

Original Research

Structural Stability Modeling of Submersible Threshold Micro-Dams under Ultra-Low Hydraulic Head Conditions

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Abstract

Structural stability assessment of compact hydraulic structures operating under ultra-low hydraulic head conditions (<0.5 m) remains insufficiently addressed in current dam engineering literature. Submersible threshold micro-dams (STHMD), characterized by limited structural height, reduced stabilizing moment, and permanent or periodic submergence, require a dedicated mechanical modeling approach distinct from conventional large-dam methodologies. This study develops a structural stability modeling framework for STHMD systems that integrates analytical equilibrium formulations and three-dimensional finite-element simulations. The proposed model unifies hydrostatic thrust, sediment pressure, uplift forces, and foundation reaction within a unified mechanical representation. The study verifies stability by systematically evaluating sliding, overturning, and uplift failure modes in



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accordance with conventional safety criteria (ICOLD, USBR). Analytical modeling yields safety factors of 12.7 for sliding, 15.8 for overturning, and 10.9 for uplift, while numerical simulations confirm structural rigidity with maximum displacement limited to 0.0139 mm and negligible volumetric strain. The combined analytical–numerical approach provides insight into load–interaction mechanisms and structural response under ultra-low head conditions. The proposed framework clarifies the mechanical behavior of the STHMD at micro-scale dimensions and establishes a reproducible methodology for structural stability modeling of compact hydraulic structures in low-gradient river environments.

Keywords

Micro-dam; structural stability; sustainable infrastructure; rural electrification; micro-hydroelectricity

1. Introduction

Access to reliable electricity in rural areas of developing countries remains a persistent challenge, particularly in regions where centralized power grids are either inaccessible or economically unfeasible. Very low-head micro-hydropower plants (head < 0.5 m) constitute a technically viable solution for decentralized energy production in low-gradient rivers. Among the various civil engineering configurations that have undergone stability assessment [1, 2], STHMDs represent compact hydraulic structures designed to operate without river diversion or significant water impoundment, thereby minimizing environmental impact and construction complexity.

Despite growing interest in very low-head hydropower technologies, research has focused primarily on hydraulic optimization, turbine performance, and electromechanical integration [3]. In contrast, the mechanical stability modeling of concrete submersible thresholds operating under extremely low-head conditions has received comparatively limited attention. Stability assessment methodologies commonly applied to hydraulic structures are largely derived from established design principles developed for medium- and large-scale gravity, rockfill, or embankment dams [4–6], where geometric scale, structural mass, and load distribution differ significantly from those of compact micro-dams [7]. As summarized in Table 1, existing stability frameworks for hydraulic structures either developed for large-scale gravity dams under substantial hydraulic heads and rely on detailed geotechnical data or physical-model testing, or focus on slope stability of small earthen structures using geotechnical software rather than a combined equilibrium-FEM cross-verification.

Table 1 Comparison of the present framework with exiting stability approaches for hydraulic structures.

Variables	Typical hydraulic head	Failure modes considered	Foundation characterization	Validation approach	References
Large-scale concrete gravity dams	>15 m	Sliding, overturning, uplift (often + seismic)	Detailed geotechnical, rock-joint characterization, and seepage analysis	FEM, reliability, Monte Carlo methods, field monitoring	[8-12]
Small/Earthen dams and embankments	Few meters	Slope stability, seepage, and sliding	Site-specific geotechnical investigation	Slope stability software (Geostudio), field data	[13-15]
Concrete buttress dams	Moderate	Sliding, overturning, under hydrostatic loading	Measured structural material properties	Physical scale model testing	[16]
Submersible threshold micro-dams (STHMD)- Present study	Ultra-low (<0.5-2 m)	Sliding, overturning, uplift	Design stage, rigid foundation assumption	Combined analytical and 3D FEM cross verification	This study

This comparison highlights the specific gap the present study addresses: the mechanical stability assessment of compact, STHMD structures under ultra-low hydraulic head conditions.

Conventional stability verification is based on analytical force equilibrium and safety factor evaluation for sliding, overturning, and uplift, in accordance with international guidelines such as those of ICOLD (CIGB) and the USBR [17, 18]. These analytical frameworks provide robust criteria for large-scale dams, ensuring safety factors exceed prescribed minimum thresholds presented in Table 2 [8, 19-21].

