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Centrifugal modelling of underwater stone descent and deposition

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ABSTRACT: Foundation mounds composed of crushed stone with particle diameters ranging from several tens of centimetres to approximately one metre are widely utilised as subaqueous structural bases in coastal infrastructure, including breakwaters, quay walls, and seawalls. In gravity-type configurations, these mounds are directly emplaced upon the seabed, serving as critical load-bearing foundations for the superstructure. Conventional construction practices typically involve the release of crushed stone from dredger or barge vessels, resulting in deposits formed without underwater compaction, primarily due to the prohibitive cost of such operations. Despite their widespread application, the mechanical stability and deformation characteristics of these mounds remain insufficiently elucidated, particularly in relation to deposition parameters such as initial relative density. The present study seeks to advance understanding of these aspects through underwater drop tests conducted within a centrifugal field, with the objective of evaluating the descent trajectories and resultant packing states of the deposited crushed stone. Prior to testing, similitude laws governing stone–fluid interactions were rigorously examined to ensure appropriate scaling of the experimental model. The findings reveal that the descent behaviour of crushed stone under terrestrial gravity ($1g$) or in air diverges significantly from that observed under centrifugal acceleration, with the latter condition yielding deposits of intermediate relative density.

1 INTRODUCTION

In coastal infrastructure such as breakwaters, quay walls, and seawalls, foundation mounds composed of crushed stone with particle sizes ranging from approximately 0.1 m to 1 m are routinely employed. In particular, Japanese breakwaters commonly adopt a composite configuration in which concrete caissons are placed atop crushed stone mounds directly deposited on the natural seabed. This structural typology, combining caisson and mound, has seen widespread implementation due to its adaptability and performance. Vertical breakwaters present numerous engineering challenges, including insufficient bearing capacity of the underlying ground, susceptibility to scour, and the necessity of employing massive caissons to ensure structural stability. In contrast, gently sloping breakwaters formed solely from crushed stone embankments are generally inadequate in resisting intense wave action, such as that generated by typhoons (e.g. Campos, 2020). As a result, composite breakwaters capable of withstanding significant water depths and offering enhanced wave resistance have become a prevalent solution.

The mound component of a composite breakwater plays a pivotal role in supporting the substantial loads imposed by the caisson. Its stabilising mechanisms include: (i) distributing structural loads uniformly to the seabed, (ii) dissipating wave-induced forces through internal friction between the mound and the foundation ground, and (iii) preventing scour beneath the structure caused by wave and tidal currents. Construction of the mound typically involves releasing crushed stone from the water surface using either a dredger or a barge, where dredgers are preferred for shallow waters and small-scale operations, and barges are employed for deeper waters and larger-scale deployments. Although compaction of crushed-stone ground below the water surface is not technically impossible, its cost-effectiveness is considered to be low. For this reason, the ground is generally used without underwater compaction.

Despite the critical role of these mounds, their mechanical stability and deformation behaviour remain poorly understood, particularly in relation to deposition conditions such as initial relatvie density. To date, limited research has addressed these aspects. While prior studies have examined the descent of granular materials like sand in air under centrifugal acceleration (e.g., Cabrera & Wu, 2017), and underwater drop tests of soil have been conducted (e.g., Miyake & Yanagihata, 1999), investigations specifically targeting the underwater deposition and packing characteristics of crushed stone are notably absent. Following the 2011 Great East Japan Earthquake, which resulted in extensive damage to composite embankments, recent engineering practices have incorporated reinforcement behind caissons using dropped crushed stone (Takahashi et al., 2021; Kurihara & Takahashi, 2023). The condition of this stone behind the caisson is now recognised as contributing to the overall stability of the composite structure.

Accordingly, the present study undertook underwater drop tests of crushed stone within a centrifugal field to evaluate the bulk density of the resulting deposits. Given the difficulty of satisfying similitude requirements for fluid viscosity in scaled model tests, the influence of viscosity was also examined. The large dimensions of crushed stone used in actual field applications render full-scale experimentation impractical, and even if feasible, accurate relative density measurement would pose considerable challenges. Moreover, conventional small model testing under terrestrial gravity fails to replicate the true dynamics of submerged descent, thereby limiting the reliability of density estimation. The reason for this will be discussed in the next chapter from the perspective of the similarity law presented therein. In light of these constraints, centrifuge model tests were employed to investigate the deposition behaviour under controlled and scalable conditions.

