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GEOTECHNICAL INSIGHTS FOR A PROACTIVE PRODUCTION SYSTEM FOR EARTHWORK

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ABSTRACT

Risk mitigation through production system design and clear communication is critical to the success of complex projects and their sustainability. This paper presents a case study describing how a team building a multi-million-dollar, mission-critical data center project decreased risks associated with geotechnical soil conditions by creating a production system design using Lean methodologies such as location-based management, takt planning, and a behavior-based quality system tailored to the demands of earthwork and civil construction.

The implementation of stacking these Lean methods improved communications, accelerated information flow, and reduced feedback loop durations, which increased the predictability of earthwork operations. Also, the paper discusses how the production system design fostered a culture of collaboration, trust, and continuous improvement. The authors advocate for new industry standards in job-sequencing, work structuring, and quality management within earthwork construction, emphasizing how stakeholders' collaborative involvement is crucial to project success. This partnership highlights the foundational importance of soil construction and establishes frameworks for trust, collaboration, and continuous improvement.

KEYWORDS

Production system design, location-based management (LBM), takt planning (TP), work structuring, behavior-based quality system (BBQS)

INTRODUCTION

Owners desire hassle-free construction and delivery of their facilities within predetermined specifications (Biton & Howell, 2013). To accomplish this, they require the assistance of several experts who convert the Owner's intentions into a format that the Contractors who build these facilities can communicate and comprehend. There is no "us versus them" in the end goal once the team has been formed, thanks to Lean Construction's integrated strategy. For a project to be successful, team members must gain from it collectively rather than as separate businesses.

Traditional project settings often operate under the assumption that plans and specifications alone sufficiently convey stakeholder expectations. However, this overlooks a project team's diverse mental models and cultures, particularly on complex endeavors involving teams operating under challenging and variable soil conditions. This can lead to fragmented thinking,

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where differing mental models result in misaligned expectations and deter effective communication and collaboration.

The complexities of earthwork construction often create rampant miscommunication and unclear responsibilities, mirroring the confusion demonstrated in the classic, "Who's on First?" comedy routine (Abbott & Costello, 1938). This paper presents an action research case study demonstrating how a novel Production System Design addressed these challenges on a multi-million-dollar, mission-critical data center project. This system strategically integrates Location-Based Management System (LBMS) (Seppänen et al., 2015), Takt Planning (TP) (Frandson et al., 2013), and a behavior-based quality system (BBQS) (Gomez, et al., 2023) specifically tailored to the demands of earthwork and civil construction.

The BBQS, as described by Gomez et al., (2023) and Arroyo & Villanueva (2024), directly enhances communication, accelerates information flow, and reduces feedback loop durations. This paper explores developing and implementing of this bespoke Production System Design, highlighting its impact on risk mitigation, communication enhancement, and predictability improvement in earthwork operations.

The study also explores how this design promoted a culture of cooperation, trust, and ongoing development, supporting new industry norms for work scheduling, quality control, and job sequencing in civil construction and earthwork. The significance of precisely outlining the responsibilities of the Geotechnical Engineer of Record (GEOR) and the Construction Materials Testing (CMT) company is also examined in this study, focusing on how their cooperative participation was essential to the project's success.

METHODOLOGY AND PROJECT BACKGROUND

This is a case study based on action research methodology where the first two authors are part of the project team, provide direct observation, and intervene in the project implementing the earthwork scope of work. This mission-critical project is based in South Carolina on a 600+ acre site with cut and fills of up to 30 feet. This project's first phase involved massive earthwork to complete the rough grading and subgrade to receive two data centers, an administrative building, two substations, and a warehouse. The researchers used Lean methods and their combined decades of experience in heavy earthwork principles to gather lessons learned and organize them into processes that were implemented by the project team. They also solicited daily feedback from relevant team members involved in production and quality execution, which elevated the team's engagement and integration.

Construction challenges within earthwork are plagued with inefficiencies. Soil conditions on-site ranged from white "sugar" sand to fat clays to Triassic materials, which is a problem within itself. Besides the building foundations were planned to be started within eight (8) months after breaking ground. With these conditions, the Client would have typically dealt with inappropriate soils and a lack of clear communication about mitigation options. This could have resulted in postponement between tasks, large modification orders, and delay claims.

