



## Stability and Metacentric Height Analysis of Foam Concrete Pontoon for Floating Portable Toilets in Flood Prone Indonesia

Eldina Fatimah<sup>1</sup>, Muhammad Fauzi<sup>1\*</sup>, Iqra Mona Meilinda<sup>1</sup>, Juellyan Iskandar<sup>2</sup>, Abdullah Mahmud<sup>1</sup>,  
Arisna Fauzia<sup>3</sup>

<sup>1</sup> Department of Civil Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

<sup>2</sup> Doctoral Program, School of Engineering, Post Graduate Program, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

<sup>3</sup> Department of Civil Engineering, Samudra University, Langsa 24354, Indonesia

Corresponding Author Email: [fauzi.yosa@usk.ac.id](mailto:fauzi.yosa@usk.ac.id)

Copyright: ©2026 The authors. This article is published by IETA and is licensed under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.18280/ij dne.210302>

### ABSTRACT

**Received:** 12 January 2026

**Revised:** 18 March 2026

**Accepted:** 28 March 2026

**Available online:** 31 March 2026

#### Keywords:

*floating toilet, foam concrete, pontoon, metacentric height, buoyancy, flood sanitation*

Indonesia, characterized by a tropical climate and high rainfall, is highly susceptible to flooding. Such events frequently damage infrastructure and disrupt sanitation facilities, including conventional portable toilets, which cannot operate effectively when inundated. This study develops and validates a floating, portable toilet supported by foam-concrete pontoons for flood-prone communities. The method combines a component-based mass budget, buoyancy evaluation using Archimedes' principle, and small-angle static stability analysis about the x-axis using a two-pontoon model. The recalculated mass budget excludes unsupported residual loads. It uses only component masses explicitly stated in the manuscript: substructure (886.752 kg), superstructure (1883.470 kg), equipment and sanitation utilities (744.600 kg), full sludge load (1072.500 kg), and a four-user live load (260.000 kg). The resulting dry mass in Scenario I is 3514.822 kg, while the maximum operating mass in Scenario V is 4847.322 kg. Each pontoon has an external size of  $0.8 \times 3.6 \times 1.0$  m, and the analytical stability calculation uses the combined waterplane geometry of the two-pontoon system. Stability analysis across five load scenarios produced positive metacentric height (GM) values ranging from 0.222 m to 0.775 m. The gross buoyancy-to-load safety factor is 1.405, exceeding the minimum criterion of 1.2. These results indicate that the two-pontoon foam concrete system can provide a technically feasible calm-water foundation for floating portable toilets in flood-prone regions. At the same time, hydrodynamic effects from current, debris, wind, waves, and mooring constraints require further testing.

## 1. INTRODUCTION

Geographically, Indonesia has a tropical climate with relatively high humidity in most of its territory [1-3]. Due to this climate, Indonesia experiences extreme rainfall during the rainy season, which can have negative impacts such as frequent flooding [4-6]. In particular, high rainfall intensity can lead to excess water that cannot be absorbed, resulting in flooding in an area [7]. As a result, floods have become a severe natural disaster worldwide due to their high frequency, widespread impact, and potential for causing significant losses to human life and property [8, 9].

According to data from the National Disaster Management Agency (BNPB), floods are the most frequent natural disaster in Indonesia, with 1,520 of the 3,522 natural disasters recorded throughout 2022 [10, 11]. In particular, floods are also the most frequent natural disaster in Aceh Province. By early 2023, at least 16 flood incidents had occurred there [12]. This disaster occurs almost every year in Aceh due to a lack of management, which exacerbates the impact of flooding on communities [13]. Moreover, although flood mitigation programs require high costs and a long time, communities in

flood-prone areas still need daily infrastructure [14].

When floods occur, conventional sanitation facilities are often damaged. At the same time, Goal 6 of the Sustainable Development Goals (SDGs) highlights the importance of adequate sanitation and clean water facilities [15, 16]. In fact, this goal ensures the availability and management of clean water and sanitation for all communities [17]. Despite this emphasis, providing sanitation facilities in areas affected by natural disasters remains a challenge [18]. For example, in flooded areas, obtaining clean water is very difficult, while sewage and wastewater treatment facilities tend to be clogged [19, 20]. Additionally, conventional portable toilets cannot operate in flooded areas and are difficult to distribute [21].

Existing emergency toilets commonly fail under flood conditions because they are inundated, displaced by flow, difficult to anchor, and vulnerable to capsizing or sewage leakage when water levels rise. These failures can be quantified through draft, buoyancy reserve, metacentric height (GM), off-center load response, and the system's ability to remain usable during inundation. The present study addresses these failure modes by proposing a floating portable toilet supported by foam concrete pontoons, with buoyancy assessed

through Archimedes' principle and stability verified using GM analysis [22].

Indonesia's geographical characteristics include many areas prone to flooding, such as estuaries, swamps, and rivers, and have a high potential for flooding [23]. As a result, areas adjacent to these flooded regions tend to lack adequate sanitation facilities, which are characterized by various sanitation problems. Furthermore, these problems are influenced by several factors, including social, economic, and cultural conditions in the surrounding environment [24]. Specifically, issues such as a lack of sanitation facilities, uneven distribution of clean water supplies, and low public awareness and knowledge about maintaining cleanliness are prevalent. Additionally, environmental conditions in densely populated residential areas near beaches, swamps, and rivers pose challenges in providing sanitation facilities [25, 26].

Indonesia still lacks adequate sanitation facilities [27]. Based on data from the Directorate of Environmental Health, Ministry of Health of the Republic of Indonesia, the average national sanitation coverage is 73.9%, and there are 26.1% of sanitation problems that need to be addressed [28]. While these figures highlight the scale of the issue, the consequences are far-reaching. For example, inadequate sanitation facilities, especially those with open drains, directly cause health, environmental, poverty-related, socio-cultural, and educational problems [29]. In addition, many people living near rivers and reservoirs still use pit latrines, which contribute to water pollution. Research shows that more than 90% of Acehnese people use individual waste disposal systems or toilets that discharge directly into water bodies [30].

The high vulnerability to natural disasters and the lack of adequate sanitation facilities have led to the development of floating portable toilets, designed specifically for use in flooded areas [31]. Because currently available portable toilets cannot adapt to changing water levels or be placed above the water surface, communities affected by floods still lack suitable sanitation solutions. Additionally, distributing portable toilets in disaster-affected areas remains challenging [32]. As a result, floating portable toilets are intended for use by communities living near water bodies and evacuees in flooded regions. The design of these toilets requires careful buoyancy planning, as this is essential to maintain stability and balance on the water surface [33].

Various aspects are considered in designing a floating portable toilet, such as dimensions, septic tank operation, floats, materials, and budget estimation. However, the design results require further research regarding the stability of the structure while floating [33]. Consequently, the floating portable toilet is analyzed based on its buoyancy capacity and stability when it is on the water surface. In this regard, the analysis of buoyancy capacity and balance follows the same principles as ship stability. Notably, stability is a very important element in ship calculations, which requires both theoretical and experimental approaches to obtain accurate results regarding loads and disturbances to ship stability [34, 35]. Foam concrete was selected as the pontoon material because of its lightweight properties, high buoyancy, durability in wet environments, cost-effectiveness, and compliance with Indonesian National Standards (SNI 1729:2020 and SNI 03-3499-2002) [36, 37]. The specific dimensions (0.8 × 3.6 × 1 m) were chosen to balance septic tank capacity, user load requirements, and ease of distribution in flood-prone areas, thereby providing a practical and scalable design basis.

## 2. MATERIALS AND METHODS

### 2.1 Design and validation

The object of this research is a floating portable toilet (FTP). The FTP will be designed to meet floating building standards. The FTP design process is carried out in two stages: modelling and physical testing. The FTP modelling process begins with the collection of primary and secondary data related to the geometry and materials of the floating building. After the data is collected, an analysis is conducted to assess the stability of the floating portable toilet.