2 SIMILARITY LAW

A geotechnical centrifuge is an apparatus designed to replicate in-situ stress conditions within scaled physical models by subjecting them to centrifugal acceleration. Given that soil behaviour is inherently stress-dependent, the application of appropriate centrifugal forces enables the reproduction of mechanical responses analogous to those observed in full-scale structures. A $1/N$ scale model subjected to Ng acceleration can emulate the stress environment of the prototype, thereby facilitating realistic simulation of its behaviour. Centrifuge modelling has been extensively employed to investigate the stability of earth structures, consolidation settlement in cohesive soils, seismic ground response, and the dynamics of liquefied ground. Moreover, by achieving a velocity similarity ratio of unity under centrifugal acceleration, Froude's law is satisfied, thereby permitting hydrodynamic experiments. Recent advancements have extended the scope of centrifuge applications to fluid-related phenomena, including wind wave and tsunami simulations (e.g., Takahashi et al., 2022).

Table 1. Similarity ratios (model/prototype).

Physical value	$1g$-field	Ng -field
Length, height	$1/N$	$1/N$
Acceleration	1	N
Velocity	$1/N^{1/2}$	1
Time	$1/N^{1/2}$	$1/N$
Volume	$1/N^3$	$1/N^3$
Compaction energy	$1/N^4$	$1/N^3$

The present study involves underwater drop tests of crushed stone, and a configuration that, to the authors' knowledge, has not been previously explored. Accordingly, the formulation of appropriate similarity laws is imperative. The physical process under consideration is highly complex: multiple stones of varying shapes and sizes descend simultaneously, interact through collisions, and ultimately settle atop previously deposited material. In addition to stone–fluid interactions, the fluid medium itself exhibits vortex formation and bubble entrainment, rendering the phenomenon analytically intractable under current theoretical frameworks. Consequently, simplification is essential when establishing similarity criteria.

In this investigation, similarity laws were considered with particular emphasis on the energy imparted to the deposited ground, namely, the compaction energy resulting from free fall. As summarised in Table 1, the energy similarity ratio in Ng-field tests is $1/N^3$, which corresponds to the volume similarity ratio of the deposited ground, thereby indicating appropriate energy transfer. In contrast, $1g$-field tests fail to generate sufficient descent velocity, resulting in inadequate compaction energy and consequently loose stone placement. This underscores the efficacy of centrifugal modelling in simulating submerged stone deposition.

It is important to note that stones falling through water are subject to both viscous and inertial drag forces. Within a centrifugal field, the similarity law for inertial drag is inherently satisfied: the projected area and flow velocity scale as $1/N^2$ and 1, respectively, yielding an inertial drag similarity ratio of $1/N^2$, which matches the force similarity ratio. However, satisfying the similarity law for viscous drag necessitates the use of a fluid with viscosity reduced by a factor of $1/N$. This would yield a viscous drag similarity ratio of $1/N^2$. In practice, preparing such a low-viscosity fluid poses significant challenges. Therefore, in this study, instead of satisfying the viscous similarity law, an approach was adopted in which the viscosity was intentionally

Figure 1. Crushed stone used in model tests.

