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Research Article

An apparatus and procedure for 1-g modeling of press-in assembled open caisson shaft construction in soft urban underground spaces

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Abstract

As metropolises expand, to accommodate infrastructure such as transport systems, ventilation networks, and utilities, underground spaces must be developed. In congested metropolitan cities characterized by soft ground conditions, press-in methods for open caisson shafts have emerged as a preferred construction technique. However, the geotechnical response of surrounding soils especially in heterogeneous grounds remains complex and insufficiently understood during press-in assembled open caisson construction. This paper presents a 1-g modelling apparatus and procedure for simulating press-in assembled open caisson construction. The system replicates vertical sinking and staged excavation processes while allowing detailed observation of soil displacement and settlement. Transparent soil was prepared to replicate silty clay and clay region from silica-based mixtures with matched refractive indices. Soil displacement fields in real time were captured using combined laser assisted imaging with Digital Image Correlation (DIC) system. Results reveal typical behavior in silty clay with deformations localized near the cutting edge and remained comparatively restricted with penetration, indicating partial drainage and a stiffer response. However, clay revealed wider propagation zones and larger displacement magnitudes at deeper penetration, consistent with plastic flow and undrained softening. This apparatus effectively investigated soil-structure interaction during caisson installation, showing the substantial influence of soil strata and penetration depth on ground movements. For future studies it offers a platform for improving predictive modeling, geotechnical design, and risk mitigation in urban underground construction.

Keywords: assembled open caissons; press in technique; 1-g physical modeling; urban underground structures

1. Introduction

Rapid urbanization has led to increasing demands on underground space. Infrastructure such as metro lines, sewers, and utilities often requires vertical access through shafts. The Open caisson technique has evolved over the past 170 years and continuous to play a significant role in modern urban construction. In soft-ground urban environments, open caisson shafts are widely used due to their compact footprint and constructability in constrained settings. These shafts are constructed by sinking prefabricated or cast-in-place segments through excavation and press-in techniques. The principle of pressure sinking is, press first and then take out the soil. The jack begins to slowly apply pressure to the caisson, as shown in Figure 1. According to Allenby et al. (2009) [1], caisson-sinking allows the shaft construction to be gradually sunk from the surface level by self-weight or with the help of jacks. To assist this driving process in this method a cutting edge is attached to the first caisson ring. Wang et al.(2025)[2]conducted systematic evaluation of conventional and mechanized shaft technologies, including open caissons, drilled shafts, and the emerging pressed-in ultra-deep assembled shafts (PIAUS). Regardless of the technique used, excavation induced displacement prediction during open caisson shaft construction is significant design issue in urban areas, that could potentially damage to existing structures. However, soil composition, the choice of construction method, and excavation geometry influenced the ground movements and settlements associated with open caisson shafts [3, 4]. Present geotechnical engineering practice strives to minimize these movements; however, precise assessment remains crucial for the successful completion of many projects. Faustin (2017)[5] observed that the amount and distribution of ground deformations were greatly impacted by the shaft construction method, which can be categorized into two main types: pre-installed shaft lining and concurrent shaft lining.

The interaction between the caisson structure and the surrounding soft soils is complex, often resulting in ground movements that could affect adjacent infrastructure. While numerical models provide insights, physical models, especially 1-g tests, remain essential to capture the behavior under controlled and observable conditions. This study develops a novel 1-g test system to simulate press-in caisson shaft construction in soft clays. For design purposes, shallow excavations like basements can be simplified to plane strain conditions. However, due to the circumferential or hoop forces in the retaining structure, axisymmetric and non-axisymmetric deep excavations vary significantly. The ground response to these various types of construction will differ, and these variables should be included in the design or settlement estimates [6]. However, approaches based on basement excavation are frequently used for deep shaft construction.

The goal of this study is to design apparatus to replicate the staged press-in sinking and excavation process of open caisson shafts. Additionally, the study aims to measure soil displacements during construction and validate the effectiveness of this apparatus in assessing the impact of caisson construction in soft urban settings.