During the design stage, the FTP model is developed in accordance with applicable regulations. It consists of five main components assembled with selected materials for comfort, safety, and ease of installation. The design process considers structural and sanitation requirements, focusing on buoyancy and stability. Table 1 illustrates the equipment and sanitation utility loads, each affecting the stability of the floating portable toilet.

**Table 1.** Equipment and sanitation utility loads [38]

No.	Item	Material	Specification	Weight (kg)	Quantity	Total Weight (kg)
1	Water Tank	Polyethylene	Volume = 300 L, Diameter = 88 cm, Height = 135.5 cm, Cover Diameter = 40 cm, Thickness = 7–10 mm	319	2	638
2	Suction Pump	—	Wasser PW-225 E water suction pump	2	1	2
3	Booster Pump	—	Wasser PB 318 EA booster pump	2	1	2
4	Solar Panel	Polycrystalline	Model = GH200P-24, Pm = 200 watt, Voltage = 24 V, Size = 130 × 100 × 3.5 cm	25	1	25
5	Clean Water Pipe	PVC	Diameter 1/2 inch or 1.25 cm	0.1	16.1	1.2
6	Waste Water Pipe	PVC	Diameter 4 inch or 10 cm	2.1	8.4	9.1
7	Sitting Toilet	Porcelain	Brand Volk, type 663	15	1	15
8	Squat Toilet	Porcelain	Brand Toto, type CE7	20	1	20
9	Door	PVC	Size = 70 × 198 cm	10.5	2	21
10	Lamp	—	Brand Hanochs	0.15	2	0.3
11	Hand Shower	Plastic	—	0.4	2	0.8
12	Bidet Shower	Plastic	—	0.3	2	0.6
13	Floor Drain	Plastic	—	0.5	2	1
14	Water Filter	—	—	4.3	2	8.6
Total						744.6

Live load assumptions are determined in accordance with the Load Design Guidelines for Houses and Buildings (SNI 1729:2020) [39], which define live load as a variable load arising from building use. Anthropometric data from the Ministry of Health of the Republic of Indonesia show that the average adult body mass is approximately 62.1 kg for men and 56.2 kg for women [40]. Accordingly, this study adopts 65 kg per person as a conservative design load. Table 2 separates substructure mass, superstructure mass, equipment and sanitation utility load, sludge load, and user live load so that each operating scenario can be traced consistently.

**Table 2.** Final component mass budget used in the stability analysis

Component	Mass (kg)
Substructure	886.752
Superstructure	1883.470
Equipment/utilities	744.600
Dry subtotal (Scenario I)	3514.822
Full sludge	1072.500
Live load	65-260
Max. operating mass (Scenario V)	4847.322

## 2.2 Physical and material testing

After the design phase, expert respondents were validated through interviews. The questionnaire was developed based on design criteria, and respondents were purposively selected based on their areas of expertise to ensure the validity of the assessment. Respondents included practitioners experienced in disaster management, building design, and members of the flood-affected community. This validation process has been conducted in previous research [33]. After the load analysis was completed, the next step was to test the stability of the FTP. Several analysis stages were required, namely septic tank storage capacity analysis, floating weight analysis of the portable toilet, float design, center of gravity analysis, and finally, stability analysis.

Once the model design and stability analysis were completed, physical testing was conducted using the actual design dimensions. For this testing, the floating platform was constructed with lightweight concrete that adheres to the Indonesian National Standard (SNI 2847:2019) [36, 37]. According to Indonesian National Standard (SNI 2847:2019) [41], structural lightweight concrete is defined as concrete that uses lightweight coarse aggregate or a mixture of lightweight coarse aggregate and natural sand, with a maximum density requirement of < 1840 kg/m.

Additionally, the concrete must meet specified compressive and tensile strength for structural use. SNI 03-3499 provides specifications for sand-free lightweight concrete, which is produced by eliminating fine aggregate in the mixture to create pores and air cavities that can reduce the overall weight [42]. In this study, the floating platform was produced using foam-based lightweight concrete to achieve the required buoyancy. The use of lightweight concrete ensures that the floating toilet complies with Indonesian construction standards while maintaining adequate strength and stability for application in flood-prone areas.

## 2.3 Model design and stability analysis

The design for calculating the floating portable toilet balance uses dimensions and materials based on the floating

toilet design. This design has been adjusted to Indonesian standards and matches the design criteria analysis in the study [33]. Materials and dimensions were chosen for comfort, safety, stability, anthropometry, and easy distribution and assembly. Figure 1 shows the resulting floating toilet design. Building on this overall foundation, the following section outlines the specific analysis stages required.

As mentioned in the previous section, several analysis stages are required at this design stage. The first of these is calculating the septic tank capacity. Specifically, in this design, the tank capacity is planned for 13 people, with a daily requirement of 25 litres per person and a standard decomposition time of 3 days. For implementation, the septic tank is constructed using a plastic drum with an empty weight of 51.6 kg and a capacity of 230 litres, with a septic tank filling capacity of 2/3 for fecal sludge and 1/3 for air.

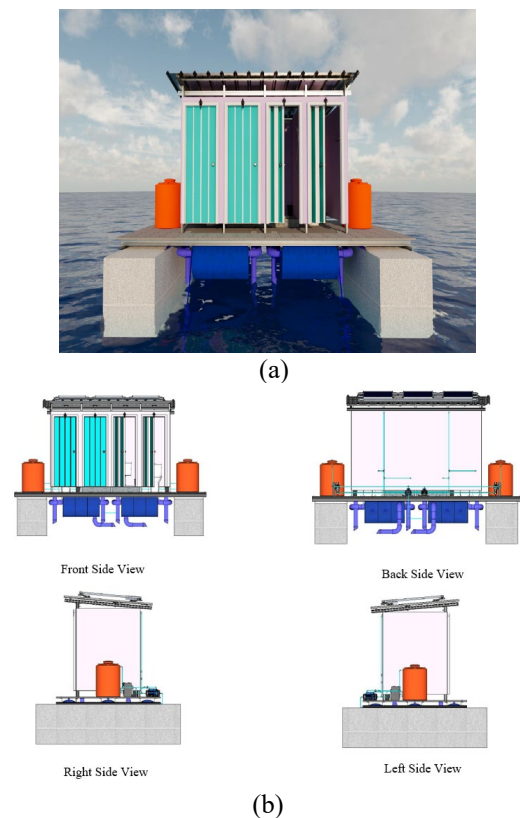
Storage analysis is calculated per plastic drum unit using Eqs. (1) and (2). After the number of drums used is obtained, the calculation of the weight of the fecal sludge is carried out using Eq. (3) [43, 44]. Next, a stability analysis of the floating portable toilet is carried out for each calculation variation.

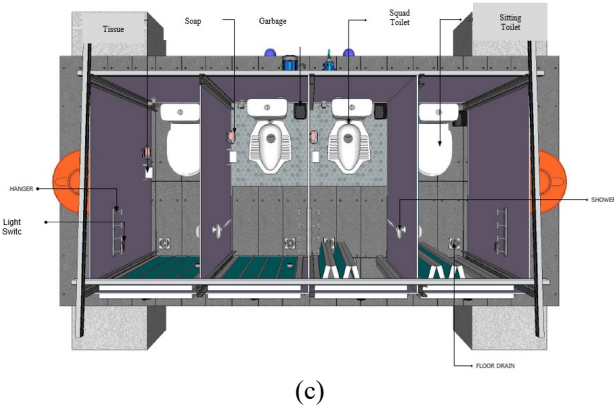
$$A_T = P \times S \times N \quad (1)$$

$$V_d = (\pi r_d^2) \times t_d \quad (2)$$

$$W_T = \rho_i \times A_T \quad (3)$$

where,  $A_T$  is the required storage capacity (liters),  $P$  is the estimated number of users (people),  $S$  is the user demand (liters/day),  $N$  is the time required for decomposition (days),  $V_d$  is the drum volume ( $m^3$ ),  $r_d$  is the drum radius (m),  $t_d$  is the drum height (m),  $W_T$  is the weight of the sludge (kg), and  $\rho_i$  is the specific gravity of the sludge ( $kg/m^3$ ). Using the above equation, the required number of drums is obtained: 6 plastic drums. These drums can hold 1,072.5 kg of sludge, which is equivalent to the needs of approximately 13 evacuees per day.