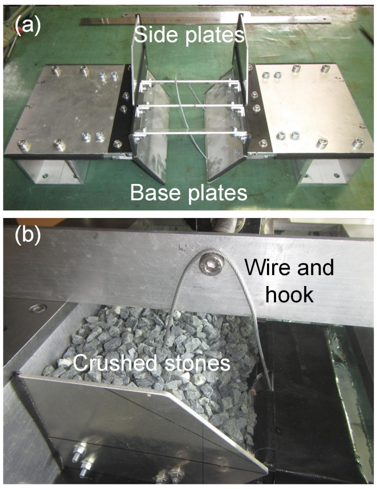
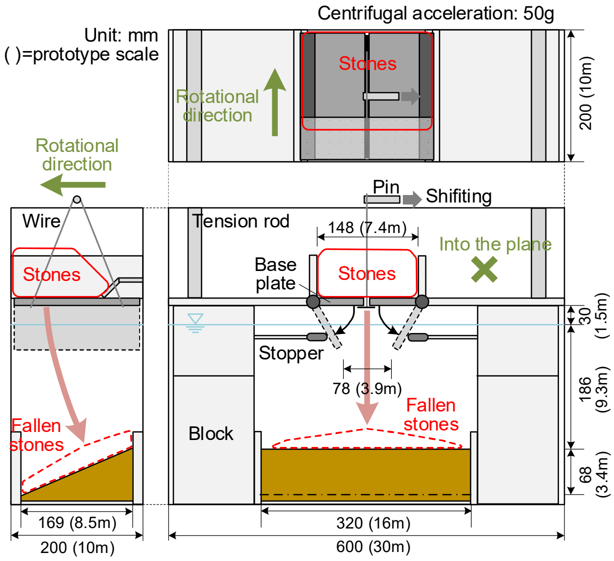
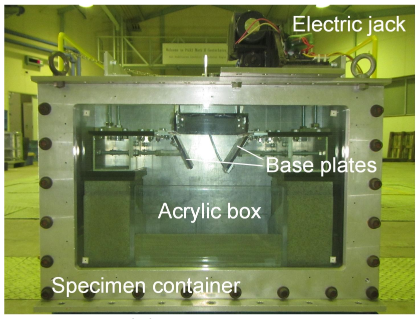


Figure 2. Stone-drop equipment.



(a) Model cross-section



(b) Model setup

Figure 3. Cross-section and setup photograph of model.

increased to examine its influence. If it is demonstrated that viscosity has no significant effect, it would suggest that the similarity requirement can be relaxed.

3 TEST CONDITIONS

With regard to crushed stone employed in foundation mounds at coastal construction sites, the Japanese Design Standards of Port and Harbour Facilities (MLIT et al., 2020) stipulate that 'stone materials used for foundation mound shall not be flat or elongated, but shall be hard, dense, durable, and resistant to weathering and freeze–thaw cycles.' In practice, hard rock conforming to Japanese Industrial Standards (JIS A5006-1995) is typically utilised. The unit weight of individual stones varies regionally, with the broadest specification range spanning from 5 to 500 kg per stone, while narrower specifications fall within the range of approximately 30 to 60 kg per stone. Based on these field conditions, the centrifuge model tests employed crushed stone with grain sizes ranging from 6.0 to 15.5 mm, averaging 10 mm in diameter and 1.385 g in mass, as shown in Figure 1. Under a centrifugal acceleration of 50g, these dimensions correspond to prototype-scale equivalents of approximately 0.5 m and 173 kg. Prior to testing, flat or elongated particles were excluded to conform with standard specifications. As shown in the figure, stones with intact corners were selected so that the dimensions in the three directions did not differ significantly. The maximum and minimum bulk densities are 1.67 Mg/m^3 and 1.44 Mg/m^3, respectively.

The crushed stones were placed within a container equipped with an openable base plate, as shown in Figure 2. During centrifuge operation, the base plate was opened to initiate stone descent. The plate consisted of two hinged sections at either end, forming a central gap through which the stones could fall. The opening width was 78 mm, corresponding to 3.9 m at the prototype scale. Reflecting field practices where stone is typically deposited in multiple stages, the model test replicated this by dividing the drop into two phases, each involving a 2 kg release of crushed stone. Although the centrifuge was temporarily halted between drops to reload the model, potentially introducing minor procedural effects, priority was placed on reproducing the multi-stage deposition process.