Table 2 Main stability criteria recommended for hydraulic structures.

Type of stability	Associated coefficient symbol used	Reference values
Sliding	F_{Sli}	1.5
Overturning	F_{Srev}	2.0
Uplifting	F_{Supl}	1.5

However, applying these frameworks directly to very low-head submersible structures raise fundamental mechanical questions. At the micro-scale, stabilizing self-weight is inherently limited, whereas uplift pressure, sediment loading, and foundation interaction may contribute proportionally more to destabilization [22-24]. Furthermore, periodic or permanent submergence alters stress distributions and hydrostatic boundary conditions compared to those in conventional gravity dam configurations.

The mechanical behavior of the STHMD is therefore governed by scale-dependent characteristics, including reduced structural height, constrained stabilizing moments, high sensitivity to foundation friction parameters, sediment deposition effects, and seepage phenomena. Existing studies on small dam stability have examined seepage forces, embankment reinforcement, seismic effects, and foundation improvement techniques [13-15, 25, 26]. However, these investigations do not establish a dedicated structural stability modeling framework specifically tailored to compact concrete thresholds operating under extremely low hydraulic loads.

A significant methodological gap, therefore, remains in developing a mechanical modeling approach capable of systematically representing the combined action of hydrostatic thrust, sediment pressure, uplift forces, and foundation reaction within a unified equilibrium formulation for STHMD. Moreover, the mechanical relevance and scale applicability of conventional safety factors under extremely low hydraulic loading conditions remain insufficiently addressed in the literature. A rigorous analytical and numerical modeling strategy is therefore required to evaluate structural response and verify the applicability of classical stability criteria at the micro-scale.

In this context, the present study develops a structural stability-modeling framework for STHMD operating under extremely low hydraulic loads. The hydraulic and energy-production design of the STHMD, including channel sizing, was developed in a previous study [27]; the present study builds on that geometric configuration to develop, for the first time, a dedicated structural stability framework for this structure. The proposed approach combines analytical equilibrium formulations with three-dimensional finite element modeling (FEM) using COMSOL Multiphysics to assess resistance against sliding, overturning, and uplift. The objective is to provide a consistent mechanical representation of load interactions and structural response, and to establish a reproducible methodology for evaluating the stability of compact concrete thresholds in very low-

gradient rural rivers. The present framework is therefore intended as a preliminary, design-stage stability assessment, to be complemented by field validation once the structure is built and instrumented. Beyond its structural contribution, this study is relevant to sustainable water resource management in rural, off-grid settings. Unlike impounding dams, the STHMD is designed to allow a continuous base flow to pass over the threshold under normal operating conditions, and to be fully overtopped during flood events, rather than permanently storing the river's discharge. This operating principle limits how much the structure interrupts natural flow continuity, compared to conventional storage dams. The structure further enables small-scale, low-carbon hydroelectric power generation for rural electrification, reducing reliance on diesel generators and biomass-based energy sources in remote communities such as those along the Douni River. Establishing a validated structural stability framework for this class of compact, low-head, continuously overflowing structures is therefore a prerequisite for the broader deployment of such water resource infrastructure in rural development contexts, in line with sustainable and low-impact water management practices.

2. Materials and Methods

2.1 Site Presentation and Project Context

The studied STHMD is intended for a river application (the Douni River) (Figure 1), non-navigable with very low elevation (<0.2 m), typical of rural areas in the northern part of the Republic of the Congo, in the Cuvette basin department, in the sub-prefecture of Makoua, at the village of Issongo.



Figure 1 River Douni-village Issongo, Cuvette, Republic of the Congo.

The micro hydroelectric dam designed for the River La Douni is shown in Figure 2. The estimated minimum electric energy production for the STHMD was 10 kW for rural electrification.