**Figure 1.** (a) Floating portable toilet design, (b) appearance of floating portable toilet from all sides, (c) floating portable toilet seen from above

After the required drum capacity was determined, the substructure mass used in the analytical stability model was retained from the documented design-stage calculation. The substructure consists of the foam-concrete float and septic-tank drum system. The foam-concrete component is 835.152 kg, and when combined with the empty drum mass, the total substructure mass is 886.752 kg. This value is used consistently in all load scenarios to avoid mixing different design-version masses or inserting unsupported residual loads.

Buoyancy was then evaluated using Archimedes' principle under the maximum operating condition [45, 46]. The analysis treated the system as a two-pontoon model and used small-angle static stability about the x-axis, which produced the lowest waterplane moment of inertia and therefore represented the critical rotation axis [34, 35]. The supported load was defined consistently as the maximum operating mass of the complete floating portable toilet, including substructure mass, superstructure mass, equipment and sanitation utilities, sludge load, and user live load. No unverified connection or installation allowance was included.

$$F_B = \rho_w \times g \times V_{disp} \quad (4)$$

$$B_{capacity} = \rho_w \times V_{disp} \quad (5)$$

$$V_p = (l \times b \times T) - ((l - 2k)(b - 2k)(T - 2k)) \quad (6)$$

$$W_p = \rho_{fc} \times V_p \quad (7)$$

$$SF = \frac{B_{capacity}}{W_{max}} \quad (8)$$

where,  $d$  is the draft height (m),  $l$  is the pontoon length (m),  $b$  is the pontoon width (m),  $T$  is the pontoon height (m),  $k$  is the pontoon wall thickness (m),  $V_p$  is the foam-concrete material volume ( $m^3$ ),  $V_o$  is the external pontoon volume ( $m^3$ ),  $V_i$  is the internal cavity volume ( $m^3$ ),  $W_p$  is the pontoon mass (kg),  $\rho_{fc}$  is the foam-concrete density ( $kg/m^3$ ),  $\rho_w$  is the water density ( $kg/m^3$ ),  $V_{disp}$  is the displaced water volume ( $m^3$ ),  $F_B$  is buoyancy force (N),  $B_{capacity}$  is buoyancy capacity expressed as mass equivalent (kg),  $W_{max}$  is the maximum operating mass (kg), and  $SF$  is the safety factor.

The superstructure consists of the lightweight steel frame, floor, wall panels, and roof. The superstructure mass used in the stability model remains 1883.470 kg, as stated from the

SAP2000-based material calculation. This value is retained to avoid replacing a documented structural mass with an unsupported residual value.

The total operating mass for each scenario was calculated from the component budget in Table 2. Scenario I represents the dry condition without users and without sludge. Scenarios II to V add the full sludge load and live loads of one to four users, respectively. The resulting masses are used consistently in the center-of-gravity, displaced-volume, and GM calculations. The criteria and layout variations for each scenario are summarized in Table 3.

**Table 3.** Summary of layout and weight variations

Scenario	Criteria
Scenario I	The weight comes from the weight of the substructure, superstructure, equipment, no users, and no fecal sludge.
Scenario II	Weight originating from the weight of the lower structure, upper structure, equipment, one user standing on the edge of the toilet, and fecal sludge.
Scenario III	The weight comes from the weight of the lower structure, upper structure, equipment, two users in the two toilet cubicles on the right, and fecal sludge.
Scenario IV	Weight originating from the weight of the lower structure, upper structure, equipment, three users, and fecal sludge.
Scenario V	The weight comes from the weight of the substructure, superstructure, equipment, four users, and a septic tank filled with fecal sludge. There are four users in the cubicle.

Based on the various scenarios run in the floating portable toilet stability analysis above, the live load for Scenario I is 0 kg (representing the minimum condition without users). Scenario II is 65 kg, Scenario III is 130 kg, Scenario IV is 195 kg, and Scenario V (maximum condition) is 260 kg. The next step is to calculate the overall weight for each scenario. The details are shown in Table 4, the total weight section.

**Table 4.** Total mass, center of gravity, and x-axis waterplane moment of inertia for the floating portable toilet

Scenario	Total Weight (kg)	X-Axis (m)	Y-Axis (m)	Z-Axis (m)	$I_{0x}$ ( $m^4$ )
Scenario I	3514.822	2.60	1.80	1.54	6.221
Scenario II	4652.322	2.58	1.80	1.66	6.221
Scenario III	4717.322	2.58	1.79	1.67	6.221
Scenario IV	4782.322	2.58	1.79	1.68	6.221
Scenario V	4847.322	2.60	1.78	1.68	6.223

The final stage of the design process is to calculate the buoyancy capacity required to support the complete floating portable toilet. The external displacement of the two-pontoon system was used to define the available buoyancy, while the component mass budget was used to define each loading scenario. The recalculated maximum operating mass is 4847.322 kg. Using the previously calculated allowable support capacity of 5674.897 kg after applying the minimum design factor of 1.2, the corresponding gross buoyancy capacity is 6809.876 kg, giving an achieved gross buoyancy-

to-load safety factor of 1.405.

$$V_{disp} = \frac{W}{\rho_w}, d = \frac{V_{disp}}{A_{wp}}, OB = \frac{d}{2} \quad (9)$$

Allowable support capacity after SF = 1.2 = 5674.897 kg.

Gross buoyancy capacity = 5674.897 × 1.2 = 6809.876 kg.

$W_{max} = 886.752 + 1883.470 + 744.600 + 1072.500 + 260 = 4847.322$  kg.

$$I_{ox} = 2[I_{x,p} + A_p(e^2)], I_{x,p} = \frac{lb^3}{12} \quad (10)$$

$$SF = \frac{6809.876\text{kg}}{4847.322\text{kg}}$$

$$SF = 1.405$$

$$SF > 1.2$$

$$1.405 > 1.2(\text{Qualified})$$

Based on the revised buoyancy analysis, the proposed foam concrete pontoon system provides sufficient reserve buoyancy for the maximum operating condition. The achieved gross buoyancy-to-load safety factor of 1.405 exceeds the minimum design criterion of 1.2, while the positive GM values across all load scenarios indicate that the structure maintains static stability after small angular disturbances.

### 3. RESULT AND DISCUSSION

#### 3.1 Stability analysis of floating portable toilets

The center of gravity analysis of the floating portable toilet was conducted for all conditions tested in the stability analysis. The analysis was conducted on the x-axis, y-axis, and z-axis of the floating portable toilet for each calculation variation. The center of gravity calculation uses Eq. (11) to obtain the OG value for each variation. In scenarios I (minimum weight) and V (maximum weight), the left and right toilet loads are symmetrical so that the center of gravity on the x-axis is exactly in the middle of the toilet. The center of gravity calculation was performed for the y-axis and z-axis. In scenarios II, III, and IV, the analysis was conducted on the x-axis, y-axis, and z-axis due to variations in the layout of the toilet users. In the stability analysis of the floating portable toilet, five variations in the layout of the load and weight were carried out to determine the stability of the toilet when floating on the water surface [47]. Stability calculations with various layouts and load variations were carried out to ensure the toilet remains stable regardless of the user's position while floating.

$$OG = \frac{\sum W_i z_i}{\sum W_i} \quad (11)$$

where,  $OG$  is the vertical center of gravity measured from the pontoon bottom or datum point (m),  $W_i$  is the mass of each component or load (kg),  $z_i$  is the vertical distance of each component or load from the datum point (m),  $\sum(W_i \times z_i)$  is the total moment of mass about the datum point (kg·m), and  $\sum W_i$  is the total mass of the floating portable toilet (kg). The results

of the center of gravity calculations for each axis are shown in Table 4.

Based on the analysis, it was found that in scenarios I and V, the x-axis was directly centered on the toilet. However, in the other axes, the center of gravity was not directly centered on the toilet because the user was not centered. In scenarios II, III, and IV, the center of gravity was not directly centered on the toilet. This inaccuracy in the center of gravity on the axes would cause the floating portable toilet to potentially rotate while floating on the water surface.

