaining walls, with construction divided into uniform, repetitive units, tend to offer clearer cost incentives due to streamlined manufacturing and assembly processes. Ultimately, a comprehensive cost-effectiveness analysis is vital in determining whether DfMA will deliver genuine cost savings and enhanced efficiency for a specific project. By systematically evaluating these factors, contractors can make informed decisions regarding the adoption of DfMA.

2 CASE STUDY – RELOCATION OF SHATIN SEWAGE TREATMENT TO CAVERNS

2.1 Project Background and DfMA Retaining Wall

The Relocation of the Sha Tin Sewage Treatment Works to caverns is a groundbreaking initiative aimed at addressing urban development challenges while prioritizing environmental sustainability. This ambitious project not only seeks to modernize existing sewage treatment facilities but also aims to free up valuable land for alternative uses, such as public infrastructure, residential development, and green spaces. Additionally, the relocation mitigates adverse impacts on the surrounding community, fostering a more sustainable and harmonious urban ecosystem. The overview of project scope is shown in Figure 1.

The project involves a wide array of complex geotechnical engineering and construction challenges, one of which is the excavation and construction of a cavern to house the sewage treatment works. Crucial to the success of this undertaking is the development of a 500-meter-long access road to the Site Explosives Magazine (SEM), a facility essential for the timely completion of cavern excavation. This road, engineered to ascend steep natural terrain while adhering to strict spatial and logistical constraints, is supported by an L-shaped retaining wall. We have selected a portion of the retaining wall RMZ3, as shown in Figure 2, located on the steepest natural terrain near the site boundary for DfMA construction. Conventional cast in-situ methods would be especially challenging in this area due to its close proximity to the site boundary, which complicates scaffolding and formwork erection, and the elevated safety risks associated with steep slopes

Figure 1: Overview of project scope

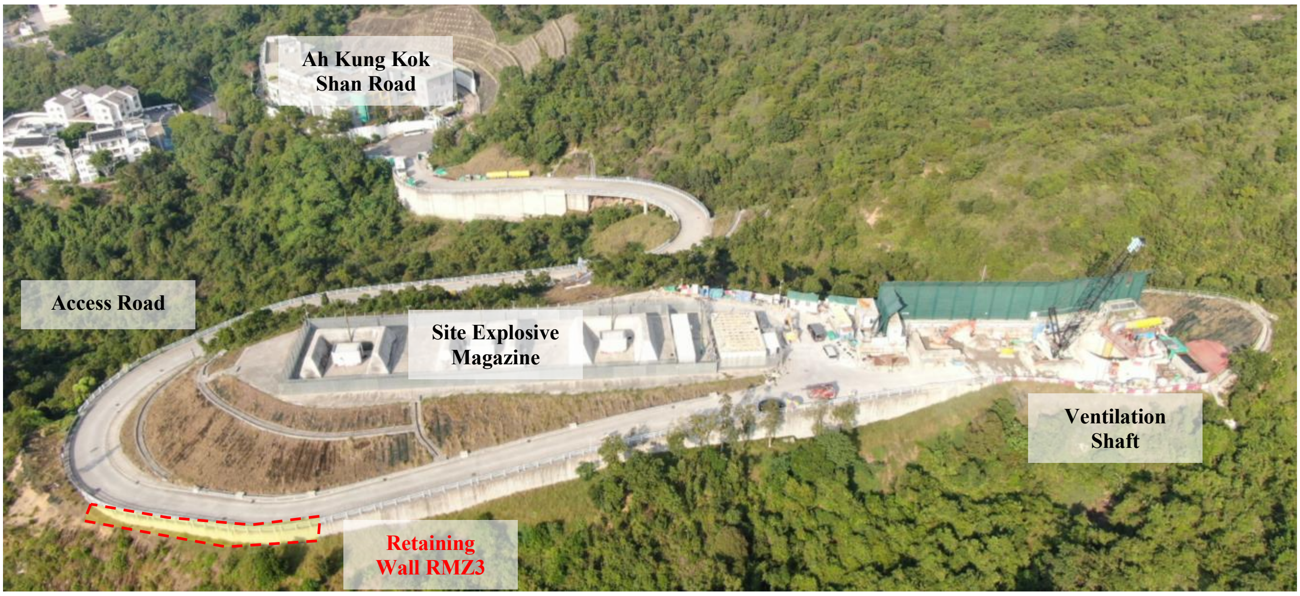


Figure 2: DfMA for retaining wall RMZ3

2.2 Conceptual Design

Retaining wall RMZ3, spanning bay 1 to bay 7 with a total length of 53 m and a maximum retaining height of 4.8 m, was selected for construction using the DFMA method. The wall is designed to be founded on completely decomposed granite with designed strength parameters (g’=19kN/m3, c’=3kPa, f’=39^{o}). The design conservatively assumes a groundwater level located at one-third of the retaining height based on available groundwater monitoring records. The overall stability of the retaining wall against sliding, overturning, and bearing failures were evaluated under a 20 kPa surcharge under normal conditions, while another loading condition, including seismic, blasting, vehicle impact, and wind loads, were also considered.