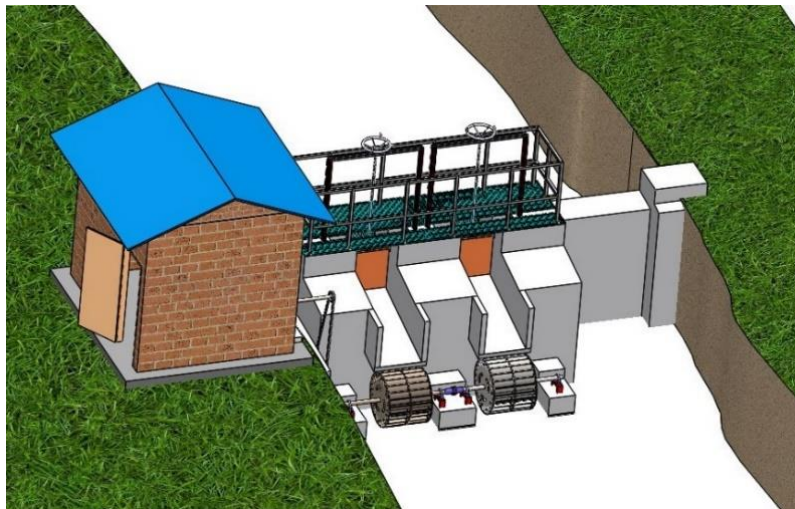


Figure 2 Presentation of the STHMD.

After various measurements, this submersible weir micro-dam was designed to accelerate water flow, driving two cross-flow turbines through these flow channels to generate electricity (around 10 kW) for rural communities. The micro-dam with its channels is directly integrated into the river. The main objective is to develop mathematical models for the stability study of this type of micro-dam.

2.2 Geometric Configurations of the STHMD

The STHMD is dimensioned according to the configuration comprising two identical parallel rectangular flow channels with a slope of 21.8° . Each has an oblique length of 2.7 m, a width of 0.6 m, and an inner usable height of 0.45 m by 0.8 m, intended to supply two cross-flow turbines coupled in the context where the diversion of the watercourse is not conceivable with respect to the topology of the site. In addition, a central submersible weir, 2.6 m long, 2.2 m high, and 0.8 m wide at the bottom and 0.5 m wide at the top, allows flood passage. The geometric shape of the STHMD for electricity production is made of reinforced concrete (steel and clean concrete). It is composed of three parts: the central part (part 1), which corresponds to the geometry of the flow channels, with a rectangular trapezoidal shape, and an open access part. The second part (part 2) corresponds to the geometry of the submersible threshold, with a trapezoidal shape, and the third part (part 3) corresponds to the lateral buttresses at the ends of the dam. The micro-dam's foothills are rectangular and identical on both sides, with respect to the length of the structure. Recall that a previous study reported the hydraulic and energy-production design of the STHMD, including channel sizing [27]. The present study builds on that geometric configuration to develop, for the first time, a dedicated structural stability framework for the STHMD. The overall configuration of the micro-dam is given by the following (Figure 3) [27].

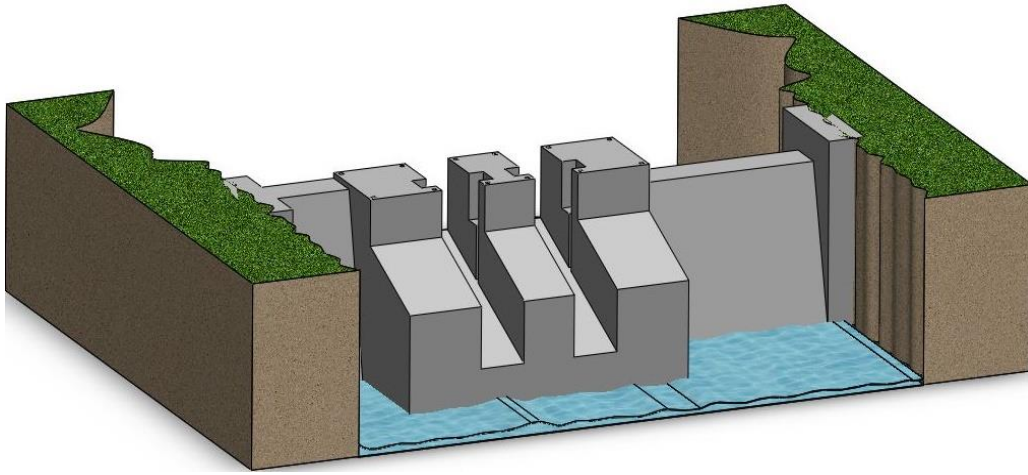


Figure 3 Conceptual presentation of the submersible threshold hydraulic micro dam (STHMD) [27].