The waterplane geometry was defined using two rectangular pontoons. For each scenario, the total displaced volume was obtained from  $V_{disp} = W/\rho_w$ , and the draft was obtained from  $d = V_{disp}/A_{wp}$ , where  $A_{wp}$  is the combined waterplane area of the two pontoons. The x-axis waterplane moment of inertia was calculated using the parallel-axis theorem,  $I_{ox} = 2[I_{x,p} + A_p(e^2)]$ , where  $I_{x,p}$  is the centroidal moment of inertia of one pontoon waterplane,  $A_p$  is the waterplane area of one pontoon, and  $e$  is the transverse distance from each pontoon centroid to the system centerline. This combined  $I_{ox}$  was then divided by the total displaced volume, not the single-pontoon volume, to obtain BM.

The calculations show that the inertia in the x-axis is smaller, making the floating portable toilet easier to rotate in this direction. Therefore, all analyses of floating portable toilet stability will use the x-axis inertia values. Table 4 presents these results.

Based on Table 4, there are no significant differences in the moment of inertia values for each variation. Displacement affects the moment of inertia about the building's center of gravity. The relative value of the moment of inertia is consistent across variations in stability calculations for floating portable toilets. This occurs because the building's center of gravity is not far from the axis of rotation. When rotating, the moment of inertia depends on how far the mass is distributed from the axis of rotation. In a floating portable toilet, the displaced mass, in the form of users, has a very small impact compared to the total weight of the toilet. Differences in the layout of multiple users relative to the total weight of the toilet do not significantly affect the shift in the center of gravity.

In calculating the stability of a floating portable toilet, the GM is required to determine the stability of an object while floating [48]. To calculate the GM, data is required regarding the height of the center of buoyancy (OB), the distance between the center of buoyancy and the center of gravity (BG), and the metacentric radius (BM) (see Figure 2).

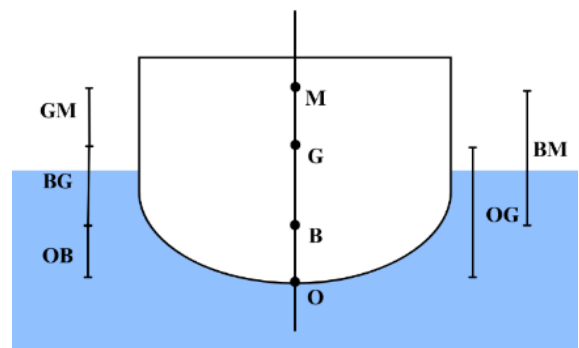


Figure 2. Size in buoyant object calculations

Source: Modified from Alamsyah et.al. [46]

The calculation continues to consider OB, BG, BM, and GM. OB can be determined based on the shape of the pontoon [47]. Portable floating toilets use a flat-bottom type (flat pontoon bottom), so the value can be determined by:

$$OB = 0.5 d \quad (12)$$

where,  $d$  is the ship's draft (m).

The BG value is the distance between the buoyancy point (B) and the center of gravity (G) on the pontoon. The BG value can vary depending on the distance between OG and OB. The BG value can be calculated using the following formula:

$$BG = OG - OB \quad (13)$$

$$GM = BM - BG \quad (14)$$

The OG value is the height of the center of gravity (G) relative to the keel or floating bottom (O). The OG value can be obtained from a stability test (inclining experiment) and then calculated using moments. The OG value is calculated by the sum of the moments used when loading occurs, or the location of the load's center of gravity on the pontoon is known, which can be referred to as the vertical center of gravity (VCG). This is then multiplied by the load weight to obtain the moment of that load. The next step is to divide the sum of the

moments from all loads on the floating object by the load weight to obtain the Ogfpt value.

BM is the metacentric radius because when a floating object tilts at a small angle, the trajectory of point B is part of a circular arc with M as the center and BM as the radius. BM can be calculated by dividing the smallest inertia of a direction on the floating object by the submerged volume of the pontoon, using the formula:

$$BM = \frac{I_0}{V_{disp}} \quad (15)$$

In this study,  $I_0$  is the combined x-axis waterplane moment of inertia of the two pontoons ( $m^4$ ), and  $V_{disp}$  is the total submerged volume displaced by the complete floating toilet ( $m^3$ ). Using total displacement ensures that BM and GM are derived from the same two-pontoon model used in the mass and buoyancy calculations.

Table 5 presents the recalculated stability results after the unsupported residual mass was removed and the displaced volume was calculated consistently from the total operating mass. All scenarios produce positive GM values, ranging from 0.222 m to 0.775 m, indicating stable equilibrium. The lowest GM occurs in Scenario V, where the combination of full sludge and four users produces the highest draft and the smallest remaining stability margin.

**Table 5.** Stability results for analytical load scenarios

Scenario	OB m	OG m	BG (OG-OB) m	$V_{disp}$ $m^3$	BM ( $I_0/V$ ) m	GM (BM-BG) m	Stability
Scenario I	0.305	1.300	0.995	3.515	1.770	0.775	Positive Stability
Scenario II	0.404	1.460	1.056	4.652	1.337	0.281	Positive Stability
Scenario III	0.409	1.468	1.059	4.717	1.319	0.260	Positive Stability
Scenario IV	0.415	1.475	1.060	4.782	1.301	0.241	Positive Stability
Scenario V	0.421	1.483	1.062	4.847	1.284	0.222	Positive Stability

### 3.2 Experimental validation and modification of lightweight concrete pontoon design

The lightweight concrete pontoon uses a hollow rectangular design with external dimensions of 0.8 m × 3.6 m × 1.0 m and a nominal wall thickness of 0.03 m. During prototype validation, the continuous 3 cm wall over a 3.6 m span was found vulnerable to bending under lateral water pressure, so the pontoon geometry was segmented for fabrication. This prototype modification is reported as a construction improvement only. For the analytical stability recalculation, the manuscript retains the documented substructure mass of 886.752 kg, so the mass budget remains consistent with the stated component values and does not mix design-version masses.

The maximum operating mass of the structure is calculated by adding the dry mass, fecal sludge load, and live load. The dry mass includes the documented substructure mass, superstructure, equipment, and sanitation utilities. No additional connection or installation allowance is included in the calculation.

$$\begin{aligned} W_{max} &= W_{dry} + W_{sludge} + W_{live} \\ W_{max} &= 3514.822 + 1072.5 + 260 \\ W_{max} &= 4847.322 \text{ kg} \end{aligned} \quad (16)$$

The pontoon design was modified because the lightweight concrete used measured 3.6 meters in length and only 3 cm in

thickness. This thin layer of concrete could not withstand the water pressure from the pontoon's sides. It was suspected of experiencing bending or even breaking. The failure resulted from the very thin design thickness and the relatively brittle nature of lightweight concrete. Therefore, the researchers modified the design by adding small supports and dividing the total length into six sections. This reduced water pressure and prevented the concrete from sagging under intense pressure. These changes led to the production of three types of lightweight concrete.

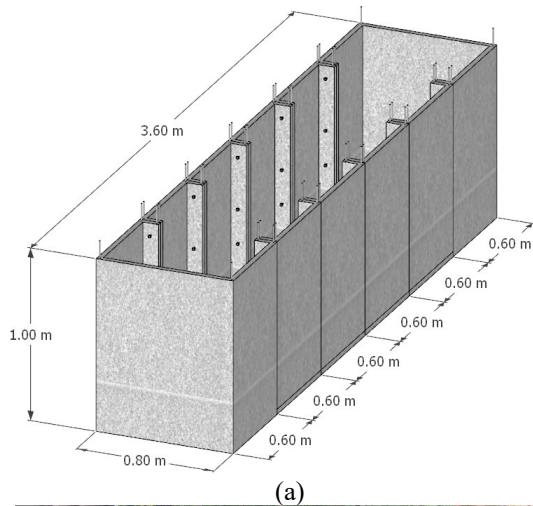
After dividing into three types, each pontoon needed two pieces of type A concrete, four of type B, and four of type C. The assembly process used bolts to connect the parts. Glue was applied to strengthen all components, as shown in Figure 3.