2.3 Evaluation of Design Scheme

According to Tan (2020), “the emerging technological advancements, such as Building Information Modelling (BIM), 3D printing, the Internet of Things (IoTs), and robotics provide the construction industry, DfMA in particular, new entry points for manufacturing knowledge and efficiency improvement”. Our project team employs these manufacturing technologies and computer software–based engineering tools in developing the DfMA design scheme. Traditionally, the precast retaining wall is regarded as an idea only because of the difficulty in aligning connection joints. This issue could be solved with the aid of BIM, as shown in Figure 3. Several schemes are designed for different splicing methods of the retaining wall units. The details of the segments, such as the shape, dimensions and connection details, are considered. The reinforcement details are also modelled to justify the best option for the project. Different design options are printed using a 3D printer, as shown in Figure 4, for easier visualization and evaluation of their structural properties. After rounds of evaluation, the retaining wall is split into two segments with structural steel beams as a connection and major reinforcement. Two separate precast elements, each incorporating an encased steel I-beam, which are connected on site to form the complete structure. For ease of assembly, the base slab has been designed to interconnect with a minor portion of the wall stem, with this connection being welded during the prefabrication process. The remaining segment of the stem includes approximately 300 mm of exposed steel that is intentionally left un-encased in concrete to facilitate bolt installation during on-site assembly. Once all connections are established, the exposed steel section is concreted to ensure full structural integration.

