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Physical Modelling in Geotechnics

Considerations for a centrifuge facility retrofit

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ABSTRACT: In 2017, facing a major renovation, the Centrifuge Research Complex housed at the US Army Corps' Engineer Research and Development Center (ERDC) in Vicksburg Mississippi (formerly the Waterways Experiment Station), reevaluated their commitment to physical scaled modeling and the investment needed to bring its facility and capabilities, most dating from late 1995, to modern standards and beyond. The diverse and ever-changing research goals at the ERDC required an agile approach to the technology which would be employed. Further, the business model was revised to meet a wider range of scalable research problems and their customers. Planning a retrofit of this nature required merging the original intent of the facility with the current best practices of similar facilities across the globe and the research interests of the US Army Corps of Engineers. The key thought processes going into the renovation and corresponding physical components on the centrifuge are explained while the avenues for future collaborations are outlined.

Keywords: Centrifuge modelling, Retrofit, Waterways Experiment Station (WES), ERDC, US Army

1 INTRODUCTION

The United States Army Corps of Engineers (USACE) Centrifuge Research Complex (CRC) features a 1,200 g-ton, 6.5m radius, large beam centrifuge with an adjustable counterweight, aerodynamic shroud, and 100 kg auto-counterbalance for fine adjustments and in-flight payload changes. At the time of commissioning in 1995, original designers (Ledbetter, 1991) had a vision to advance the use of physical modelling techniques beyond geotechnical engineering which aligned with the diverse mission set of the Waterways Experiment Station (WES). In 1998, all USACE laboratories in Mississippi, Illinois, New Hampshire, and Virginia were combined to form the Engineer Research and Development Center (ERDC), an organization which would be able to utilize the centrifuge to tackle unique mission sets that corresponded to the objectives of the seven labs. Currently, the ERDC is pursuing five main research and development areas which include (1) military engineering, (2) civil works, (3) engineered resilient systems, (4) installations and operational environments, and (5) geospatial engineering.

In 2017, following a failure of the motor control units and the retirement of existing personnel, the centrifuge sat dormant for 32 months before ERDC leadership reinvested in the CRC's full operation. The scope and scale of the planned renovation embraced the original design intent because fundamentally the centrifuge and associated facilities would not change. A renovation this comprehensive is rare, typically a new centrifuge/facility happen once a decade and upgrades follow as needed or affordable. There was limited reference material available which spoke to the planning required for a full mechanical, electrical, and electronic overhaul of a centrifuge of this size. This paper endeavours to provide a resource to other large facilities if/when they attempt similar projects.

Fig 1. 1,200 g-ton, 6.5m radius centrifuge at ERDC after renovations. Aerodynamic shrouds not pictured.

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2 RETROFIT CONSIDERATIONS AND IMPLEMENTED SOLUTIONS

Over ten years was originally spent planning and constructing the CRC. The latest renovation lasted 2.5 years and started in 2019. The breakdown of the funding for the project can be seen in Figure 2.

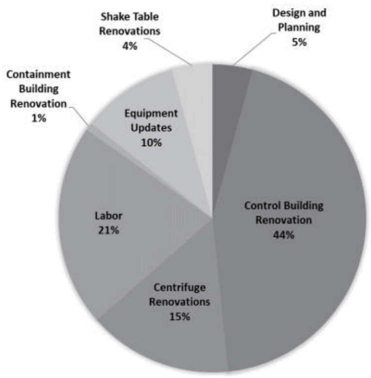

Fig. 2. Funding distribution for the renovation of the CRC at ERDC.

The considerations made by Ledbetter et al (1994) provided a starting point for the planning, but the expansion of capability seen in centrifuge physical modelling over the last 30 years drove a need for substantial updating and modernization. To start, several best practices were identified from facilities world-wide and paired with the 2020-2030 research strategy of the ERDC (Pittman et al, 2021). Following this, key design criteria was identified, and decisions were made by combining previous specifications outlined in the literature with previous personal experience. The remainder of this paper discusses the key decisions that were made and the corresponding thought processes.

2.1 Large loads

Trends towards physical modelling of larger prototypes (Iai et al, 2005, Kim et al, 2013) and more complex phenomena (Madabhushi et al, 2012) have pushed the boundaries of what is physically possible. In the beginning, interest in research applications across WES

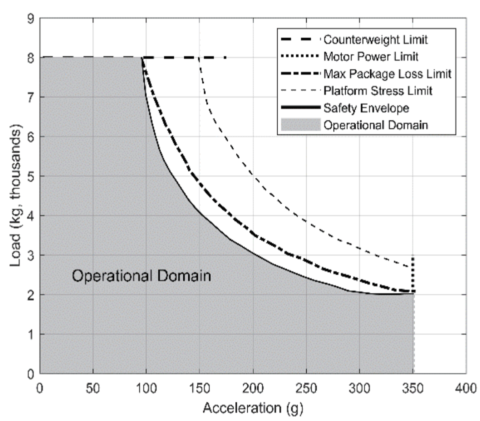

Fig. 3. Current performance envelope of the ERDC's centrifuge.

drove the desire for larger payloads (1.3m x 1.3m x 2m - max 8,000 kgs) and higher accelerations (10 to 350g's). In view of the success of, and increased demand for, larger models, performance requirements remained unchanged for the ERDC centrifuge. The current operational domain and the original limit states are shown in Figure 3.