The general dimensions of the STHMD, represented in Figure 4 and its different parts, allow for better sizing of the hydraulic structure and better analysis of stability, as shown in the following Table 3.

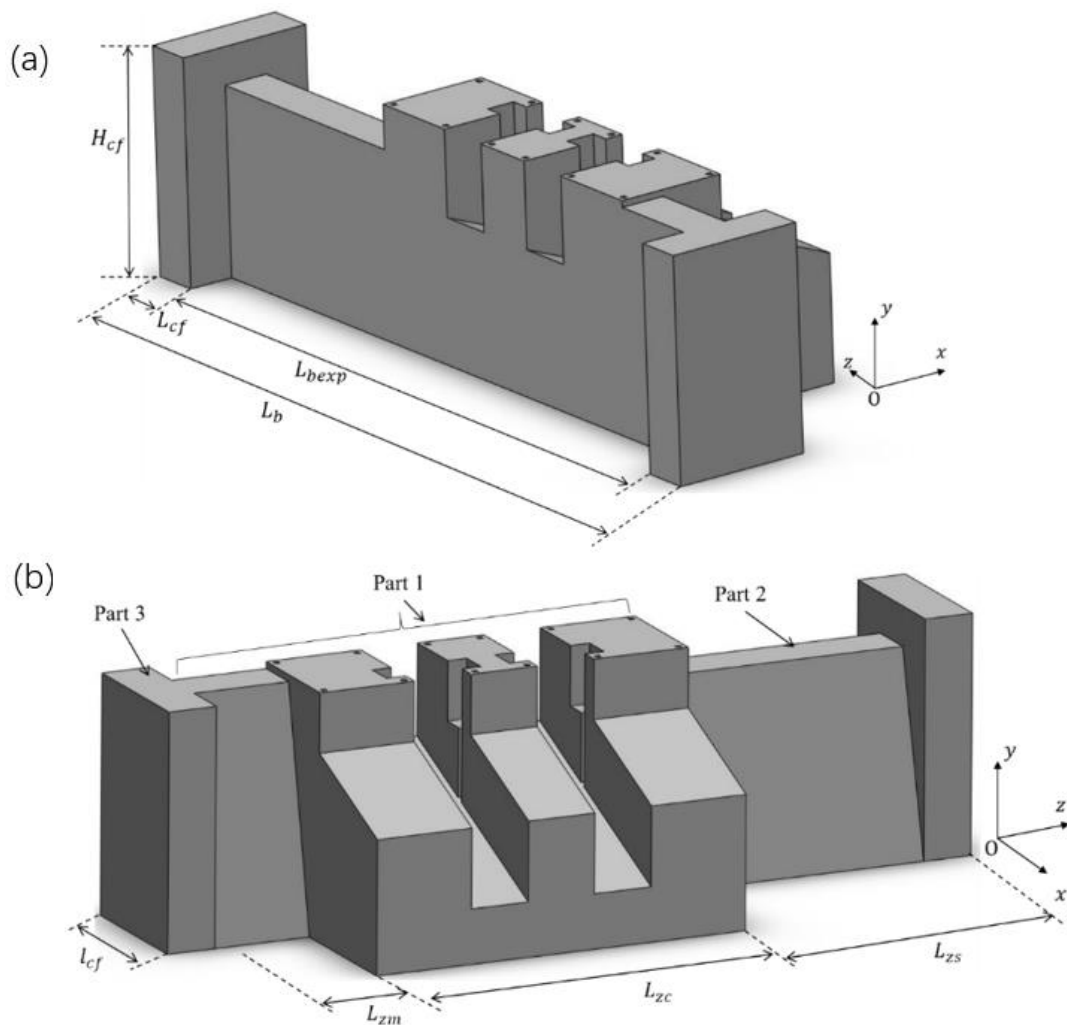


Figure 4 Different parts of the STHMD: (a) view upstream, (b) view downstream.

Table 3 Overall dimensions of the STHMD.

Variables	Symbol	Unit	Values
Height dam	H_1	m	2.67
Height of the downstream dam	H_2	m	1.55
Dam length	L_b	m	8.5
Exploitable length	L_{bexp}	m	7.5
Length of zone channels	L_{zc}	m	2.7
Submersible threshold length	L_{zs}	m	2.6
Counter length	L_{cf}	m	1
Length zone maintains	L_{zm}	m	0.5
Dam mass	m_b	t	62
Dam volume	V_b	m ³	26

Table 4 presents the dimensions of the central part of the structure (part 1), corresponding to the micro-dam's water-flow channels, based on the hydrodynamic flow study results.