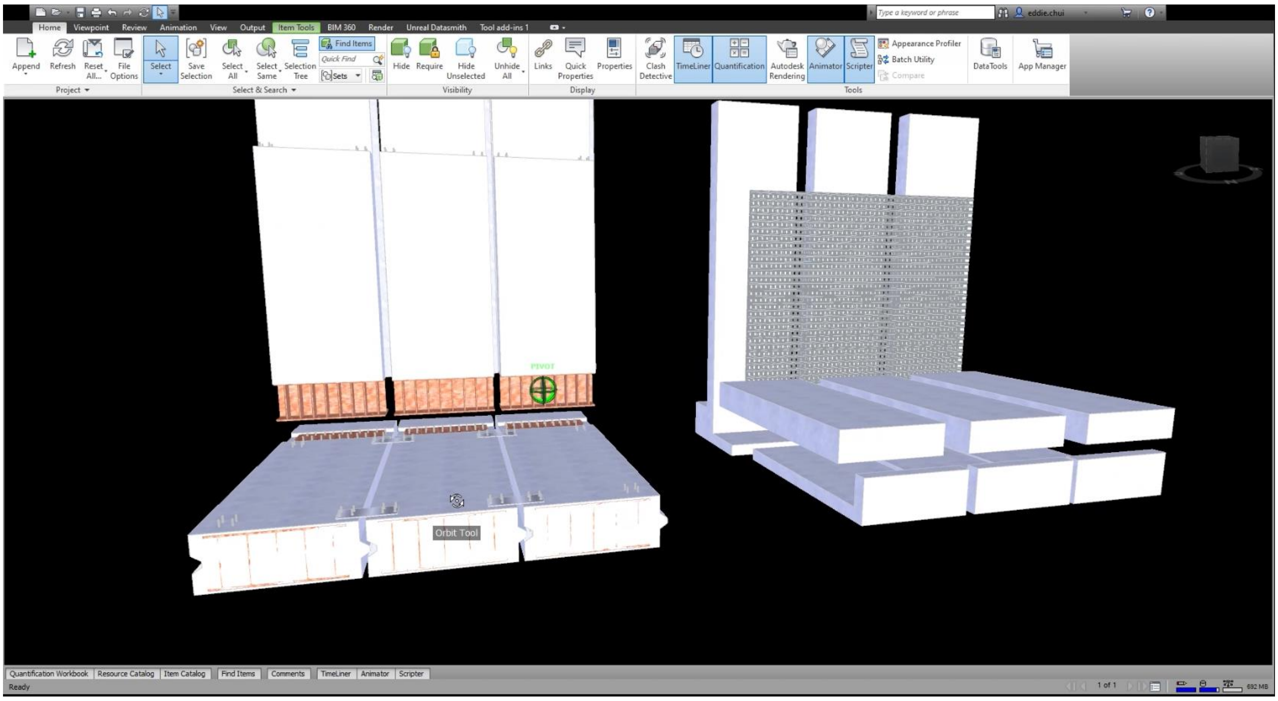


Figure 3: Evaluation of different design schemes

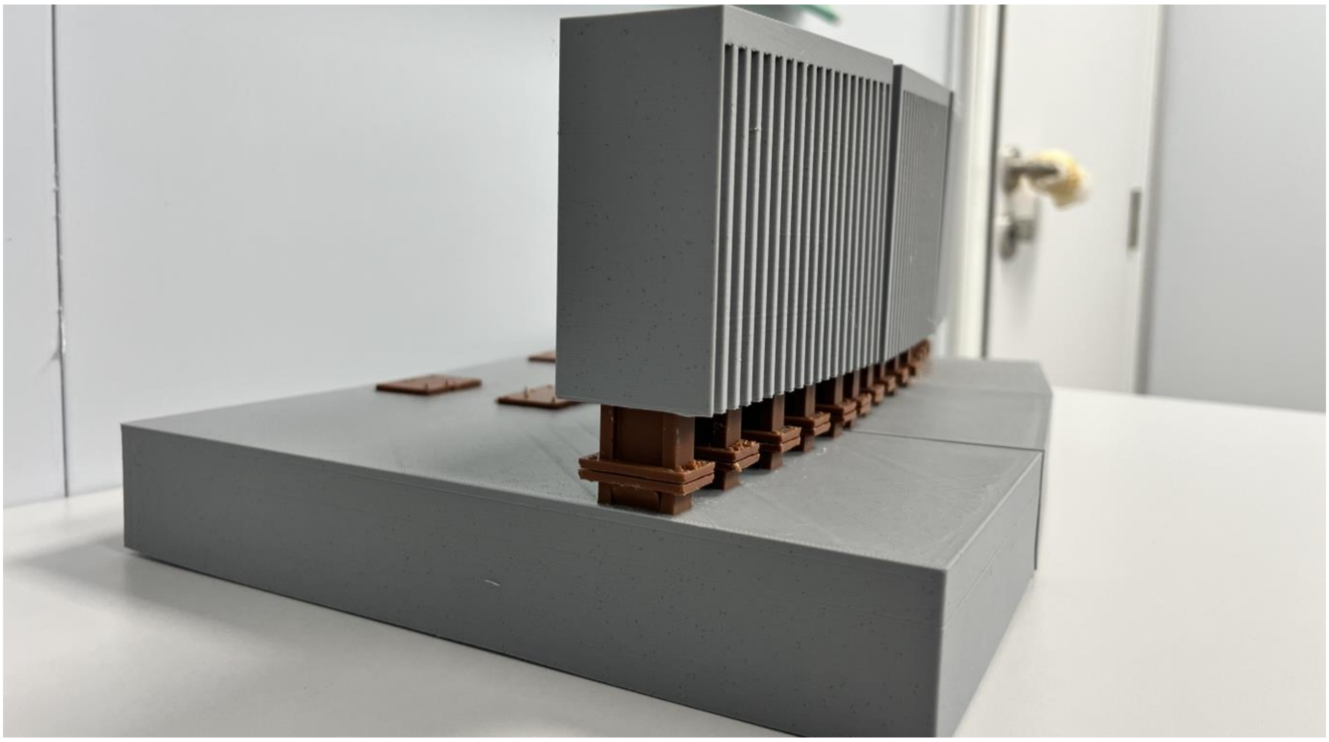


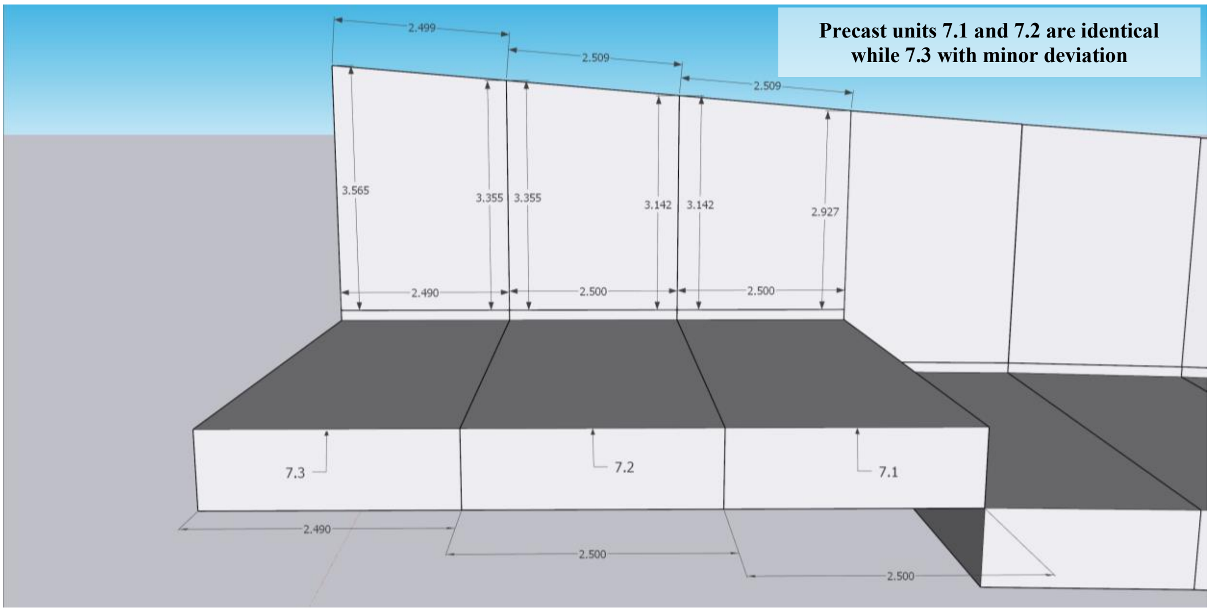
Figure 4: 3D printing model of RMZ3

2.3.1 Connections between Precast Units

This design scheme, which uses structural steel beams, is more efficient for both design and construction than a scheme that uses rebar. Only the connection portion is cast in situ, thereby minimizing on-site construction work. The connection between the wall base and the stem is achieved via a base plate secured with four bolts. These bolts are fixed during assembly to ensure the stability of the wall elements throughout the temporary construction stage. Since the bolts provide robust support for the wall stem, no additional temporary support is necessary during the concreting of the 300-mm un-encased concrete portion. In contrast, if conventional rebar were used, the numerous connections between the wall stem and the base would be difficult to manage. Such a design would require extra supports to hold the wall stem upright and in position during the concreting of the 300-mm un-encased concrete portion. Moreover, these temporary supports would need to remain in place until the concrete gain sufficient strength, thereby introducing higher risks during construction.

2.3.2 Division of Precast Units

The retaining wall is constructed with a uniform base and stem, incorporating only minor height variations to support the ascending access road. Each bay of the wall spans approximately 7.5 meters in both width and length. Several schemes for dividing the structure into manageable units were explored with the aid of BIM, as shown in Figure 5. For ease of transportation and to avoid the need for special wide and long load permits, each bay is divided into three modular precast units. Each unit