2.2 Flexibility

System flexibility in terms of instrumentation, power, data acquisition and communication are widely desired features of centrifuge facilities (Kim et al., 2013, Boulanger et al., 2020).

Novel instrumentation techniques, Fiber Bragg for displacement monitoring, fiber enabled high-speed cameras, and fiber capable computers to name a few, are being implemented in centrifuges across the world (Elgamal et al, 2010). Owing to renewed interest in dynamics for applications such as earthquakes, as well as military applications, high frequency strain sensing is advantageous. In preparation for implementation of fiber optic strain sensing in both structural and geotechnical applications, the CRC's fiber optic rotary joint (FORJ) was expanded to 7 channels. Fiber optic cable and network switches connect the centrifuge directly to both the on-board equipment and the control room eliminating the need for individual fiber media convertors and limiting the need for more traditional Ethernet switches. These changes were implemented to reduce data loss between the centrifuge and control room which are separated by approximately 100 meters. As part of the initial system performance evaluation after the facility reopened, the power loss (dB) of the fiber was monitored with centrifugal acceleration (g level) and it was found that the loss did not change as a function of g-level and only slightly (~2dB) as a function of distance. Through this implementation of fiber, the CRC has the capability to transfer data at a rate of 40GB per second, meeting the data acquisitions needs for today and the future.

Flexibility, in the context of data acquisition (DAQ), was another key need identified at the CRC. To obtain this flexibility, two Hi-Techniques™ Synergy CS DAQs were installed, each consisting of 16 modules, 14 of which were 2 MS/s Universal modules and 2 of which were 100 kS/s high density modules, allowing for sampling rates fast enough for static and dynamic testing. When combining the capabilities of both DAQs, there are 176 total possible channels for accelerometers, displacement lasers, linear variable differential transducers (LVDTs), pore pressure transducers (PPTs) and other possible instrumentation. The DAQs are housed in the on-board central services cabinet. The high-density instrumentation wire connects these to custom made junction boxes. The junction boxes and instrumentation connectors are standardized so that any

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instrument can be plugged into any junction box which can in turn, be placed in any location on the platform.

Finally, a simple and modular power system was designed to support instrumentation requiring >10 VDC, lights, cameras, motors, pumps, and other assorted equipment. Remotely controlled 120 VAC power distribution units provide main power. Four DC power supplies in common voltages (5V, 12V, 15V, and 24V) were also added. Universal power supplies were added to protect the DAQ and network components in case of a power failure during spinning. Beyond this, any unique electrical power need can be supplied through fittings on either side of the power slip ring. Similar to the instrumentation system, custom designed power boxes can be universally used, moved, or removed depending on the needs and configuration of the model.

2.3 Safety & reliability

Early centrifuge papers from Schofield (1980) and Craig & Rowe (1981) laid the basic groundwork for the comprehensive safety guidelines most geotechnical centrifuges follow. The common hazards present in a physical modelling facility can generally be controlled through a combination of engineering and administrative controls.

Engineering controls, such as pre-determined safety factors, are applied to the structural components. In 1989 a generous safety factor of 2.7 to the elastic limit was used to design the main centrifuge structure and facility; this was continued in the development and addition of new components. For instance, over time on many centrifuges, individual instrumentation wires accumulate between the platform and the central arm services as sensors and capabilities are added. The combined weight, as well as the complication to the on-board instrumentation system is increased. During the CRC retrofit, current and anticipated growth was accounted for from the start by designing multi-strand wires coupled with large capacity mil-spec connectors. Each of these high density cables supports 48 distinct power and signal connections. To ensure the cables would withstand g-loading, strain relief in the form of aircraft wire, was designed using the 2.7 safety factor which was weaved into each cable.

The other element of a facility wide safety program is ensuring adequate administrative controls exist to reduce instances of human error. For example, adopting routine procedures and comprehensive safety check lists during all stages of operation. ERDC is committed to ensuring that an experienced centrifuge modeler and technician is part of the facility team. Doing so will reduce common errors due to inexperience, mitigate potential safety concerns, and protect the USACE investment.

2.4 Productivity

Centrifuge models are an alternative to costly field tests. Productivity is generally a major consideration in the design and layout of their facilities, ensuring efficiency and self-sufficiency. The original designers of the CRC addressed this through the creation of a large, accessible loading area, convenient on-board access to models and transducers, easy access to electrical, fiber optic, and fluid connections for repairs and inspection, and control systems which featured automatic, programmable operation, in-flight balancing, and controlled shut down.