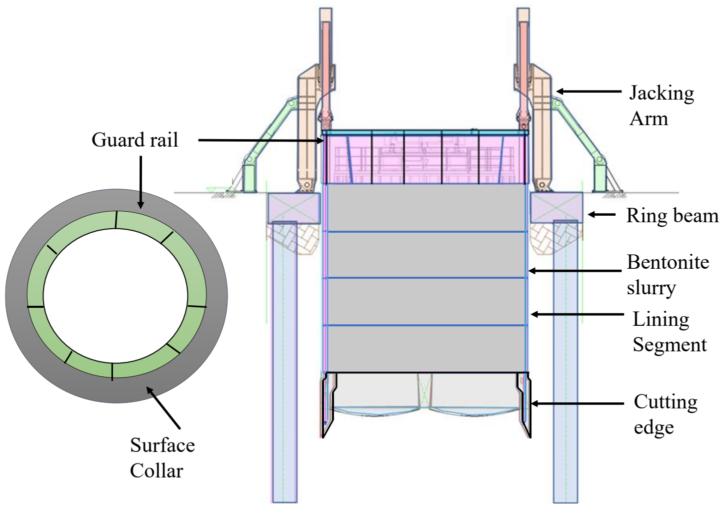

Figure 1. Schematic of Press in open caisson sinking construction.

2. Review of ground movement prediction methods for open caisson shaft construction

In literature, the complexity and variability of soil behavior during construction is highlighted in ground movements resulting from open caisson shafts in soft ground. Open caisson shaft construction, often employed in urban environments for infrastructure projects, can induce significant ground displacements, posing risks to nearby structures. Understanding the causes underlying soil deformation, the efficacy of construction methods, and the creation of prediction models to reduce these risks are the main objectives of the research. To best of our knowledge, the only well-documented case study to date is the construction of a 26 m deep shaft in London clay [7]. Recent field monitoring studies [6, 8] have primarily examined alternative construction methods, such as diaphragm walls, and have focused exclusively on surface settlements. Although centrifuge modelling studies [9] have advanced understanding of soil settlement mechanisms, no experimental data currently exist on the settlements induced by open caisson sinking in sand. The most widely used empirical method for predicting soil settlement due to open caisson construction is the parabolic relationship proposed by New and Bowers (1994). However, this approach has two key limitations: (a) it neglects the influence of shaft diameter (D) on settlements, and (b) it is specific to clayey soils. Schwamb (2014) [6] reported that conventional design methods considerably over-predicted field measurements in construction of two urban open caisson case studies. Mitigating these uncertainties and overly conservative predictions is essential for optimizing design efficiency and minimizing dependence on costly protective measures in engineering practice. Therefore, this study aims to develop 1-g model apparatus designed to quantify and validate the subsurface displacements induced by press in open caisson shaft excavations in heterogeneous grounds.

3. Physical model testing

3.1. Previous physical model testing

Numerical modeling and back analysis with well-defined and controlled boundary conditions can be made possible by physical modeling under 1-g, which can provide a reliable data source. Under normal gravity conditions, Tobar and Meguid (2009) [10] performed several tests to study variations in lateral earth pressure induced by the radial displacement of shaft linings. Their developed apparatus allowed for the modeling of the full shaft geometry and the lining's radial displacement. Song and Sheil (2023) [11] investigated soil deformation mechanisms during caisson construction in dry sand, identifying that the main mechanisms causing ground movements was a compressive bearing front below the cutting face and a frictional contribution above the cutting face. Chavda and Dodagoudar (2022) [12] conducted a series of 1-g model studies to analyze the load–penetration behavior and the soil flow behavior around the cutting edge of a circular open caisson in sand. By considering both full and half open caissons with varying cutting edge tapered angles and employing image-based deformation measurement techniques, they evaluated that both blade foot depth and slope angle substantially influence the resistance and the flow behavior of the soil adjacent to the blade foot. However, their research was constrained to 1-g model conditions, which may not fully replicate the field complexities and focused on sandy soils, leaving the response in other soil types unexplored.

Based on the aforementioned studies, an apparatus has been developed for 1-g modelling caisson-sinking induced settlements in multi layered grounds. The model test apparatus developed has been divided into two main systems (i) segments sinking system and (ii) soil excavation system.