measures roughly 2.5 meters in width and 7.5 meters in length. At least two of these modular units per bay are designed with identical widths, while the third unit may have a slight deviation, which is accommodated by an adjustable mold design. This strategy minimizes the number of different molds required, thereby streamlining construction and reducing costs. The division of the precast units also needs to consider lifting operations, as the crane must operate near the edge of the natural terrain. Consequently, stringent limits on the weight of both the crane and the lifting load must be strictly enforced. Thanks to BIM, the precise weight of the precast units, which is composed of steel members, steel reinforcement, and concrete, can be quickly determined, facilitating an efficient evaluation of different division schemes.



Precast units 7.1 and 7.2 are identical while 7.3 with minor deviation

Figure 5: Division of the precast unit by BIM

2.3 On-site Casting Yard

The on-site casting yard, as shown in Figure 6, minimizes long-distance hauling, thereby reducing transportation costs and streamlining overall project logistics, a compelling incentive for adopting DfMA principles throughout construction. Although a 150 mm sub-base must be laid at the contractor's expense to establish a stable, level foundation for the casting yard, its benefits extend well beyond casting. The on-site casting yard enables workers to cast precast units from ground level rather than working at heights, as required with conventional cast-in-situ methods, significantly enhancing safety and improving overall construction quality. A detailed digital simulation of the precast process, developed using software Fuzor, enhances project efficiency by providing clear, on-site demonstrations for staff and serving as a crucial tool during client meetings to secure approvals.