Figure 3 presents the model cross-section and the photograph of the complete setup. The stone drop equipment was mounted atop a rigid specimen container, within which an acrylic box was installed to

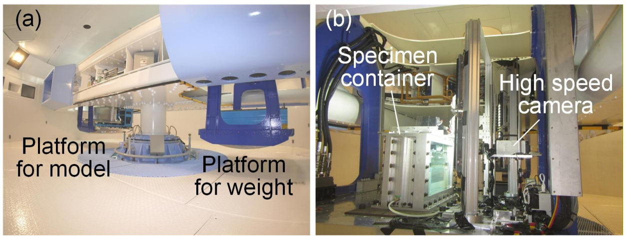


Figure 4. Centrifuge PARI Mark 2 and its platform.

Table 2. List of test cases.

Case	Content	g	Fluid
T-V01	Base case		Water
T-V0.6, 04, 10, 30, 50, 100	Viscosity	$50g$	Viscous fluid (0.6–100 times)
T-A	In air		Nil
T-G	$1g$-field	$1g$	Water

receive the falling material. A dense sandy soil layer, simulating the natural seabed, was prepared inside the acrylic box using Iide Silica Sand No. 7, achieving a relative density of 86–89%. It should be noted that in a centrifugal acceleration field the Coriolis force acts on the stone and alters its falling trajectory, preventing it from descending in a straight line. The effects of the Coriolis force on granular flows have been discussed using numerical analyses in studies such as Cabrera et al. (2019) and Leonardi et al. (2021). In this test, the crushed stone exhibited velocity components not only in the vertical direction but also toward the observation window. To ensure that the stones impacted the sandy soil surface perpendicularly, the seabed surface was inclined accordingly. Following two drop events, the density of the resulting crushed stone deposit was measured under terrestrial gravity, reflecting the post-unloading state. Although some reduction in relative density may occur upon unloading, the volumetric expansion of the crushed stone layer was considered negligible.

The centrifuge machine employed in this study was provided by the Port and Airport Research Institute. Figure 4 shows the overall configuration of the machine and platform. For detailed specifications, refer to Takahashi et al. (2019). The platform measured 1.7 m × 1.6 m and was capable of supporting a load of up to 2.7 tonnes. The specimen container and stone drop equipment were mounted on this platform, and all tests were conducted under a centrifugal acceleration of $50g$. Table 2 summarises the test cases, which included variations in fluid viscosity relative to the baseline case T-V01, as well as reference cases conducted without fluid and under standard gravitational conditions. The viscosity was increased by adding methyl cellulose to water. The case with 0.6 times the viscosity was conducted by increasing the water temperature.

Table 3. Descent velocity of crushed stone.

Case	Lowest point	Centre of mass
T-V0.6	3.5 m/s	2.2 m/s
T-V01	3.5 m/s	2.0 m/s
T-V04	3.2 m/s	2.2 m/s
T-V10	3.6 m/s	1.8 m/s
T-V30	3.4 m/s	2.0 m/s
T-V50	3.3 m/s	2.1 m/s
T-V100	3.3 m/s	2.0 m/s
T-A	11.7 m/s	11.9 m/s
T-G	0.5 m/s	0.3 m/s

4 TEST RESULTS AND DISCUSSIONS

4.1 Characteristics of stone descent in water

Figure 5 presents sequential high-speed camera images capturing the first and second stone-fall events in the baseline case T-V01. Owing to hydrodynamic resistance, the crushed stones did not descend in a purely vertical trajectory; rather, they dispersed laterally as a cohesive group. The initial fragment to contact the sandy ground surface became embedded, forming a nucleus upon which subsequent fragments accumulated. As deposition progressed, the fragments migrated downslope along the flanks of the growing pile, ultimately spreading toward the periphery. The final slope angle of the deposit was notably gentler than the natural angle of repose, suggesting that fluid-induced forces influenced the deposition morphology. This behaviour was similarly observed during the second stone-fall event. Notably, no discernible differences attributable to variations in fluid viscosity were evident from the visual records.

In contrast, case T-A, where the crushed stone fell through air, exhibited markedly different behaviour. The fragments maintained a concentrated trajectory, impacting the apex of the existing mound and rolling down its surface without significant lateral dispersion. The resulting slope was considerably steeper than that observed in the submerged case.