A cultural shift was required to help the project team recognize the value of earthwork and utility aspects, which are often overshadowed by a focus on the building's critical electrical, communications, and mechanical systems. Recognizing that a successful earthwork phase was more than just a construction need but a critical component of the project's success, the team adopted a combined approach to quality and production. A significant problem was establishing a shared understanding through a common language, which would strengthen reliable promises and provide a framework for successfully organizing and disseminating information throughout the whole project team. A daily touchpoint of collecting feedback from stakeholders executing these processes at the field level helped the team understand and own the process.

The researchers designed and implemented a production system for earthwork by:

- Step 1: Breaking the project into manageable locations and establishing a production rhythm by naming location-based areas using LBMS and TP.
- Step 2: Defined clear expectations of how to meet the intent of the design by creating a Subgrade Acceptance Guide Process using BBQS.
- Step 3: Coached Trade Partners to follow the specifications by linking existing processes to the Subgrade Acceptance Guide and proactively provided recommendations for on-site issues.
- Step 4: Developed a Field Communication Plan for the personnel in a way that was easily grasped.
- Step 5: Steps were tailored, updated, and improved iteratively by receiving feedback from the project team that improved the system continuously through its design and rollout.

LITERATURE REVIEW

This section presents relevant literature to understand soils in construction and the complexities of construction personnel when driving towards a common goal, which for this Client was speed to market without compromising safety or quality.

SOILS IN CONSTRUCTION

Modern construction projects demand a deeper understanding of soil mechanics due to evolving contract structures and complex site conditions (Warrington & Schroeder, 2019). Contractors must possess some geotechnical knowledge to confirm structural integrity, especially with the growing use of design-build contracts. Many first-year engineering students are introduced to soil and aggregate materials early in their education, but the practical importance of proper soil installation often takes time to appreciate fully.

One of the fundamental aspects of soil mechanics is recognizing that soil consists of air, solid particles, and water, as shown in Figure 1 (Warrington & Schroeder, 2019). Understanding soil particle size distribution is crucial, affecting construction stability (Warrington & Schroeder, 2019). Sands and gravels behave differently from silts and clays due to their interaction with water and chemical composition. These characteristics directly impact a project's foundation and must be strictly adhered to as contract documents outlined.

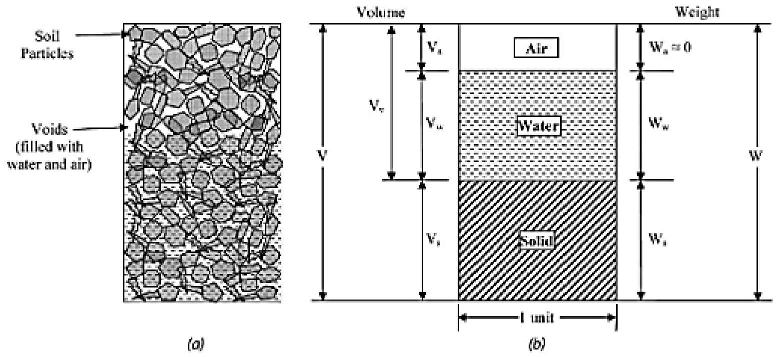

Figure 1: Air-Soil-Water Phase Calculations. (a) Actual particle state. (b) Schematic of phases

In practice, another recurring challenge from this same perspective is that while General Contractors (GC) and their Trade Partners ("Trades") acknowledge and certify their responsibilities during the bidding process by submitting a proposal (Warrington & Schroeder, 2019), there is often a gap in fully understanding and addressing the existing site conditions with the specifications. This is manifested in how the specifications outlined in the Geotechnical Report and other contract documents are realized on many projects.

PROJECT LEADERSHIP AND THE ART OF MANAGING INVOLVEMENT

Effective leadership in construction is about more than just planning—it involves active engagement and commitment from all team members. Napoleon once said, "Plans are nothing, but planning is everything" (Clark, 2001). A project's success hinges on the planning process rather than just the documentation itself. Project managers must make certain all stakeholders participate in decision-making to foster commitment and accountability.

Any project scope encompasses both the intended results and the work material. Identifying all the tasks that need to be completed, the resources used, and the final products—along with quality standards—make up the project scope. Controlling a project's aims and objectives through the phases of conceptualization, complete definition, execution, and termination is known as scope management. It results from pre-development planning since it offers the framework on which all project activity is built. (Pinto, 2016)

Lack of involvement in planning often leads to failed execution (Clark, 2001). Strong leaders balance decision-making with inclusive collaboration and ensure that resources are used efficiently, and goals are aligned. When team members understand and buy into the plan, they are more likely to execute it effectively, minimizing misallocated efforts and project delays.