3.2. Model test apparatus

The schematic sketch of the physical model test is shown in Figure 2. The adopted scaling factor for the model and prototype is 1:100. The model shaft diameter is 80 mm with segments height 20mm each with 3.5 mm thickness are used such that deformation of the caisson segments itself are negligible. The model test system is self-designed specifically for this experiment and comprises of a model tank, caisson model, hydraulic jack a computer, a CCD high speed camera, an optical laser and program for Digital Imagine Correlation (DIC). Model box dimensions are 1 m × 1 m × 1 m (length × width × height). The front, rear, left and right windows are made of 15mm thick transparent plexiglass viewing panels on two adjacent faces: one facilitates the transmission of the laser light sheet through the soil model while other enables visualization of soil movements along the plane of interest. In order to ensure that the sidewall's lateral displacement could not exceed 0.1%, transparent windows were designed to be 15 mm thick [13].

The test area measures 0.5 m × 0.5 m × 0.5 m (length × width × height), filled by transparent soil, as shown in Figure 2. The base is made of 15mm thick steel plates. Parts are connected and reinforced with steel frames. Drainage holes were left at the bottom of the model container to allow the dissipation of excess water pore pressure, which can have a significant impact on the long-term behavior of open caisson.

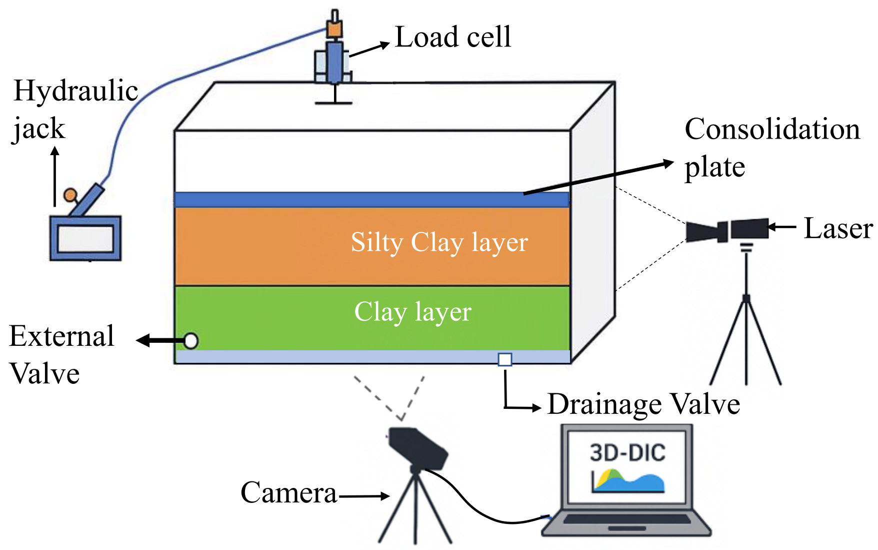

Figure 2. The schematic sketch of the 1-g physical model.

3.3. Transparent soil preparation

In this study amorphous silica powder having size ranging from 1.6-2μm and 80:20 concentration by weight and silica gel having size 0.075-0.15 mm was used to replicate clay and silt respectively. Material used in model test and its preparation procedure is illustrated in Figure 3. The mixture was prepared with oil and soil in a weight ratio of 12.5:1 for preparation of clay layer whereas for silty clay layer, mixture was prepared with amorphous silica powder, silica gel, and oil in a weight ratio of 4:1:50. 1:1 blend of mineral oil and n-dodecane is used to prepare transparent soil mass having same refractive index of 1.447 at 24℃.

Figure 3. Illustration of material used in model experiment and its preparation.

For the sample preparation, firstly an amorphous silica powder slurry was made by mixing with pore fluid and a separated specimen was made of silica gel and amorphous silica powder. Secondly, a vacuum was applied to de-air both specimens until they turned transparent. Third, silica slurry was poured into the Plexiglas mold and consolidated by draining fluid to achieve desired density. Forth, de-aired silica gel and amorphous silica powder was poured on top of amorphous silica powder sample after its consolidation. Polyamide Resion Particle (PSP) tracer particles were mixed with soil in pre-determined amount to generate speckle pattern necessary for geoPIV/DIC [14] to be able to monitor the subsurface displacements as shown in Figure 4.