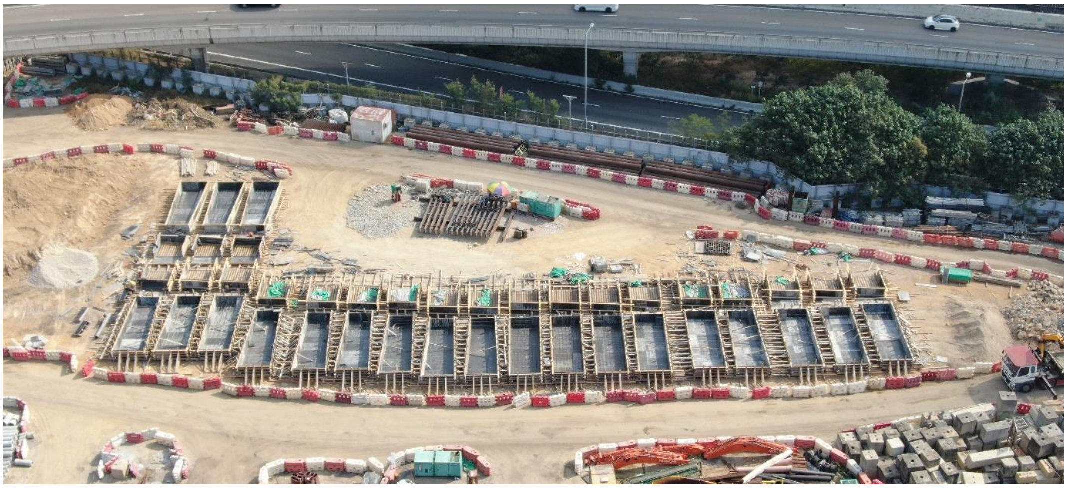


Figure 6: On-site casting yard

2.4 Transportation

The dimensions of the precast segments were carefully optimized to meet transportation requirements, following a comprehensive survey from the on-site precast yard to the designated installation area. Based on the design loads of the precast units, the project deployed two types of trailers: one with a maximum gross combined weight of 44 tonnes and a total length of 15.8 meters for wall base units, and another with a maximum gross combined weight of 38 tonnes and a total length of 11.2 meters for wall stem units. Two potential routes were identified and evaluated using Autodesk Vehicle Tracking software to conduct a swap path analysis for assessing the feasibility of turning. Although the shorter route was initially considered, it was ultimately rejected due to its abrupt junctions and a highway bridge with low headroom that restricted the passage of precast units. Instead, a slightly longer route featuring gentler turns and no height restrictions was finally adopted. In addition, since the proposed installation location is within natural terrain, a haul road is required to access it. A photogrammetric model of the site haul road was developed, and its gradient was assessed using Vehicle Tracking software to ensure that the maximum allowable load can be transported. Re-levelling a portion of the haul road, which is at the contractor's expense, was required to ensure smooth transportation of the precast units. In a related logistical challenge, the delivery truck was unable to execute a U-turn on the limited space available on the haul road. To resolve this, the project team deployed a crawler crane to assist the truck in turning around safely. A detailed simulation was prepared and presented as a safety demonstration to the site staff, ensuring that all personnel were aware of and prepared for the new manoeuvring procedures

2.5 Lifting

The BIM model serves as a critical tool during the planning of lifting operations by providing an integrated, data-rich digital representation of each segment's weight, dimensions, and assembly details. This detailed model enables engineers to accurately calculate the load of each precast segment and simulate the lifting sequences, ensuring that every step from crane positioning to the safe placement of wall components is well coordinated. By integrating the crawler crane's specifications, including its safe working load and allowable working radius, the BIM model allows engineers to assess various lifting scenarios, optimize operational pathways, and identify potential hazards before they occur on site. In addition, the clear visualization provided by the BIM model facilitates effective communication among the project team, thereby enhancing overall operational efficiency and risk management during the construction process. Lifting of precast unit is shown in Figure 7.

Figure 7: Lifting of precast unit

2.6 Match Cast

The success of DfMA construction heavily relies on high-quality workmanship during the connection process. Numerous factors—such as an uneven blinding layer, movement between the wall base and the wall stem during concreting, or deviations even in the controlled environment of the casting yard—can compromise alignment. Since the wall base and wall stem connect via five I-beams per bay, precise alignment is essential. Any deviation in one of the I-beams, whether due to levelling issues or discrepancies in length, can hinder the connection and cause the wall stem to tilt, thereby raising both safety and structural integrity concerns. To ensure a secure and accurate connection, a detailed survey was conducted to scan the blinding layer and verify its levelness, as shown in Figure 8. After positioning the wall base, a pre-assembly check was performed to ensure a seamless connection and to verify the leveling of the base plate relative to the I-beams, as shown in Figure 9. The resulting point cloud is first imported into Autodesk Recap Pro for a preliminary review and then into Autodesk Civil 3D. In addition, a match cast is performed for the wall stem's I-beams to guarantee a gap-free fit and symmetry, with minor adjustments made to the length of un-encased I-beams as necessary. These meticulous measures collectively uphold both safety and structural integrity throughout the construction process.