BEHAVIOR-BASED QUALITY SYSTEM

Among BBQS's objectives includes the labor necessary to deliver high-quality and remain aware of the assumptions people make about quality management, such as the expected behaviors and conduct norms (Gomez, et al., 2023). Techniques and resources that support the processes of producing quality must be identified, and procedures must address the actions and individuals needed to provide quality. To bring all stakeholders into alignment, this strategy strongly emphasizes quantifiable results and explicit expectations. Teams can increase productivity and collaboration by streamlining complicated procedures and creating a common language.

PRODUCTION PLANNING, LAST PLANNER SYSTEM©, LOCATION BASED MANAGEMENT SYSTEM, AND TAKT PLANNING

Koskela's groundbreaking work served as the foundation for the evolution of Lean construction. He put up a logical theory incorporating ideas and procedures from the Toyota Production System (Biton & Howell, 2013).

Ballard et al. (2001) included both global organization and operational design, such as deciding who should be involved in what tasks and how the actual work will be completed in production planning within construction. In the past, the focus of construction project planning has been on organizational structure and the development of work breakdown structures that separate the tasks that need to be completed. The production system entails switching to the TFV (Task/Flow/Value) production model from a vision that only considers the transformation of inputs.

Seppänen et al. (2015) application of the Last Planner System© (LPS), LBMS, and continuous learning principles further strengthened project coordination. The areas with the greatest room for growth are progress tracking, forecasting, control action, and the look-ahead planning phase, where both LBMS and LPS make significant contributions on their own, and their combination is not insignificant.

Reducing variability and aiming for continuous workflow in production are two of the most important Lean construction tenets (Yassine et al., 2014). Reduced variability, a shorter project length, and lower project costs are the advantages that Takt time brings to the project. Takt time refers to how quickly the Client requests the goods, which determines how quickly manufacturing should satisfy those demands precisely on schedule while avoiding needless inventory. Finding and verifying the time needed to complete the task is one way to base the demand; another is to see if increasing the slowest trade's capacity is feasible (Yassine et al., 2014). A study demonstrated how the Last Planner System's© enhanced socially interactive planning process may guarantee that the advantages of Takt-based scheduling are realized. The amount of time needed by each trade to finish specific work is known as the tasks and resources needed are known.

Currently, the literature on these concepts is limited within the context of soil, Civil Engineering, and Geotechnical Engineering scope.

PRODUCTION SYSTEM FOR EARTHWORK CASE STUDY

Leveraging “Production System Design in Construction,” by Ballard et al. (2001), the authors utilized that this system design should include both the global structure of the Owner’s program and the operational design of the GC, such as considerations on who will be involved in which tasks and how the work will be carried out. This basic understanding of what the production system design was created for was applied to improve the execution of civil work and minimize waste. For this team to synchronize what needed to be accomplished, Location-Based Management System, Last Planner System©, Takt Planning, and continuous process improvement with input from the Geotechnical/Construction Materials Firm’s expertise needed to be brought together.

STEP 1: NAMED LOCATION-BASED AREAS

Effectively communicating the exact location of work operations was one of the project's early hurdles. The methods used by various parties to identify places varied. The Geotechnical Firm used a grid plan method with 10,000-square-foot grids to test the placement of mass fill. While the Trades used their own paperwork and geographical terminology, the Owner gave the GC pre-released drawings for mass grading, utilities, and structures. As shown in Figure 2: Location-Based Visual Framework, the initial step in creating the Production System Design was establishing a single Named Location-Based Area (Step 1) to address these discrepancies.