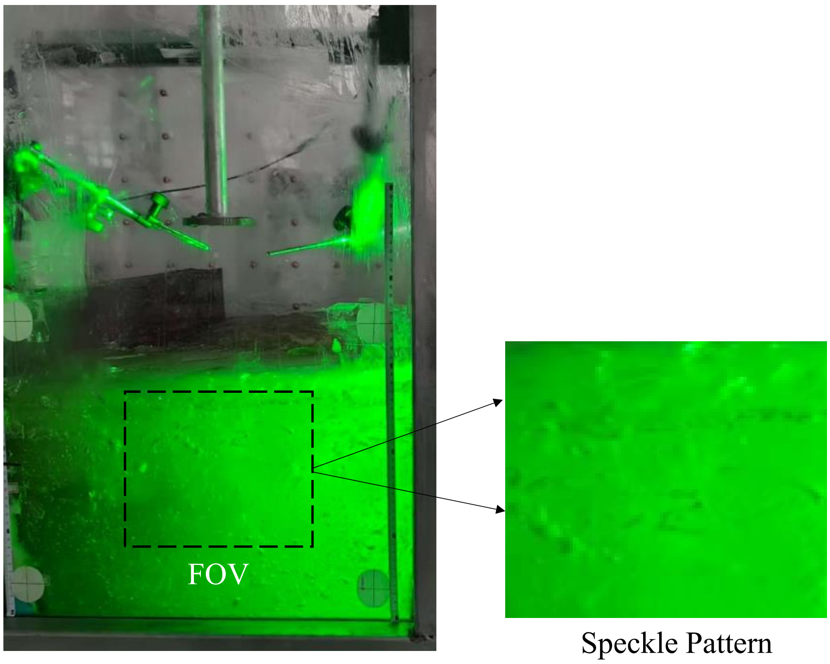

Figure 4. Speckle pattern generated by using laser.

3.4. Testing Procedure

The testing procedure involved simulating caisson construction in two repeating stages: (a) model caisson sinking and (b) internal soil excavation. The sinking of the open caisson is done by using hydraulic jack and load is measured from load cell and deflection in caisson is measured by using LVDT. Caisson sinking and internal soil excavation process is performed simultaneously by the jacking pressure and by using the manual method (using spoon) and each segment of 20mm are inserted. The penetration interval was selected based on scaling field measurements [15]. To Ensure consistency and repeatability in soil removal, the rate and depth of excavation was controlled (4mm per time up to 20 mm depth in 5 times) according to the prototype as 40cm per time up to 2 meters depth in 5 times. A total of 7 segments are inserted by this repetitive process, while continuously capturing images of the transparent soil surface using the DIC camera system. These stages were repeated until the sinking depth, H, reached a maximum value of one caisson diameter, i.e., $Hmax/D$ = 1.45.

4. Results and Discussions

4.1. Displacement fields in multi layered soft grounds at different caisson penetration depths

Soil displacement during caisson sinking in multi layered soft grounds is examined by using DIC method. Color-filled maps illustrated the displacement magnitude and deformation patterns are shown as contour plots. This combined approach offers clearer insight into how soil response changes with increasing penetration depth.

4.1.1. Displacement fields in silty clay region

Results of soil deformation during caisson movement in the silty clay region at different penetration depths of 5 mm and 80 mm are shown in Figure 5(a) and (b). These figures illustrate the magnitude of soil displacement around the caisson cutting edge. Soil deformation is highly localized at the initial penetration stage, exhibiting symmetric bulb of vertical displacement just beneath the cutting edge. Small displacement magnitude concentrated around the caisson edge, and almost undeformed surrounding soil, indicating primarily elastic response and a highly localized influence zone. Contours show that deformation remain confined with limited influence on the surrounding soil mass