Table 4 Central dimensions part, geometry of the micro-dam flow channels.

Variables	Symbol	Unit	Values
Upstream height channel	H_{bc}	m	2.67
Downstream height	H_2	m	1.55
Length zone channels	L_{zc}	m	2.7
Width of the dam zone channel	l_{bc}	m	2.5
Head length 1	L_1	m	1
Head length 2	L_2	m	0.7
Head width	l_1	m	1.2
Head height	h	m	0.6

The geometric shape and configuration of this central part are illustrated by the following Figure 5.

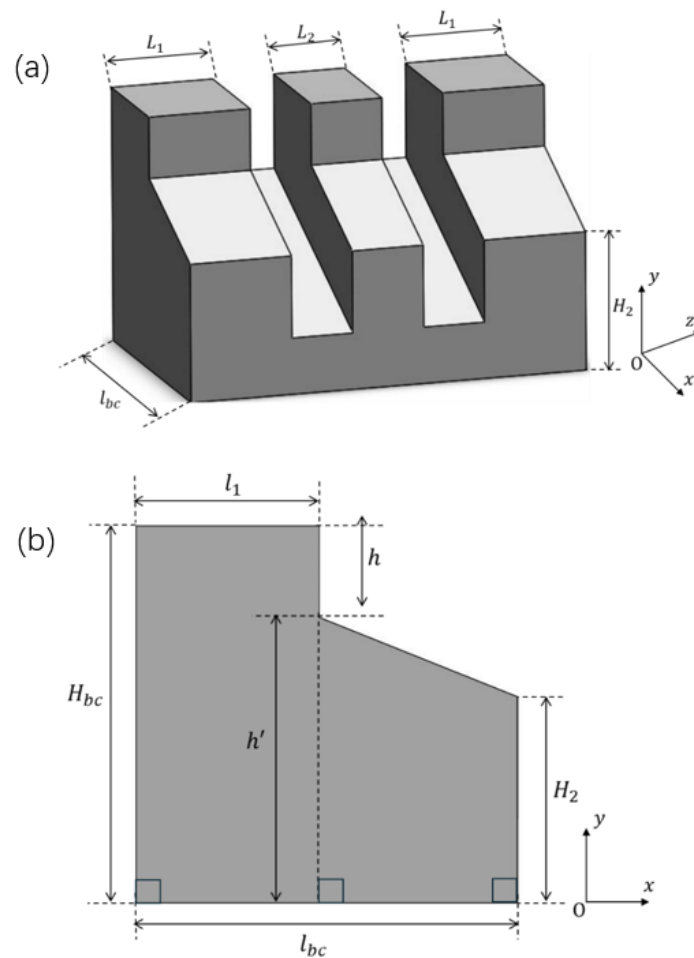


Figure 5 Presentation of the first part: (a) 3D view, (b) view of the trapezoidal-rectangular shape at the level of the flow channels.

The dimensions of the submersible sill and side buttresses, corresponding to part 2 and part 3, illustrated in Figure 6, are also mentioned in the following Table 5 according to the direction and plan of the river.

Table 5 Dimensions of the buttresses and submersible threshold.

Variables	Symbol	Unit	Values
Threshold height	H_s	m	2.2
Threshold length	L_{zs}	m	2.6
Threshold width	L_{2s}	m	0.5
Counterfort height	H_{cf}	m	2.6
Counterfort width	l_{cf}	m	1.5
Counter length	l_{cf}	m	0.5