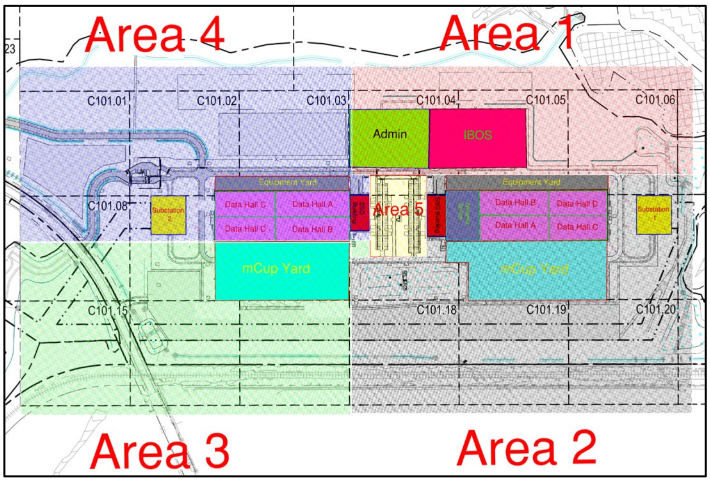

Figure 2: Location-Based Visual Framework

The Trades acknowledged that, depending on their layout drawings and internal procedures, different trades have historically used different terminology and naming standards for the same site. In order to proactively address this, the LBMS created a common language that makes communication easier by offering a precise and unambiguous method of referring to particular places and workspaces. Without LBMS, for instance, an electrical contractor would designate a spot as "Medium Voltage Ductbank B, Section 3." In contrast, an earthwork contractor might refer to the same region as "the electrical duct bank in Area 2." However, with LBMS, both might use a project-specific code, like "1ERA.DS-BW.01 TO 1ERC.BW.R01," to refer to the same ductbank. Once the coding logic is understood, the code provides the exact location and system information.

Determining Takt Time Earthmoving Operations:

Takt time was calculated using the overall project schedule objectives and the earthwork phase production needs. The LBMS was used to analyze job content to determine time-consuming, critical path operations and evaluate scope. By allocating a distinct Takt time to each area, which represents the anticipated amount of time needed to complete the earthwork, the integration of TP and LBMS was crucial in creating a distinct, visible production rhythm. Takt time was visually represented in schedules and on-site visual management tools using a time-location matrix, which improved efficiency and coordination. This strategy aligns with the idea of work density proposed by Frandson et al. (2015), which considers elements like productivity, expected production rates, work volume, staff capabilities, equipment types, work direction, and gross areas. The team developed the Takt time framework using these components to determine time allotments for every zone. The system, which is frequently called "Takt wagons" (Binninger et al., 2017), made it easier to match trade flows between multiple locations.

The anticipated production rhythm was adhered to thanks to a strong Takt control system. Using the LPS (Ballard H. G., 2000), daily huddles functioned as sessions for tracking progress in real-time. Teams could promptly detect and address deviations from the TP thanks to the LBMS visual framework (Figure 3). While dashboards emphasized key performance indicators (KPIs) linked to schedule performance and production rates, visual control tools, such as color-coded control charts, showed Takt adherence and real-time project status. Since certain LBMS locations were associated with quality problems, such failed density testing, issue management was also essential. In addition to ensuring prompt resource allocation for resolution, a color-coded signaling system helped avoid ignored difficulties.

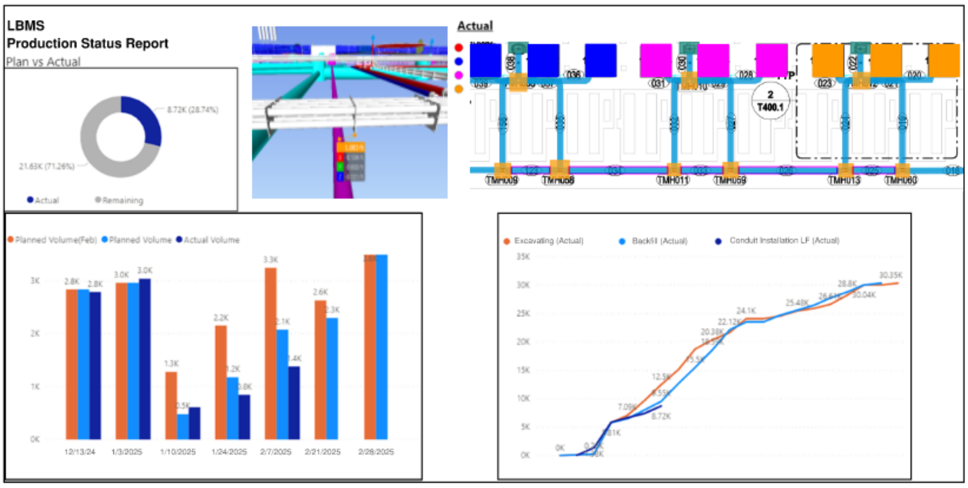

Figure 3: LBMS Production Status Report

Through the integration of Lean Construction concepts, TP, and LBMS (Lehtovaara et al., 2021; Frandson et al., 2015), the team developed an organized, flexible method for earthwork operations. While preserving a steady, well-balanced workflow, this system successfully addressed soil fluctuations, new communication patterns, and team dynamics.