Facility contributions to productivity need to align with appropriate staffing levels and be flexible enough to adapt to research needs and funding. For the CRC, this means a full-time researcher and two technicians solely dedicated to overseeing operation, maintenance, and safety of the centrifuge and research activities being performed. It is the goal of the facility that any given customer can bring a problem set from which a model can be designed to meet the client's needs without being a specialist in centrifuge technology. As work and future collaborations increase, additional researcher/technician teams will be added in rotation to support the workload.

2.5 Other Considerations

2.5.1 Standardized mechanical and electrical parts

The majority of the original machine was manufactured in France and the United Kingdom which meant the mechanical and electrical components of the centrifuge were manufactured using European standard parts. This ended up being very costly for the US centrifuge when repairs needed to be made. To avoid this in the future, the CRC converted as many of these components to US standard parts as possible and would recommend future facilities ensure manufacturer components for the centrifuge agree with geographical availability.

2.5.2 Economical to operate

The ERDC centrifuge was optimized for aerodynamic efficiency and cooling (machine and building) during the original construction, a strategy that was proven to be effective and therefore this aspect of the original design was not altered. However, if building a new facility, any power drained from the centrifuge, for example when the centrifuge is braking, should be recirculated into the power supply instead of being drained into resistors, something the researchers at the CRC would have implemented if it had been financially feasible.

3 COLLABORATION AND FUTURE WORK

3.1 Avenues for collaboration

The CRC is looking forward to rekindling old partnerships while also developing new ones. The ERDC's annual research portfolio consists of a diverse mixture of military and civil works challenges, as well as support for other research partners and customers.

Figure 4 outlines partnership processes between potential collaborators and the Centrifuge Research

Complex. In this context, collaborators can be both domestic and international student researchers, faculty, academic institutions, and industry companies. There are several collaboration mechanisms between ERDC and collaborators which can broadly be broken down into three categories 1) collaborations in kind where intellectual property may be exchanged (and protected for all parties) without the exchange of money, 2) ERDC paying for work to be executed either at the CRC or another facility, and 3) ERDC being paid for the design and execution of work in exchange for client ownership of the resulting data.

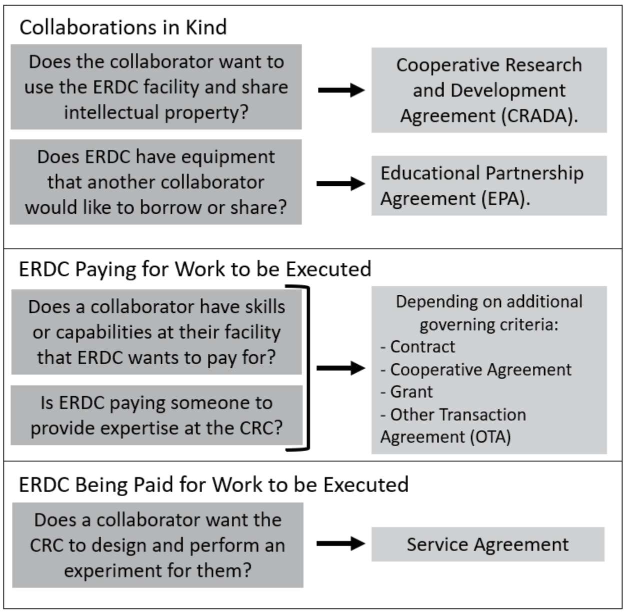

Fig. 4. Avenues for collaboration with domestic and international partners.

3.2 Future Work

Now that the centrifuge retrofit and renovation is complete and the centrifuge is fully operational, in the immediate future, researchers at the CRC are developing a proof-of-concept model to conduct levee overtopping research in partnership with the Department of Homeland Security (DHS). This work will require fluid circulation in flight to properly model controlled and repeatable flood conditions.

Looking further into the future, the CRC plans to develop partnerships to create a robust network which can utilize the physical modelling capabilities of the ERDC centrifuge while also collaborating with other domestic and international researchers, in both academia and industry, to solve important and complex problems.

4 CONCLUSIONS

Physical modelling, especially in the context of centrifuge research, facilitates knowledge development of complex phenomenon across engineering disciplines. Centrifuge modelling is an essential research tool best used when (1) calculation methods are inadequate, (2) to validate numerical methods for prototype behaviour, (3) for parameter studies which allow a fixed variable to be changed in a controlled environment and (4) to study failure mechanisms which would be impractical or not feasible in prototype situations.

This paper reports on the key thought processes and corresponding decisions that occurred during the ERDC centrifuge retrofit in an attempt to aid other researchers performing similar retrofits to their facilities in the future. The paper also touches on the original vision of the centrifuge from the US Army Corps of Engineers when it was first commissioned and how the facility was modified for the future of the Centrifuge Research Complex (CRC) at the Engineering Research and Development Center (ERDC). The key components that were implemented to anticipate future needs, such as the implementation of fiber and the ability for system flexibility, are discussed. Finally, the business approach and avenues for future collaboration are outlined.

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