In addition to the mathematical analysis, the foam concrete pontoon was tested in a calm laboratory pool and then in the Titinjang River, Alue Naga, Banda Aceh. The laboratory test used still-water conditions so that the observed draft and heel response could be compared directly with the static stability model. The pontoon was restrained with guide ropes during placement to prevent lateral drift, but the restraints did not support the vertical load.

Loading was applied gradually to represent the operating scenarios. Equivalent dead loads were positioned according to the assumed user and sludge layouts, including edge and asymmetric load positions. The draft was read after the water surface became calm at the port and starboard sides, and additional visual checks were used to confirm whether

excessive heel, rotation, or local submergence occurred. The test was repeated by taking several readings at each loading stage rather than relying on a single instantaneous observation.

The measured draft under the representative loading condition was approximately 40 cm, which was close to the theoretical prediction of 41.7 cm. The deviation was less than 5%, indicating that the analytical displacement model provided a reasonable estimate for the prototype.



**Figure 3.** Combination of 3 types of lightweight concrete, (a) combination design, (b) physical combination results

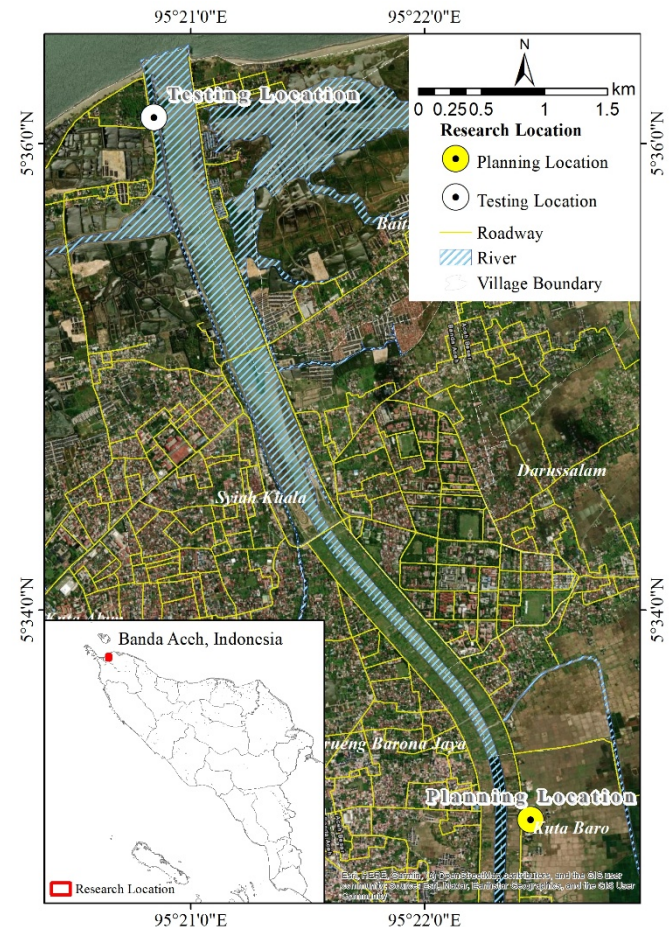
Field testing was then conducted on the Titinjang River, Alue Naga, Banda Aceh, to examine flotation behavior outside the laboratory setting. The selected river segment had calm flow during testing and sufficient depth for the pontoon to float without touching the riverbed. The pontoon was lifted and lowered using a truck crane from the bridge. A support frame, wooden blocks, and steel slings were used so that lifting forces were distributed and the concrete surface was not damaged.

### 3.3 Stability testing of lightweight concrete pontoons

In addition to mathematical stability analysis, experimental testing of the floating portable toilet pontoon was conducted to validate the theoretical results. The prototype was tested in a controlled laboratory pool with calm water conditions, without waves or currents. The pontoon was carefully lowered into the pool. Loads were then gradually applied to simulate the weight of users and septic tank sludge. The loading procedure was carried out in stages, starting with no users and reaching a maximum scenario with four users and a full septic

tank.

Following the staged loading in the laboratory pool, the pontoon draft was measured using calibrated instruments. The observed draft was approximately 40 cm, which was very close to the predicted value of 41.7 cm from the mathematical analysis. This small deviation (< 5%) confirmed the reliability of the theoretical calculations. The pontoon remained stable throughout the loading process, without excessive tilting or rotation. Visual documentation of the testing process was also recorded, showing the pontoon floating stably under various loading conditions, as presented in Figure 4.



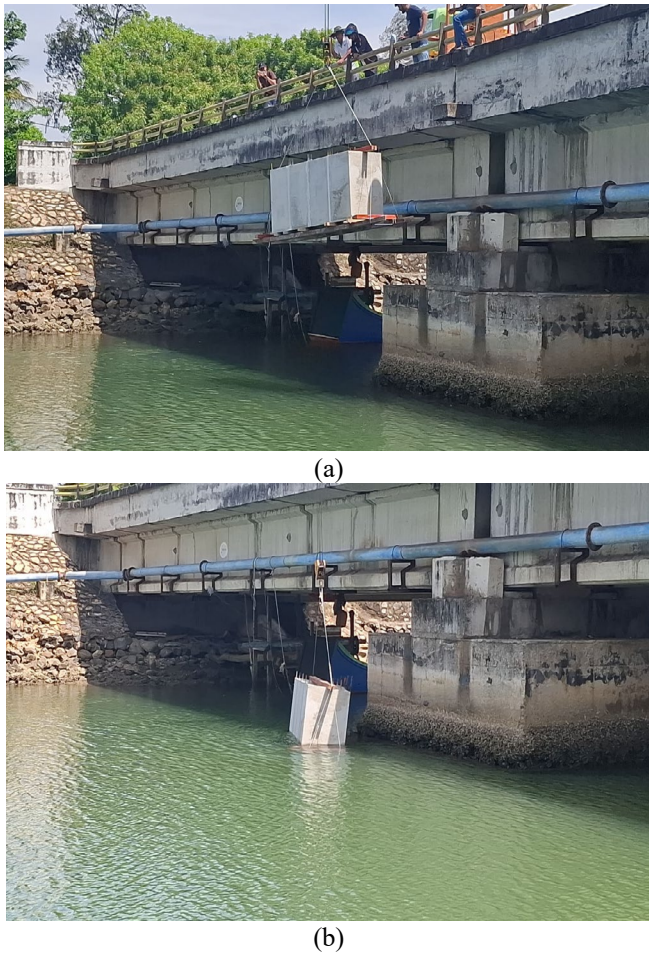
**Figure 4.** Site planning, construction, and testing of a floating portable toilet pontoon on the Titinjang River, Alue Naga

These laboratory tests demonstrate that the lightweight concrete pontoon can safely support the designed loads and remain stable under real-world conditions. The consistency between measured and predicted values provides strong evidence that the floating portable toilet design is technically feasible and practically reliable for use in flood-prone areas.

Building on the laboratory findings, field testing of the lightweight concrete pontoon was conducted on the Titinjang River, Alue Naga, Banda Aceh. This location was chosen due to its calm water conditions and accessibility, allowing the use of a crane from the bridge. A support frame was constructed to facilitate lifting and prevent direct contact between the steel slings and the concrete surface. This preparation ensured that the pontoon could be safely transported and lowered into the river without damage.

During the river test, the slings remained attached as a safety restraint to limit drift caused by the current while still allowing the pontoon to float freely. This condition is reported as a

restrained field-flotation test rather than an unmoored free-drift test. The procedure allowed buoyancy and draft response to be observed while reducing the risk of uncontrolled movement, as illustrated in Figure 5.



**Figure 5.** (a) Lowering of the pontoon into the Titinjang River, (b) documentation of the pontoon floating on the water surface

The pontoon was then lifted using a truck crane. Steel slings were carefully attached to the support frame, and wooden blocks were placed across the pontoon to prevent the steel cables from pressing directly on the concrete surface. This step was crucial to prevent structural damage during the lifting process.