STEP 2: SUBGRADE ACCEPTANCE GUIDE

Work pertaining to soil is complicated by specialized knowledge, overlapping regulations, procedures, and duplicate systems. Here, Sidney Dekkar's theory of system complexity is very pertinent (Biton & Howell, 2013). To navigate this complexity, the team focused on behaviors that promote clarity and accountability, ensuring that all aspects of the earthwork phase were systematically executed. This structured approach reduced rework from 57% to 29%, intending to reach 20%.

Development of the Guide

Recognizing the need to standardize the subgrade turnover process, the GC's quality team used the Takt time method given by Yassine et al. (2014) to break down the necessary steps. The team collected information from key stakeholders such as the Trades, the Geotechnical/Construction Materials Testing Firm, and the Civil Engineer of Record to confirm that the guidance was thorough and practical. These discussions shed light on task execution, staff productivity, and cash flow management, helping clarify the process' components.

The Subgrade Acceptance Guide was started through a collective effort during daily quality huddles. These sessions enabled the GC and Geotechnical Firm to improve the document by identifying areas where personnel needed further training and resolving misunderstandings in project requirements and expectations. the team enhanced collaboration and efficiency by reducing complicated processes and developing a shared language.

Understanding Responsibilities: Who's on First?

One significant problem in the development of this process was determining who should be notified and when. Miscommunication and confusion frequently resulted in delays and inefficiency. To address this, the team clarified the duties of important roles:

- **Geotechnical Engineer of Record (GEOR):** The licensed professional engineer who signs and seals the geotechnical engineering paperwork for a project. By signing and sealing, the GEOR confirms that the geotechnical-engineering analyses were completed or overseen and that the design documents related to the project's geotechnical components—including, if necessary, the corresponding specifications and drawings—were prepared or overseen (Geoprofessional Business Association, 2018).
- **Construction Materials Testing (CMT) Firm:** Owner's independent testing and inspection agency that may either self-perform materials testing and inspections in-house or employ a firm for specific testing and inspections.

These two roles work together by having the GEOR engaged early in the project during site selection to conduct a Phase 1 Geotechnical Report, which involves minimal drilling to assess feasibility. If the site is viable, a more detailed Phase 2 Geotechnical Report is conducted before construction begins. Once construction starts, the CMT Firm aquires testing and verification duties.

Using the same firm for geotechnical engineering and material testing presents several advantages. Continued oversight is one key benefit, as the GEOR already has in-depth knowledge of the site's conditions and design recommendations, making it easier to address unexpected issues. Effective communication is another advantage—consistent teams reduce misunderstandings and confirm that construction decisions support the initial assessments. Additionally, this stability helps save time and costs by avoiding duplicate reviews or the need to onboard new experts. Finally, improved accountability results from consolidating responsibilities, confirming that testing and verification support with the original geotechnical recommendations, reducing legal risks and discrepancies.

Compaction Equipment for Shallow Lifts

When any GEOR writes their report for a project, compaction equipment and the compacted or loose lift thickness are recommended for certain soil types to obtain the minimum density required. These recommendations come from the NAVFAC DM 7.02 (Naval Facilities Engineering Command, 1986) which was the standard for more than 50 years. From that information and the Geotechnical Engineer's Report, the team derived this information to simplify equipment selection for the backfill loose lift thickness, which was just one of the elements incorporated into the Step 2: Subgrade Acceptance Guide Process. The NAVFAC DM 7.02 has been incorporated into UFC 3-220-01N, Geotechnical Engineering Procedures for Foundation Design of Buildings and Structures.

When we gave the basis of how compaction equipment and the methods needed to generally meet the specifications were presented to the team, it assisted in the understanding that these were historically developed and tested which eased tensions of 'means and methods' conversations since the CMT Firm wasn't directing it. Since the local Trades had not been exposed to this educational material and type of process-driven thinking, it proved to be more challenging to get these stakeholders on board with this way of executing their work.