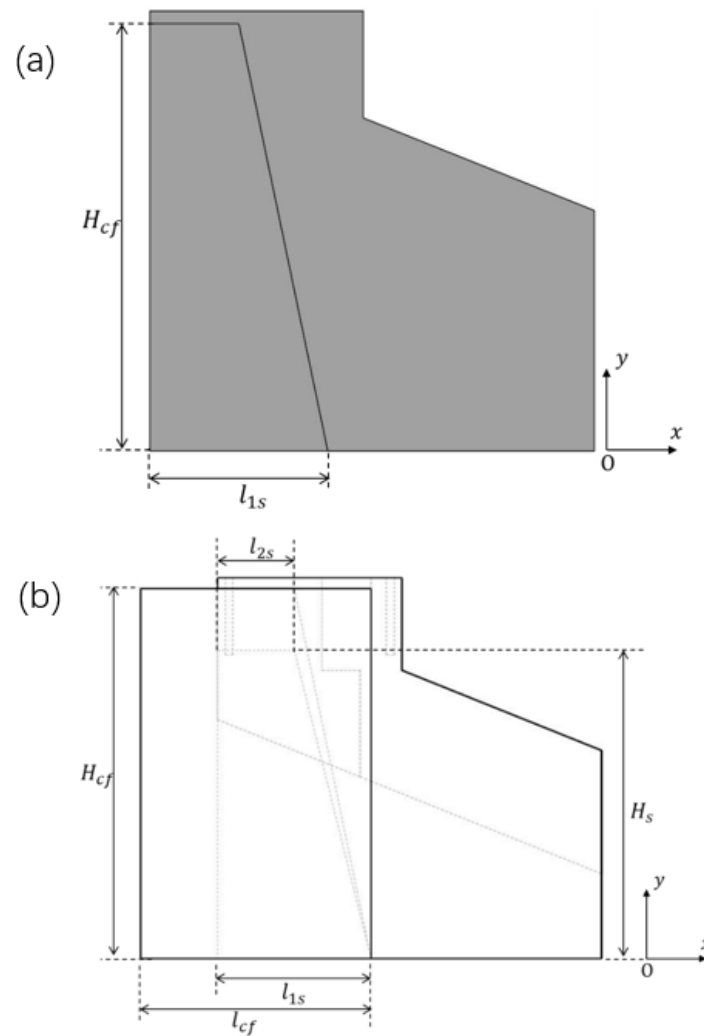


Figure 6 Presentation of the geometric shape: (a) side view of the buttresses, (b) submersible sides of the STHMD.

The following figures illustrate each dimension in relation to the structure's geometry, as presented in Figure 4, which clearly shows the threshold submersible and lateral buttresses.

2.3 Modeling of the Stability Equation of the STHMD

The analysis of dam stability is based on the identification and evaluation of mechanisms likely to compromise its structural integrity. The conventional methods consider three fundamental verifications (sliding, overturning, uplift). The following simplifying assumptions allow this study to be carried out effectively. The structure is modelled as a gravity dam subject to gravity forces; the upstream hydrostatic pressure is assumed triangular, based on the maximum water head; the downstream pressure and thrust are considered negligible under normal operating conditions and are assumed to vary with sill submergence and flow through the channels because of a supercritical flow regime occurring over the STHMD at the operating water levels. The abutments are assumed rigid and uncracked in the main calculation. The STHMD is founded on a rigid base, which does not contribute to sliding resistance through adhesion. The assumption of rigid foundations was adopted in this study in order to represent a conservative case corresponding to favourable geotechnical conditions, such as foundations on sound rock or highly compacted soil, which are frequently

encountered at micro-hydraulic structure sites. No dedicated geotechnical investigation (borehole logging, in situ shear testing, or permeability testing) has yet been conducted at the site; the friction angle and the linear piezometric uplift distribution adopted here follow standard preliminary-design assumptions recommended by ICOLD/USBR guidelines [8, 17, 18], rather than site-specific measurements. This choice is further justified by the study's preliminary nature, which aims to assess the overall stability of the structure prior to detailed geotechnical investigations. The sliding resistance calculation excludes cohesion and adhesion, which is a conservative assumption for the rock-founded condition of the structure. This study does not include checks for tensile and compressive stresses, as the structure falls into the massive, low-height, and low-slenderness category, where stress verification is typically not governing. The overall rigidity of the massif and the homogeneous distribution of vertical loads ensure a quasi-uniform transfer of stresses to the ground, thereby reducing the risk of exceeding permissible limits. As the structure is at the preliminary design stage, a perfect bond between steel and concrete was assumed, consistent with standard design practice. Seismic effects are not considered because the Republic of Congo has a low seismic hazard [28-30]. The fundamental relationships given generally apply to different types of dams (in earth with a drainage, weights, buttresses, etc.); the micro-dam studied is a complex of different forms. Given that the structure is composed of three substructures, the following equations provide an analytical model for the STHMD, adapted to the different safety factors based on the hydraulic parameters. In this study, the analytical calculations of the parameters are carried out per unit length along the river's width, simplifying the equations while preserving unit homogeneity and maintaining the model's generality. However, the model is numerically simulated by multiplying the different real lengths of the studied structure.