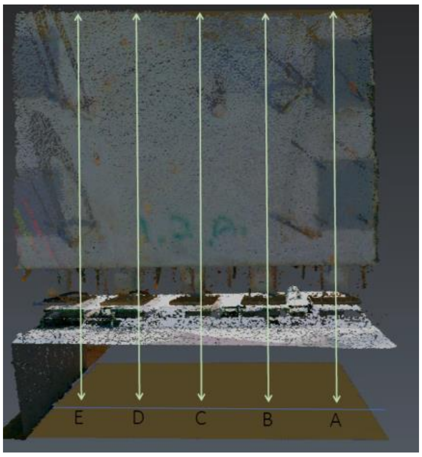


Figure 8: Scanning the segments (left) ; Figure 9: Check the alignments with point cloud

2.5 Design Review

A scan-to-BIM process was employed after connecting the base plates of the I-beams between the wall base and wall stem, and before concreting the 300 mm un-encased length. Using the integrated Autodesk Revit plugin, the Revit BIM model was seamlessly exported to Autodesk Robot Structural Analysis for a detailed design review, automatically transferring the alignment and properties of as-structure without requiring additional manual input. The key reinforcement members were then evaluated against both ultimate and serviceability limit states under various load cases, with axial, shear, bending, stress, and deflection parameters computed to verify capacity of each component. Additionally, internal forces at the connections were extracted to inform the design of connection details, ensuring that real-world deviations are incorporated into the analysis. Autodesk Robot Structural Analysis further accounts for stress concentrations by applying a workmanship factor that captures the effects of slight misalignments, details often oversimplified or overlooked in hand calculations or conventional analysis software that assume ideal, perfectly upright members. This integrated approach aligns all digital models and data inputs, ensuring that the design review accurately reflects the true conditions of the construction and meets the required design standards. The output of Robot Structural Analysis is shown in Figure 10.