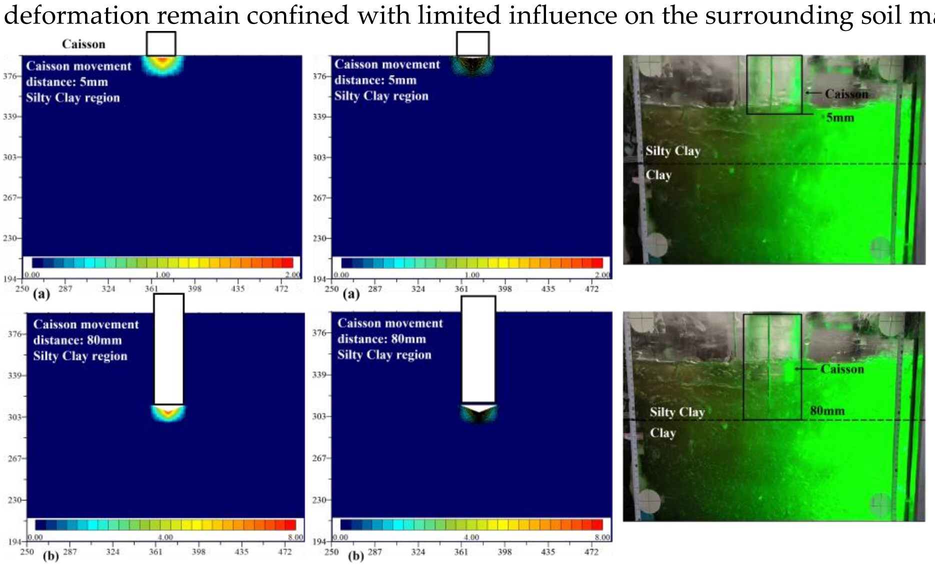

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Figure 5. DIC results of soil displacement in the silty clay region during caisson penetration at depths of (a)5 mm and (b) 80 mm with corresponding transparent soil images.

The displacement magnitude increases significantly at a deeper penetration stage. Stronger soil mobilization beneath the cutting edge demonstrated the downward and slight lateral expansion of deformation zone. The contour plots show that deformation field broadens and more defined as the caisson advances, representing progressive stress redistribution. The findings show that deformation during caisson sinking in silty clay soils, progresses from a confined zone at penetration of 5 mm to a wider, more significant displacement field at larger depth of 80 mm. The color maps and contour plots show magnitude changes, deformation patterns and extents of soil movements are at the caisson base. These results highlight that as caisson depth increases, soil resistance progressive mobilized resulting in development of settlement.

From DIC results, higher stiffness or faster pore pressure dissipation in the silty clay region are more evident. These characteristics are driven by lower plasticity index, partial saturation, or better drainage, which effectively limit pore pressure buildup and the development of plastic strains, resulting in localized displacement zones. This resulting behavior suggests that material behaves with an elasto-plastic response with progressive loading.

4.1.2. Displacement fields in clay region

As caisson penetrates in the clay layer region, resulting soil displacements evolve from localized deformation under the cutting edge to more intense and widespread deformation as shown in Figures 6 (c) and (d). This behavior aligns with the expected soil–structure interaction mechanisms during caisson sinking.