Particle image velocimetry (PIV) analysis of the first stone-fall sequence yielded the results summarised in Table 3. The table reports the velocities of the descending stone mass immediately prior to impact with the sandy ground, measured near the lowest point and near the centre of the mass. A deviation of 22° in the landing angle, induced by the Coriolis force, led to the measured velocity appearing up to 7% lower. In the base case T-V01, these

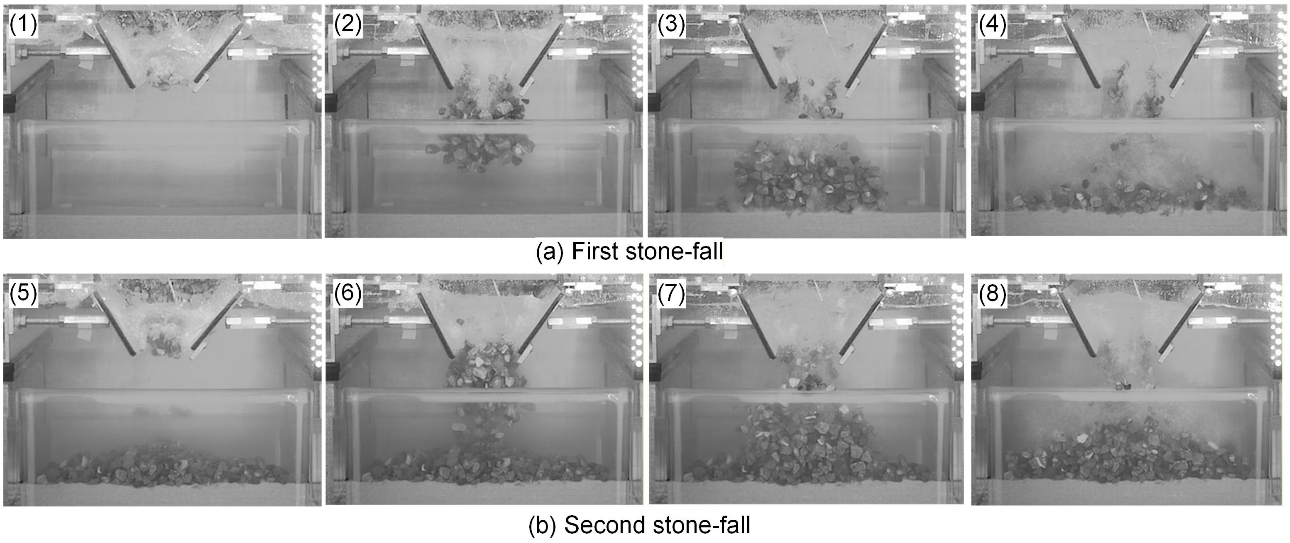


Figure 5. stone-fall behaviours (T-V01).

velocities were 3.5 m/s and 2.0 m/s, respectively. The higher velocity near the lowest point is attributed to inter-particle collisions and energy dissipation occurring more frequently near the centre of the falling mass. Across all cases involving variations in fluid viscosity, the measured velocities remained nearly identical, indicating that viscosity had negligible influence on the descent velocity. This suggests that even with fluids of lower viscosity than water, similar descent velocities would be expected. Conversely, in the airfall case T-A, velocities were substantially higher (11.7 m/s and 11.9 m/s) due to the absence of fluid drag. In the gravitational field underwater case T-G, velocities were significantly lower at 0.5 m/s and 0.3 m/s, respectively.

4.2 Characteristics of stone deposition

The relative density of the deposited crushed stone layer was evaluated following the stone-fall tests conducted under centrifugal acceleration. After returning the sample to a gravitational field and draining the water, the surface profiles of both the crushed stone deposit and the underlying sandy ground were measured using a laser displacement sensor. To avoid disturbing the sand surface, the crushed stone was carefully removed prior to measurement. The sensor was traversed along parallel lines spaced at 10 mm intervals to capture surface topography. An example of the measurement results for the base case T-V01 is shown in Figure 6. The volume of the deposited stone was calculated from the elevation differences, and the separately measured mass of the dropped stone was divided by this volume to obtain the bulk density. The relative density was then calculated and plotted in Figure 7.