Based on project specifications and team experience, a workflow shown in Figure 4 (simplified) was created to address soil-related issues competently during construction. This illuminated responsibilities and provided a structured methodology for resolving concerns, answering the question, "Who's on First?" (Abbott & Costello, 1938).

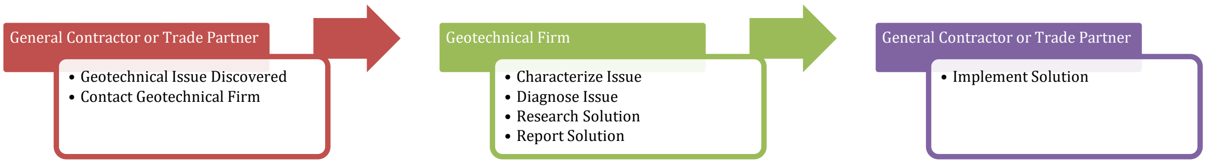

Figure 4: Geotechnical Issue Resolution Workflow

Implementing a Behavior-Based Quality System

Recognizing that construction projects—especially earthwork—often suffer from fragmented communication, this project adopted BBQS (Gomez, et al., 2023). This method emphasizes clear expectations and measurable outcomes to align all stakeholders, as shown in Figure 5: Behavior-Based Quality System. teams can improve collaboration and efficiency by simplifying complex processes and establishing a common language.

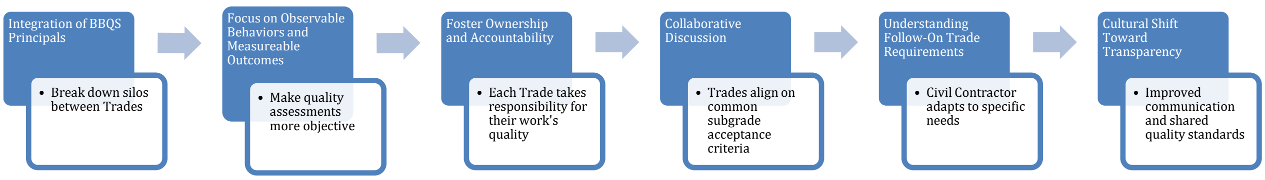

Figure 5: Behavior-Based Quality System

By focusing on behaviors that drive clarity and accountability, the team focused on all aspects of the earthwork phase, so they were systematically executed, reducing errors and improving project outcomes – which was witnessed in the reduction of rework from 57% to 29%, with a goal of 20%.

STEP 3: LINKING EXISTING PROCESSES TO THE SUBGRADE GUIDE

While the project targeted for disciplined adherence to Takt, it also recognized the natural unpredictability in earthwork operations. Instead of relying solely on buffers, the team focused on enhancing stability and expertise, facilitated by the Owner's digital checklists which were collaboratively written by all the Geotechnical/CMT Firms in the program.

The checklists served as hold points within the production system, safeguarding that each step met the required quality standards before proceeding. Through process improvement and their integration with the data-connected LBMS, the checklists were streamlined to avoid becoming bottlenecks in the production system. The digital acceptance and sign-off of checklists released specific zones within the LBMS, signaling that the next Takt wagon could begin its work in that location. This hands-on approach moved beyond inspection, embodying Koskela's (2000) assertion that quality methods have shifted "from an inspection orientation through process control to continuous process improvement and designing quality in the product and process."

STEP 4: FIELD COMMUNICATION PLAN

The Trades and CMT Firm could promptly resolve problems and coordinate efforts because of this decentralized communication through WhatsApp (Figure 6). For instance, "Subgrade Section 4 in Area 3, Zone 2B is ready for inspection," the earthwork contractor would write in the chat window, accompanied by images of the region and the green ribbon. If it satisfied the standards, the Concrete Foreman might reply, "Subgrade accepted," and include a picture of his acceptance signature.

1. Visual Signaling: A simple yet effective visual signaling system was implemented in the field. Stakes with colored ribbons were used to show subgrade status:
    - Green Ribbon: The subgrade had passed compaction tests and was ready for acceptance by the next trade.
    - Red Ribbon: Rework was needed, triggering further investigation and action.
2. FEMA-Inspired Markings: For utility backfill, markings inspired by FEMA's Search and Rescue symbols (FEMA, 2006) were used on precast concrete vaults:
    - Single Slash (/): Indicated that the vault was ready for backfill.
        - Cross (X): Signaled that the vault had been backfilled.