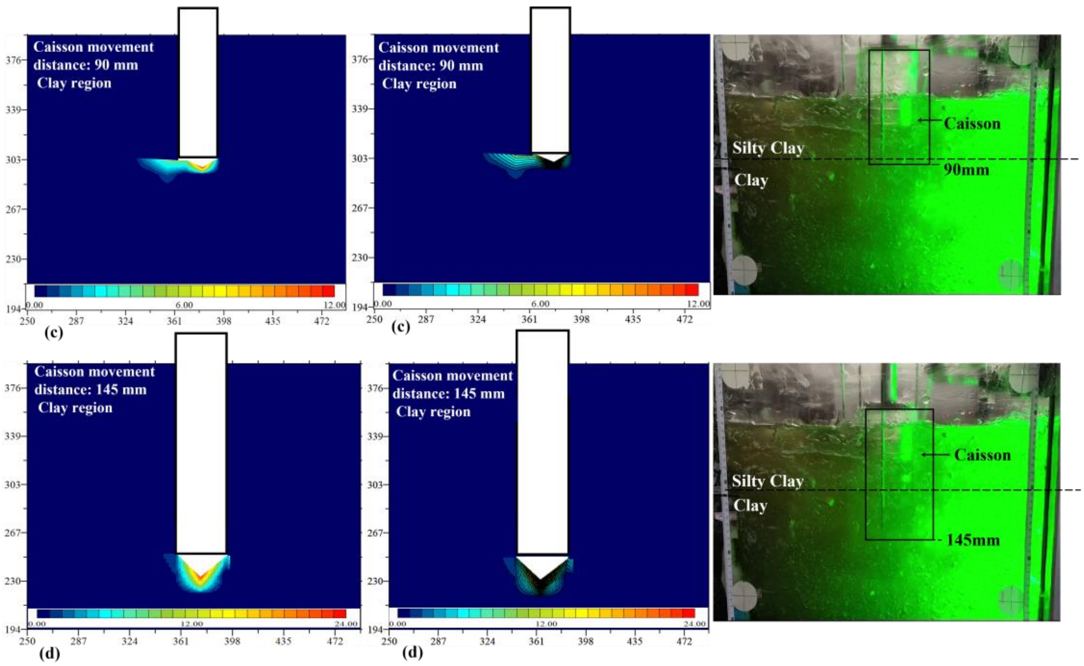

Figure 6. DIC results of soil displacement in the clay region during caisson penetration at depths of (c) 90 mm and (d) 145 mm with corresponding transparent soil images. deformation under the cutting edge that intensifies and spreads with depth

Figure 6 shows that as the penetration depth increases the clay region experiences noticeably more deformation in terms of both magnitude and spatial extent. At a penetration of 90 mm (Figure 6c), displacement propagates noticeably in both vertical and horizontal directions whereas the deformation zone expands considerably, reaching deeper into the subgrade and displaying higher displacement magnitudes at penetration depth of 145 mm (Figure 6d). This behavior is typical of high-plasticity clays under undrained conditions, where pore pressure buildup reduces effective and triggers strain softening behavior. Ultimately, the result shows the soil transitioning from an initial elastic response to a fully plastic flow, a phenomenon aligns with the critical state soil mechanics, and undrained shear strength theory where soil resistance diminishes with continued strain [16].

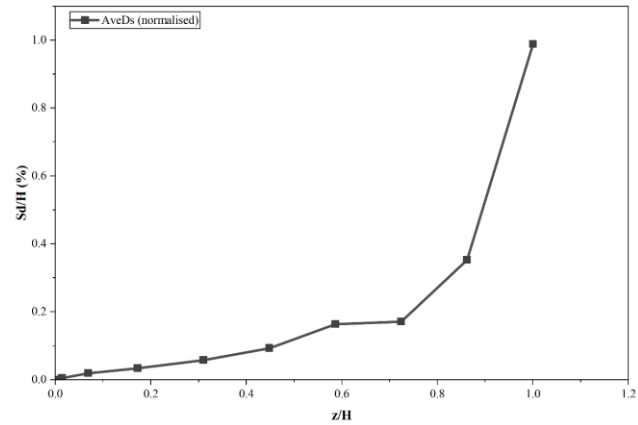

Figure 7. Normalized average displacement magnitude for the caisson in multilayered soils.

The evolution of the normalized average displacement magnitude (Sd/H) with normalized penetration depth (z/H) for the caisson in the layered silty clay and clay region is shown in Figure 7. In the overlying silty clay region at z/H<0.55, Sd/H remains very small (<0.1%), indicating limited global deformation of the soil mass and largely restricted to a limited area around the cutting edge. The average displacement increases significantly as penetration proceeds into the underlying clay region (z/H>0.55), with a substantial rise from roughly 0.35% to almost 1.0% between z/H≈0.85 and 1.0. These observations align well with the DIC displacement fields presented in Figures. 5 and 6, which depicts a change from a diffuse deformation bulb within the silty clay region to a more concentrated and intense plastic zone around the cutting edge upon entering the clay region. This transition underscores the dominant role of the deeper clay in dictating the final stage deformation response of the system.

5. Conclusions and future work

To replicate open caisson shaft construction in soft urban soils, a 1-g physical modeling apparatus has been developed. This system allows detailed observation of soil responses during press-in and excavation, replicating the ground movement patterns observed in real field conditions. Outcomes presented that at shallow depths silty clay soils exhibited localized deformations, while clay soils displayed deeper and widespread displacements, mainly in higher penetration depths. These findings highlight the strong influence of soil type and penetration depth on ground response and emphasize the need for accurate settlement prediction to safeguard nearby structures during urban construction.

To expands its geotechnical engineering applications future improvements to the apparatus may include pore pressure control, multi layered soil configurations, and studies on caisson–soil interaction. Also, research should focus on field validation, investigating other soil types and to compare model results with real-world caisson sinking data.

Furthermore, additional investigation could be carried out to explore different caisson configurations, including large-diameter and combined open caissons, using this developed 1-g apparatus.

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Conflicts of Interest: Authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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