From the bridge, the pontoon was slowly lowered into the river until it was fully afloat. The lowering process was carried out carefully to maintain stability, and the slings remained attached throughout the test to prevent movement due to strong river currents. This procedure ensured the pontoon entered the water in a controlled manner.

Draft was measured at the starboard and port sides after the pontoon reached a stable floating condition. The starboard side measured 45.5 cm, and the port side measured 17.5 cm during the restrained river placement, giving an average of 31.5 cm under that uneven external condition. In the later stability test without external lifting effects, the draft was approximately 40 cm, close to the theoretical prediction of 41.7 cm.

The buoyancy capacity of the final configuration was confirmed from the recalculated mass budget and displacement calculation. The maximum operating mass of the complete floating portable toilet is 4847.322 kg. The allowable

support capacity after applying the minimum design factor of 1.2 is 5674.897 kg, which remains higher than the maximum operating mass. This corresponds to a gross buoyancy capacity of 6809.876 kg and an achieved gross buoyancy-to-load safety factor of 1.405. Thus, the design still meets the minimum structural safety criterion without adding unsupported residual mass.

After release, the pontoon floated stably. Although slightly tilted due to uneven external loads, it maintained buoyancy and did not sink. This shows that the lightweight concrete provides sufficient buoyancy in real conditions. Building on this initial assessment, further measurements were conducted to evaluate submersion depth. The draft measurement and stability validation are shown in Figure 6.



**Figure 6.** Draft measurement during pontoon testing

The draft was measured at several points. The starboard side measured 45.5 cm, the port side 17.5 cm, averaging 31.5 cm. In later stability tests without external loads, the draft was about 40 cm, which closely matched the theoretical 41.7 cm. This small deviation (< 5%) confirms the model's accuracy.

Measured and predicted draft values were consistent, with less than 5% difference. The pontoon stayed stable during loading, showing no excessive tilting or rotation. These results validate that lightweight foam concrete works as a buoyancy material in real-world conditions. This provides confidence in the design assumptions. Building on this validation, the next step focused on confirming the pontoon's buoyancy capacity.

The buoyancy capacity confirmation is therefore based on

the corrected maximum operating mass of 4847.322 kg, not on a back-calculated mass that includes unsupported residual loads. This correction keeps the analytical mass budget, buoyancy calculation, and GM results consistent.

Experimental testing of the lightweight concrete pontoons showed an actual draft of approximately 40 cm, close to the theoretical value of 41.7 cm. The deviation of less than 5% supports the reliability of the analytical model for calm-water conditions. This finding extends previous theoretical work on floating portable toilet stability by providing prototype-scale validation and by linking draft observation with a complete component mass budget [40].

The recalculated analytical stability results show positive GM values in all five operating scenarios, ranging from 0.222 m in the maximum-load condition to 0.775 m in the dry condition. Although the revised values are lower than the preliminary calculation because the total displaced volume is now applied consistently, they remain positive and therefore indicate stable equilibrium under small-angle static assumptions. Experimental pontoon tests also produced positive GM values for one- and two-pontoon configurations, supporting the suitability of the two-pontoon arrangement and reinforcing earlier material recommendations for floating portable toilet applications [50].

The achieved gross buoyancy-to-load safety factor of 1.405 exceeds the minimum threshold of 1.2 used in the design criterion [51]. This reserve is important because floating sanitation infrastructure may experience load uncertainty, uneven user positioning, partial sludge accumulation, and additional installation accessories during field deployment. The revised mass budget reduces the risk of overestimating reserve buoyancy because all major loads are now explicitly separated and no unsupported residual mass is inserted.

#### 4. DISCUSSION

Compared with polyethylene and fiberglass pontoons, foam concrete offers different advantages and limitations. Polyethylene floats are lighter and have high buoyancy efficiency, but they may require specialized fabrication, are more vulnerable to puncture and UV degradation, and can be more difficult to repair locally [52]. Fiberglass provides good strength-to-weight performance, but it requires skilled lamination, careful quality control, and higher material costs [53]. Foam concrete is heavier, yet it is locally producible, dimensionally stable, fire resistant, compatible with ordinary construction skills, and less dependent on imported modular components [54, 55]. For flood-prone communities, this trade-off supports the choice of foam concrete when local fabrication, durability, and repairability are prioritized over minimum self-weight.

In addition, although foam concrete is heavier, its local material availability and lower production costs make it a more affordable long-term option, especially for areas with limited access to lightweight material fabrication technologies like fiberglass or polyethylene. While polyethylene and fiberglass offer better buoyancy performance due to their lighter weight, both materials have significant drawbacks, such as lower resistance to physical damage and degradation, and they require specialized manufacturing and maintenance skills. Therefore, foam concrete's choice can be justified if the focus is placed on local fabrication and repair capabilities, which are crucial during emergencies or in disaster-prone areas where

access to imported materials is limited.

However, it should be noted that real flood conditions may reduce the available safety margin compared to calm-water testing. Currently, debris impact, waves, wind, and imperfect mooring can introduce dynamic forces and off-center moments that lower the effective GM response and increase the risk of heel or collision [56]. Therefore, the system should be deployed with mooring lines, lateral bumpers, controlled access, balanced sludge management, and regular inspection of pontoon joints. The present results should be interpreted as static calm-water validation, while future studies should add hydrodynamic tests under flow, waves, impact, and mooring constraints to gain a more accurate understanding of foam concrete's performance in dynamic flood conditions.

#### 5. CONCLUSIONS

This study confirms that the revised hollow foam concrete pontoon system can support a floating portable toilet for flood-prone areas under calm-water static conditions. The recalculated maximum operating mass is 4847.322 kg, consisting of substructure mass, superstructure, equipment and sanitation utilities, full sludge load, and four users. The allowable support capacity after applying the minimum design factor of 1.2 is 5674.897 kg, while the corresponding gross buoyancy capacity is 6809.876 kg. This produces an achieved gross buoyancy-to-load safety factor of 1.405, exceeding the minimum design criterion of 1.2. Stability analysis across five load scenarios produced positive GM values ranging from 0.222 m to 0.775 m, confirming that the system maintains positive static stability under the evaluated loading conditions.

Experimental validation in the laboratory pool and in the Titinjang River showed stable flotation and a measured draft close to the theoretical estimate, with less than 5% deviation. These findings indicate that foam concrete pontoons can function as a feasible buoyant foundation for emergency sanitation infrastructure, especially in communities where conventional portable toilets fail due to inundation, displacement, or deployment difficulty.

For practical deployment, pontoon dimensions should be standardized, the two-pontoon spacing should follow the validated stability model, and installation should include mooring lines, lateral bumpers, balanced access points, and routine inspection of bolts, adhesive joints, waterproofing layers, and septic tank connections. A basic maintenance schedule should include pre-deployment inspection, daily checks during flood operation, sludge-level monitoring, post-flood cleaning, and structural inspection before reuse. Future studies should evaluate hydrodynamic performance under currents, waves, debris impact, wind, and more severe off-center loading.

#### ACKNOWLEDGMENT

The authors are grateful for the contributions of the Institute for Research and Community Service, Syiah Kuala University, and the Ministry of Higher Education, Science, and Technology in funding this study through the Regular Fundamental Research Grants under Contract BIMA No. 113/C3/DT.05.00/PL/2025 (May 28, 2025) and Contract USK No. 184/UN11.L1/PG.01.03/DPPM/2025 (June 4, 2025).