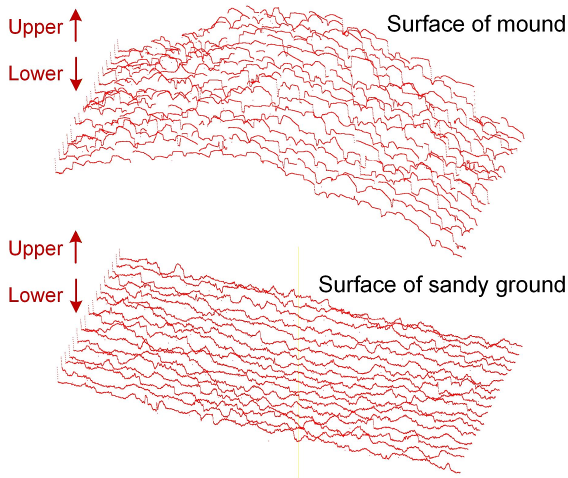


Figure 6. Measured ground surface heights (T-V01).

As shown in the figure, the relative density for the base case T-V01 was 52%. Increasing the fluid viscosity resulted in a marked reduction in relative density; in case T-V100, where viscosity was increased by a factor of 100, the relative density decreased to 13%, indicating a substantially looser packing state. Given that viscosity did not influence the descent velocity, it is inferred that viscosity affects the post-impact settling behaviour, specifically, the ability of particles to rearrange and interlock upon deposition. Within the tested viscosity range, the relative density did not converge to a constant value, precluding extrapolation to viscosities lower than that of water.

In separate free-fall tests, one conducted in a gravitational field with a 0.2 m drop height, and another in a centrifugal field (case T-A), the relative density was consistently 53%. These results suggest that achieving higher relative densities would require active compaction methods such as vibration. It may therefore be concluded that a relative density in the

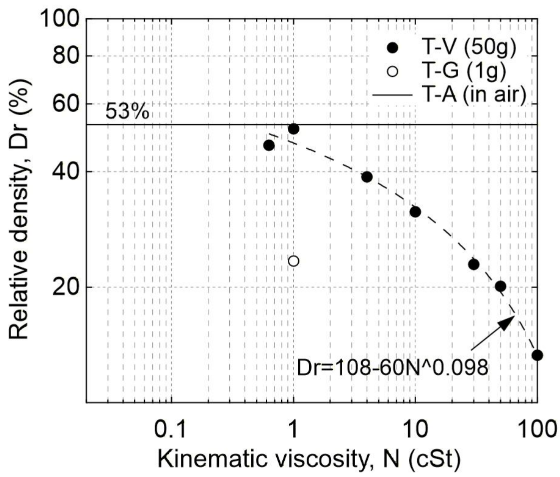


Figure 7. Relationship between relative density and kinematic viscosity.

range of approximately 50–60% represents the upper bound achievable through passive deposition alone. Consequently, even in field conditions where the fluid viscosity is lower than that of water, a moderate relative density comparable to that observed in case T-V01 is anticipated. Notably, in case T-G (underwater drop under gravitational acceleration), the relative density was only 23%, significantly lower than that achieved under centrifugal conditions, further underscoring the efficacy of the latter in replicating realistic deposition behaviour.

5 CONCLUSIONS

This study conducted underwater drop model tests of crushed stone within a centrifugal field to investigate the descent and deposition behaviour under simulated in-situ stress and water pressure conditions. The results demonstrated that the deposited crushed stone ground exhibits a moderate relative density. Given that the model setup did not satisfy similitude requirements related to fluid viscosity, supplementary tests with varied viscosity were performed to assess its influence. While falling velocity remained largely unaffected, the relative density of the deposit was found to decrease with increasing viscosity, suggesting that fluid properties influence post-depositional particle rearrangement. It should be noted that the present tests were conducted using a limited range of crushed stone shapes and grain sizes. To enhance the generality and applicability of the findings, future research should incorporate a broader spectrum of particle geometries and size distributions. Such investigations will contribute to a more comprehensive understanding of the deposition mechanics and packing characteristics of crushed stone under submerged conditions.

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