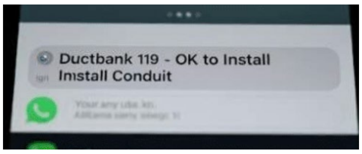

Figure 6: WhatsApp for Decentralized Communication

STEP 5: FEEDBACK FROM THE PROJECT TEAM

The daily huddles revealed a recurring problem in the subgrade acceptance process. The handoff between the earthwork contractor preparing the subgrade and the subsequent trades installing utilities or foundations historically was frequently fraught with issues. Rework, retesting, and layout adjustments were common (57%), leading to delays and frustration. These problems came from a blend of:

- **Differing Mental Models:** Each trade operated with its mental model of what was acceptable subgrade, often using different terminology and relying on confirmation bias rather than the explicit standards. This resulted in misaligned expectations and a lack of shared understanding of the acceptance criteria.
- **Cultural Norms:** Prevailing industry culture often fostered an "us versus them" mentality between trades, hindering collaboration and creating an environment where issues were more likely to be concealed than openly addressed. The Trades would blame each other rather than look for internal process changes they could implement. This highlighted a need for greater ownership and accountability at all levels.
- **Inefficient Communication:** Communication between trades was often ad hoc, relying on verbal exchanges prone to misinterpretation, especially on a sprawling 600+ acre site. The Trades would describe their work in terms of lift thicknesses, density readings, and elevations. The follow-on Trades would only describe the subgrade as having the wrong layout and needing rework without clearly articulating their specific needs.

Another example of some of the challenges we faced was that the soil bearing capacity necessitated using medium-dense material, requiring over-excavation to a minimum depth of two (2) feet. Despite this requirement being clearly outlined, it was met with resistance, as the Trades failed to review the specification initially due to their bias, resulting in delays to their work schedule.

Using the graphic in Figure 5, the project team applied BBQS principles to enhance subgrade acceptance by fostering collaboration and accountability among trades. the system changed somewhat subjective quality assessments into a shared, objective understanding by emphasizing observable behaviors and measurable outcomes. This approach encouraged each trade to take ownership of their work's quality and its impact on others. Through discussions, trades aligned on acceptance criteria, and the earthwork contractor adjusted to follow-on trade requirements. Ultimately, BBQS promoted transparency and cultural change within the project team.

This integrated and collaborative approach also stimulated a culture of learning and ongoing improvement. The daily huddles provided open discussion, issue solving, and shared decision-making. This allowed team members to take ownership of the activity and make reliable pledges. The BBQS, with its emphasis on feedback and data analysis, provided significant insights into the value of these strategies and helped to fine-tune the subgrade acceptance process over time. The WhatsApp chat can give a written record of previous incidents, which could be reviewed for training purposes. Using these touchpoints to educate, refocus, realign, and demonstrate what good looks like concerning their peers in the program has effectively taught an old dog new tricks.

CONCLUSION

This case study documents the iterative process of developing a Production System aligned with the Owner's vision of "Speed to market without compromising safety and quality." The system was built on decades of earthwork experience, emphasizing behavior-driven improvements through BBQS to integrate LBMS within the project team. TP was applied to simplify the earthwork scope, enabling discussions for system improvements. The collaborative Production System Design improved soil dependability–which reduced project risks, and enhanced communication, resulting in a faster, higher-quality data center that met the Owner's goals. Additionally, this system positioned the GC to manage future projects with this Owner efficiently, providing actionable feedback to refine program standards.

Key lessons included effective communication with on-site team members, reviewing project requirements as if they were new, understanding the rationale behind task execution, and consistently reinforcing these concepts for both new and experienced team members. Direct involvement in building the Production System Design fostered a sense of ownership, significant positive outcome. This shared learning experience helped break down common industry behavioral barriers.

Future research could quantify the benefits of this Production System Design and explore its application in other megaproject scopes. A comparative study of this project against a similar one could provide insights into cost and schedule savings. While the authors acknowledge that this approach may be overwhelming for smaller projects or impractical in different process structures, many lessons can be adapted to smaller-scale efforts. The broader implication of this case study is the integration of siloed Lean concepts into a cohesive, true Lean vision.

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