## REFERENCES

- [1] Putra, I.D.G.A., Nimiya, H., Sopaheluwakan, A., Kubota, T., Lee, H.S., Pradana, R.P., Alfata, M.N.F., Perdana, R.B., Permana, D.S., Riama, N.F. (2022). Development of climate zones for passive cooling techniques in the hot and humid climate of Indonesia. *Building and Environment*, 226: 109698. <https://doi.org/10.1016/j.buildenv.2022.109698>
- [2] Mamenun, Koesmaryono, Y., Sopaheluwakan, A., Hidayati, R., Dasanto, B.D., Aryati, R. (2024). Spatiotemporal characterization of dengue incidence and its correlation to climate parameters in Indonesia. *Insects*, 15(5): 366. <https://doi.org/10.3390/insects15050366>
- [3] Marina, R., Ariati, J., Anwar, A., Astuti, E.P., Dhewantara, P.W. (2023). Climate and vector-borne diseases in Indonesia: A systematic literature review and critical appraisal of evidence. *International Journal of Biometeorology*, 67(1): 1-28. <https://doi.org/10.1007/s00484-022-02390-3>
- [4] Yamamoto, K., Sayama, T., Apip. (2021). Impact of climate change on flood inundation in a tropical river basin in Indonesia. *Progress in Earth and Planetary Science*, 8(1): 5. <https://doi.org/10.1186/s40645-020-00386-4>
- [5] Supari, Tangang, F., Salimun, E., Aldrian, E., Sopaheluwakan, A., Juneng, L. (2018). ENSO modulation of seasonal rainfall and extremes in Indonesia. *Climate Dynamics*, 51(7): 2559-2580. <https://doi.org/10.1007/s00382-017-4028-8>
- [6] Kurniadi, A., Weller, E., Min, S.K., Seong, M.G. (2021). Independent ENSO and IOD impacts on rainfall extremes over Indonesia. *International Journal of Climatology*, 41(6): 3640-3656. <https://doi.org/10.1002/joc.7040>
- [7] Arifin, M., Rasyid, A.R., Yudono, A., et al. (2021). Flood disaster management concept in the Perumnas Manggala housing complex in Makassar City. *Jurnal Tepat: Teknologi Terapan untuk Pengabdian Masyarakat*, 4(2): 151-165. [https://doi.org/10.25042/jurnal\\_tepat.v4i2.196](https://doi.org/10.25042/jurnal_tepat.v4i2.196)
- [8] Zhang, H., Wu, W., Hu, C., Hu, C., Li, M., Hao, X., Liu, S. (2021). A distributed hydrodynamic model for urban storm flood risk assessment. *Journal of Hydrology*, 600: 126513. <https://doi.org/10.1016/j.jhydrol.2021.126513>
- [9] Pantusoknaporn, W., Masthawee, F., Patsinghasanee, S., Kuntiyawichai, K. (2023). Assessment of flood mitigation services in Khon Kaen City through integrated modelling and scenario simulations. *Engineering and Applied Science Research*, 50(6): 664-675. <https://doi.org/10.14456/easr.2023.68>
- [10] Junianto, D., Hendriani, D. (2024). The influence of disaster simulation models on students' preparedness attitude values in social sciences subjects. *CENDEKIA: Jurnal Penelitian dan Pengkajian Ilmiah*, 1(1): 47-55. <https://doi.org/10.62335/k0zhsw43>
- [11] Soleman, S.R., Zahra, S.A., Sandra, F.A. (2024). Overview of knowledge about psychological first aid in disaster volunteers. *An Idea Health Journal*, 4(2): 38-44. <https://doi.org/10.53690/ihj.v4i02.223>
- [12] Yolanda, Y., Oktari, R.S., Sasaki, D., Sofyan, H. (2025). Spatial patterns and longitudinal trends of disaster losses in Aceh: A retrospective analysis. *IOP Conference Series: Earth and Environmental Science*, 1479(1): 012033. <https://doi.org/10.1088/1755-1315/1479/1/012033>
- [13] Rahman, B., Akmal, M., Muzaffarsyah, T., Yunanda, R. (2024). The effectiveness of flood management system in ACEH. *Environmental & Social Management Journal*, 18(6): e05000. <https://doi.org/10.24857/rgsa.v18n6-070>
- [14] Putra, A.Z.J., Masimin, M., Fatimah, E. (2018). Flood risk loss assessment on the Krueng Meureubo River. *Jurnal Arsip Rekayasa Sipil Dan Perencanaan*, 1(2): 172-182. <https://doi.org/10.24815/jarsp.v1i2.10966>
- [15] Arora, N.K., Mishra, I. (2022). Sustainable development goal 6: Global water security. *Environmental Sustainability*, 5(3): 271-275. <https://doi.org/10.1007/s42398-022-00246-5>
- [16] United Nations. (2023). *Blueprint for Acceleration: Sustainable Development Goal 6 Synthesis Report on Water and Sanitation 2023*. New York, NY, USA: United Nations.
- [17] Hasan, N., Pushpalatha, R., Manivasagam, V.S., Arlikatti, S., Cibin, R. (2023). Global sustainable water management: A systematic qualitative review. *Water Resources Management*, 37(13): 5255-5272. <https://doi.org/10.1007/s11269-023-03604-y>
- [18] Paudel, J. (2023). Challenges in water and sanitation services: Do natural disasters make matters worse? *Review of Development Economics*, 27(4): 2565-2582. <https://doi.org/10.1111/rode.13012>
- [19] Awang, S.S., Hassan, H.A., Fakuradzi, W.F.S.W.A. (2024). Disaster waste challenges and management during and post flood. *Zulfaqar Journal of Defence Science, Engineering & Technology*, 7(2): 1-6. <https://doi.org/10.58247/jdset-2024-0702-12>
- [20] Aldardasawi, A.M., Eren, B. (2021). Floods and their impact on the environment. *Academic Perspective Procedia*, 4(2): 42-49. <https://doi.org/10.33793/acperpro.04.02.24>
- [21] Borges Pedro, J.P., Oliveira, C.A.D.S., de Lima, S.C.R.B., von Sperling, M. (2020). A review of sanitation technologies for flood-prone areas. *Journal of Water, Sanitation and Hygiene for Development*, 10(3): 397-412. <https://doi.org/10.2166/washdev.2020.019>
- [22] Clara, B.F., Fauzi, M., Fatimah, E., Kiswanto, Fauzia, A. (2025). Eco-friendly sanitation system design for floating portable toilets in flood-prone regions. *IOP Conference Series: Earth and Environmental Science*, 1510(1): 012069. <https://doi.org/10.1088/1755-1315/1510/1/012069>
- [23] Merten, J., Nielsen, J.Ø., Soetarto, E., Faust, H. (2021). From rising water to floods: Disentangling the production of flooding as a hazard in Sumatra, Indonesia. *Geoforum*, 118: 56-65. <https://doi.org/10.1016/j.geoforum.2020.11.005>
- [24] Yamauchi, T. (2022). Interactions between health and socio-culture in sanitation. In *the Sanitation Triangle: Socio-Culture, Health and Materials*, Singapore: Springer Nature Singapore, pp. 91-100. [https://doi.org/10.1007/978-981-16-7711-3\\_6](https://doi.org/10.1007/978-981-16-7711-3_6)
- [25] Akpabio, E.M., Mwathunga, E., Rowan, J.S. (2022). Understanding the challenges governing Malawi's water, sanitation and hygiene sector. *International Journal of Water Resources Development*, 38(3): 426-446. <https://doi.org/10.1080/07900627.2021.1897947>
- [26] Bishoge, O.K. (2021). Challenges facing sustainable water supply, sanitation and hygiene achievement in urban areas in sub-Saharan Africa. *Local Environment*, 26(7): 893-907.