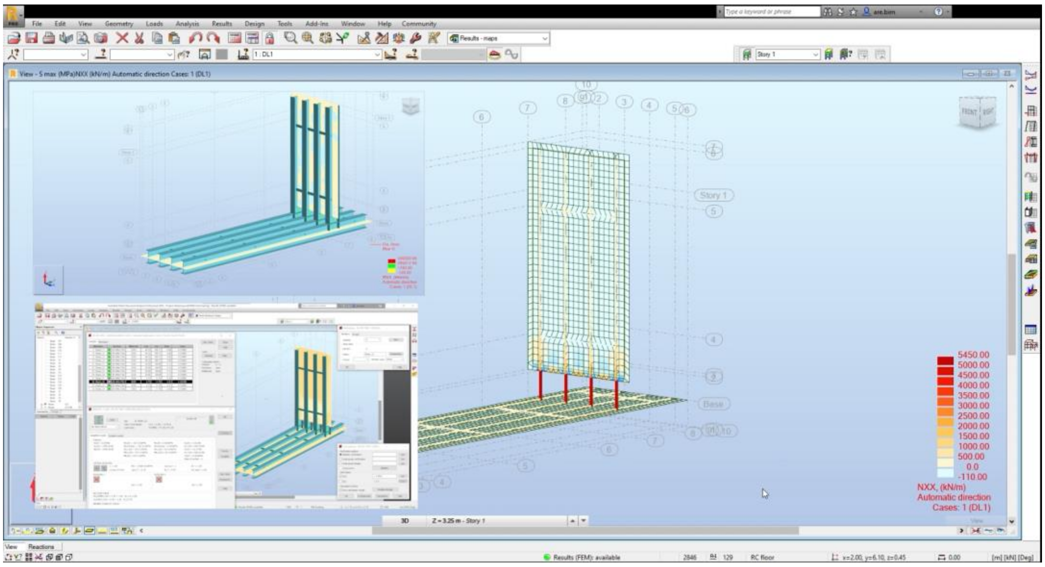
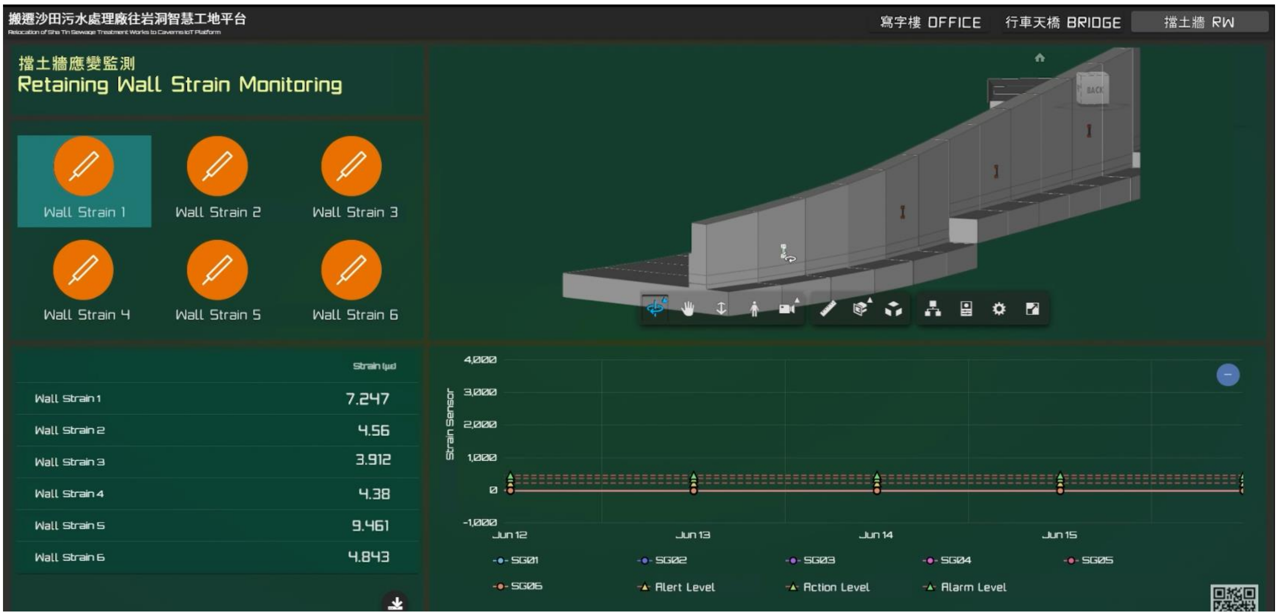


Figure 10: Structural load analysis with Autodesk Robot Structure Analysis

2.9 Operational and Maintenance

Since this is the first time DfMA has been applied to retaining wall construction in Hong Kong, sensors with real-time monitoring capabilities have been installed to record the strain induced in the wall's structural elements, addressing concerns regarding structural performance. The collected data is transmitted to an IoT platform, where engineers can access real-time strain values and receive alerts if those values exceed set limits. Additionally, ground settlement caused by wall deflection can be monitored, providing comprehensive data for engineers to assess performance. This combined monitoring approach ensures structural integrity during construction and offers valuable insights for future projects. The IoT platform is shown in Figure 10.



	Strain (με)
Wall Strain 1	7.247
Wall Strain 2	4.56
Wall Strain 3	3.912
Wall Strain 4	4.38
Wall Strain 5	9.461
Wall Strain 6	4.843

Figure 10: Lifting of precast unit

2.10 Superior Outcome Achieved by DfMA

The adoption of DfMA for the retaining wall in the Sha Tin Cavern project has delivered exceptional results, with substantial improvements over the conventional cast in-situ method. Table 3 illustrates these comparative outcomes, emphasizing the remarkable efficiency achieved through DfMA principles in geotechnical works. It is particularly noteworthy that the conventional cast in-situ method required 21 days per bay, resulting in a total construction time of 147 days for seven bays of retaining wall. the detailed breakdown of the construction programme is shown in Figure 11. In contrast, DfMA completed each bay in approximately one day, with a conservative buffer accounting for a total of around 10 days for all seven bays.