- <https://doi.org/10.1080/13549839.2021.1931074>
- [27] Umami, A., Sukmana, H., Wikurendra, E.A., Paulik, E. (2022). A review on water management issues: Potential and challenges in Indonesia. *Sustainable Water Resources Management*, 8(3): 63. <https://doi.org/10.1007/s40899-022-00648-7>
- [28] Wulandari, R., Iswara, A.P., Qadafi, M., Prayogo, W., Astuti, R.D.P., Utami, R.R., Jayanti, M., Awfa, D., Suryawan, I.W.K., Fitria, L., Andhikaputra, G. (2024). Water pollution and sanitation in Indonesia: A review on water quality, health and environmental impacts, management, and future challenges. *Environmental Science and Pollution Research*, 31(58): 65967-65992. <https://doi.org/10.1007/s11356-024-35567-x>
- [29] Akpabio, E.M., Wilson, N.A.U., Essien, K.A., Ansa, I.E., Odum, P.N. (2021). Slums, women and sanitary living in South-South Nigeria. *Journal of Housing and the Built Environment*, 36(3): 1229-1248. <https://doi.org/10.1007/s10901-020-09802-z>
- [30] Mutia, N., Fatimah, E., Suhendrayatna, S. (2018). Analysis of the results of community-based MCK plus development in Aceh Province. *Jurnal Arsip Rekayasa Sipil dan Perencanaan*, 1(1): 101-111. <https://doi.org/10.24815/jarsp.v1i1.10360>
- [31] Nuraini, E., Tawaf, N., Mustaqim, J. (2023). Portable toilet planning in refugee locations for natural disaster victims in Sumbawa Regency. *Jurnal SainTekA*, 4(3): 23-27. <https://doi.org/10.58406/sainteka.v4i3.1364>
- [32] Soshino, Y., Miyata, A. (2024). Innovative sanitation system for disaster victims and social sanitation challenges. In *Technology Innovation for Sustainable Development of Healthcare and Disaster Management*, pp. 159-177. [https://doi.org/10.1007/978-981-97-2049-1\\_9](https://doi.org/10.1007/978-981-97-2049-1_9)
- [33] Fatimah, E., Fauzi, M., Fauzia, A., Kiswanto, K., Abdullah, A., Clara, B.F., Syahna, D. (2023). Determination of design criteria for floating portable toilet applied at flood prone area. *International Journal of Disaster Management*, 6(2): 251-262. <https://doi.org/10.24815/ijdm.v6i2.33651>
- [34] Huebner, S. (2025). Coastal urban climate adaptation and the advance onto aquatic surfaces using floating solutions: Historical challenges and potential future benefits of floating homes and similar structures. *Ocean & Coastal Management*, 261: 107433. <https://doi.org/10.1016/j.ocecoaman.2024.107433>
- [35] Yang, M., Fu, X., Liu, H., Wang, L., Li, Q. (2024). Influencing factors, design methods, and buoyancy reduction measures for basement anti-flotation engineering. *Buildings*, 14(9): 3005. <https://doi.org/10.3390/buildings14093005>
- [36] Parung, H., Tumpu, M., Tjaronge, M.W., Amiruddin, A.A., Walenna, M.A., Mansyur. (2023). Crack pattern of lightweight concrete under compression and tensile test. *Annales de Chimie: Science des Matériaux*, 4(1): 35-41. <https://doi.org/10.18280/acsm.470105>
- [37] Puspitasari, E.T., Dewi, S.M., Soehardjono, D.A. (2023). Experimental study of flexural capacity strength in-plane load on wall panels using autoclaved aerated concrete block and bamboo reinforcement. *International Journal of GEOMATE*, 24(103): 17-25. <https://doi.org/10.21660/2023.103.3325>
- [38] Zahranti, F.A. (2024). Stability analysis of floating portable toilet on water surface. Undergraduate thesis, Universitas Syiah Kuala, Banda Aceh, Indonesia. [https://etd.usk.ac.id/search/index.php?p=show\\_detail&i d=123624](https://etd.usk.ac.id/search/index.php?p=show_detail&i d=123624)
- [39] Suwondo, R., Keintjem, M. (2024). Embodied carbon reduction strategies for steel structures: A parametric design approach. *Asian Journal of Civil Engineering*, 25: 3215-3223. <https://doi.org/10.1007/s42107-023-00973-y>
- [40] Ministry of Health of the Republic of Indonesia. (2022). Regulation of the Minister of Health Number 2 of 2020 concerning Children's Anthropometric Standards. Jakarta, Indonesia: Ministry of Health. <https://peraturan.bpk.go.id/Details/152505/permenkes-no-2-tahun-2020>
- [41] Liguori, A., Formato, A., Pellegrino, A., Villecco, F. (2021). Study of tank containers for foodstuffs. *Machines*, 9(2): 44. <https://doi.org/10.3390/machines9020044>
- [42] Setjo, T.B., Saptomo, S.K., Wirasembada, Y.C. (2017). Planning of a communal septic tank in Suwaru Village, Pagelaran District, Malang Regency, East Java 2017. *Jurnal Teknik Sipil dan Lingkungan*, 1(3): 159-173. <https://agris.fao.org/search/en/providers/122323/records/685175f453e52c13fc76c0c9>
- [43] Alami, A.H., Ayoub, M., Yasin, A., Alashkar, A., Aljaghoub, H., Alabdalla, S.A. (2023). Performance assessment of buoyancy work energy storage system with various buoy materials, coatings, and gasses. *Journal of Energy Storage*, 72: 108524. <https://doi.org/10.1016/j.est.2023.108524>
- [44] Varkey, M.V., Philip, P.M. (2022). Flood risk mitigation through self-floating amphibious houses-Modelling, analysis, and design. *Materials Today: Proceedings*, 65: 442-447. <https://doi.org/10.1016/j.matpr.2022.02.547>
- [45] Li, X., Wen, H., Fu, J., Zhang, X., Zhou, H., Yao, B., Lian, L., Yu, D., Mao, L. (2023). Modeling and system analysis of floating underwater vehicle with variable mass and center of gravity. *Ocean Engineering*, 267: 113303. <https://doi.org/10.1016/j.oceaneng.2022.113303>
- [46] Alamsyah., Hijrah, M.F., Setiawan, W., Pawara, M.U., Wulandari, A.O., Suardi, Habibi. (2025). Static and dynamic stability analysis of liftnet fishing vessel. *AIP Conference Proceedings*, 3032: 070004. <https://doi.org/10.1063/5.0264749>
- [47] Sun, X., Ni, Y., Liu, C., Wang, Z., Yin, Y. (2021). A practical method for stability assessment of a damaged ship. *Ocean Engineering*, 222: 108594. <https://doi.org/10.1016/j.oceaneng.2021.108594>
- [48] Syahna, D. (2024). Design and development of a floating portable toilet in flood-prone areas. Undergraduate thesis, Syiah Kuala University, Banda Aceh, Indonesia. Retrieved from Universitas Syiah Kuala ETD Repository. [https://etd.usk.ac.id/search/index.php?p=show\\_detail&i d=121818](https://etd.usk.ac.id/search/index.php?p=show_detail&i d=121818)
- [49] Ramadhan, R. (2024). Physical model study of floating portable toilet under wave influence. Undergraduate thesis, Syiah Kuala University, Banda Aceh, Indonesia. Retrieved from Universitas Syiah Kuala ETD Repository. [https://etd.usk.ac.id/search/index.php?p=show\\_detail&i d=123625](https://etd.usk.ac.id/search/index.php?p=show_detail&i d=123625)
- [50] Wang, Y., Feng, G., Lin, N., Lan, H., Li, Q., Yao, D., Tang, J. (2023). A review of degradation and life prediction of polyethylene. *Applied Sciences*, 13(5): 3045. <https://doi.org/10.3390/app13053045>
- [51] Wijewickrama, L., Jeewantha, J., Perera, G.I.P.,

- Alajarmeh, O., Epaarachchi, J. (2025). Fiber-reinforced composites used in the manufacture of marine decks: A review. *Polymers*, 17(17): 2345. <https://doi.org/10.3390/polym17172345>
- [52] Gencil, O., Bilir, T., Bademler, Z., Ozbakkaloglu, T. (2022). A detailed review on foam concrete composites: Ingredients, properties, and microstructure. *Applied Sciences*, 12(11): 5752. <https://doi.org/10.3390/app12115752>
- [53] Sulik, P., Kukfisz, B., Dowbysz, A., Oszczak-Nowińska, A. (2024). Fire resistance of foamed concrete for discontinuous partition filling. *Materials*, 17(6): 1315. <https://doi.org/10.3390/ma17061315>
- [54] Rui, S., Zhou, Z., Gao, Z., Jostad, H.P., Wang, L., Xu, H., Guo, Z. (2024). A review on mooring lines and anchors of floating marine structures. *Renewable and Sustainable Energy Reviews*, 199: 114547. <https://doi.org/10.1016/j.rser.2024.114547>