Table 1: Comparison between DfMA and cast in-situ method for retaining wall RMZ3

	Cast In-situ Method	DfMA	Comparison
Duration for On-site activities (days)	147	~10	~137 days saved
On-site activities (Categories)	70	21	49 categories reduced
Working at height activities (nos.)	42	0	42 nos. eliminated

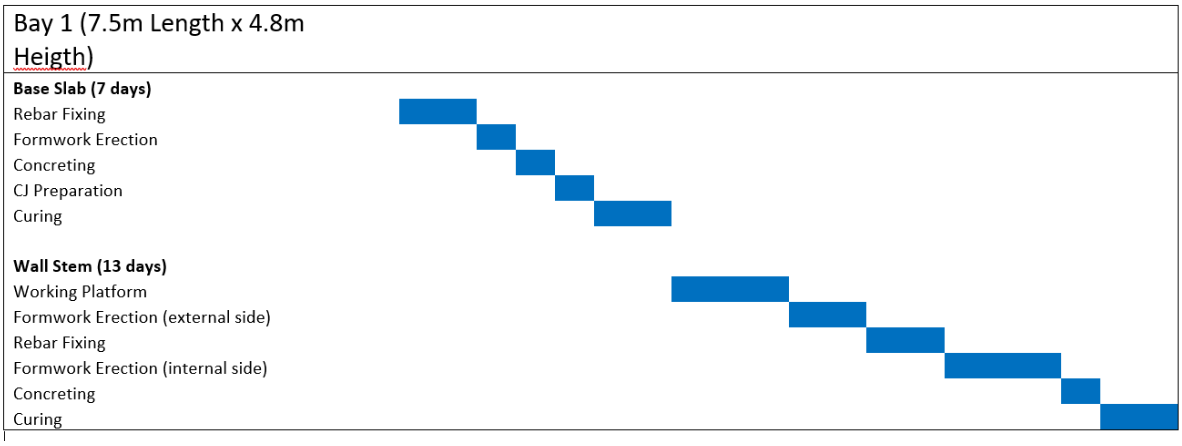


Figure 11: Breakdown of programme for conventional cast in-situ method

3 DISCUSSIONS

Given the diverse factors influencing the cost-effectiveness of DfMA across projects, there is a critical need to develop a standardized evaluation protocol. This protocol would empower engineers with a reliable framework to assess whether DfMA offers genuine benefits compared to conventional construction methods. By integrating key parameters—such as labor costs, transportation and lifting expenses, stockpiling requirements, temporary works, and regional cost differences—into a systematic assessment tool, the decision-making process becomes more streamlined. Furthermore, the protocol would account for project-specific conditions, such as the uniformity and repetitiveness of construction units, ensuring that the advantages of DfMA are accurately measured. Ultimately, such a standardized approach would enable engineers to make informed judgments and optimize construction strategies for safety, efficiency, quality, and sustainability.

4 CONCLUSIONS

The principle of "starting with the process in mind" is a foundational element of DfMA, guiding the design process by fostering a comprehensive understanding of the entire project lifecycle from initial design through manufacturing, transportation, lifting, and final assembly. This approach ensures that each phase is optimized, risks are minimized, and the project aligns with its ultimate goals from the outset.

The Sha Tin Cavern project serves as a compelling example of DfMA's transformative potential in geotechnical engineering. By leveraging early collaboration among stakeholders and robust client support, the project successfully addressed the challenges of urban construction, delivering impressive results:

- 93% reduction in on-site construction time: Off-site fabrication and streamlined processes drastically shortened the construction schedule.
- Enhanced safety: The elimination of working-at-height activities reduced risks to workers.
- Improved quality: Controlled off-site fabrication ensured higher precision and consistency.
- Digital integration: Effective use of digital tools enhanced planning, monitoring, and execution.

However, these outcomes are not guaranteed across all projects. The success of DfMA hinges on project-specific factors such as scope, site conditions, and regional cost variations. As a result, Resident Site Staff (RSS) and contractors must undertake a thorough cost-effectiveness analysis to assess the financial viability of adopting DfMA. This analysis should account for variables like labor costs, transportation expenses, lifting requirements, and the need for temporary works, ensuring that the benefits justify the investment. The achievements of the STC project highlight the importance of developing standardized evaluation protocols to systematically evaluate DfMA's cost-effectiveness. Such protocols would provide engineers with a consistent framework to assess whether DfMA is suitable for a given project, enabling data-driven decisions that optimize safety, efficiency, quality, and sustainability. By establishing this foundation, the geotechnical engineering industry can encourage the wider adoption of DfMA, unlocking its benefits for a broader range of applications.

ACKNOWLEDGEMENTS

The authors would like to extend their sincere appreciation to the Drainage Services Department of the Government of Hong Kong SAR for granting permission to publish this paper. Special recognition is also extended to China State Joint Venture, Sheung Ying Construction Limited for their invaluable assistance and hands-on experience in implementing DfMA practices in the construction of retaining walls.

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