2.3.1 Geometric Conceptual Model of the Hydraulic Structure

The model of the different parts constituting the STHMD is represented by three parts (the central part with an associated block, the submersible threshold, and the buttresses). The lateral joints at the ends of this structure are entirely linked into the banks. Each sub-part contributes differently to stabilizing (self-weight, leverage) and destabilizing (hydrostatic thrust, sediments, and lifting) efforts. It is assumed that, after the flow in the channels and at the submersible threshold, the downstream thrusts (downstream water and sediments) are negligible compared to the upstream thrusts, due to supercritical flow. The composition of the micro-dam is described through three distinct models, as detailed in the subsections (a), (b) and (c).

(a) Since the model of the central part of length L_{zc} is not a conventional dam model, it is a composite of a rectangle and a trapezoidal prism, illustrated by the Figure 7 below:

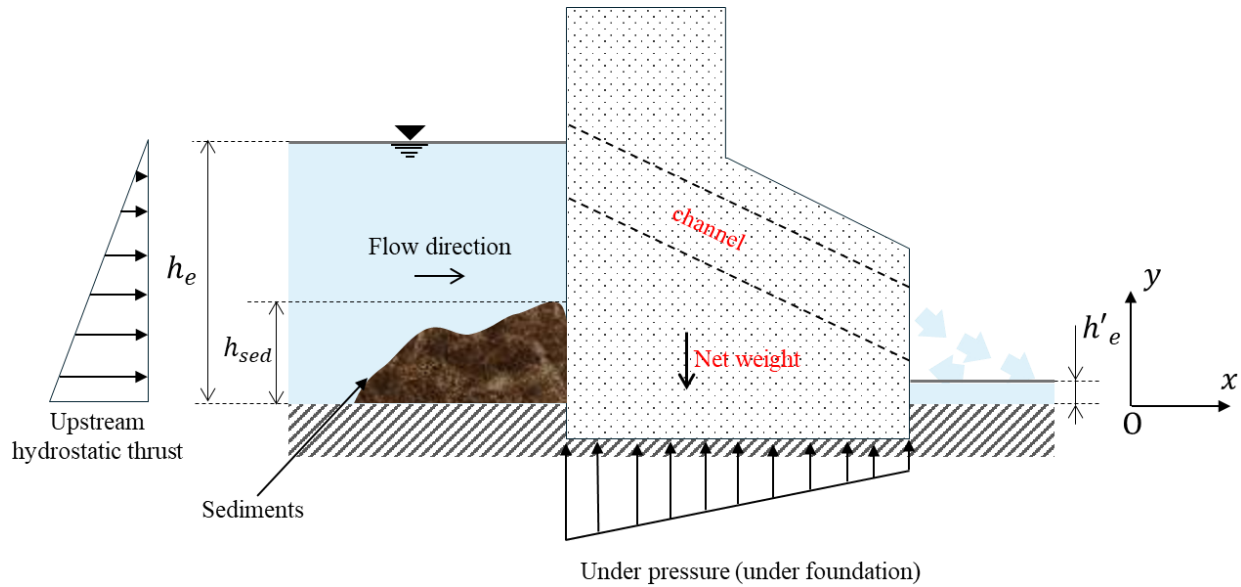


Figure 7 Conceptual model of the central part of the STHMD.

A trapezoidal block is also associated with this model, as shown in Figure 4, with a length L_m at the submersible threshold shape. In this figure, the upstream water depth considered at the maximum height of the submersible threshold is noted h_e (m) and h'_e (m) is the downstream water depth. The calculation of the geometric parameters of the central part makes it possible to establish the relationships between weight and center of gravity [9, 10, 31]:

- The weight of the central part W_{pc} (kN) is determined by the product of the relative volume and the specific gravity of concrete γ_c (kN). From Figure 5 and Figure 7, the weight can be determined by the following relationship:

$$W_{pc} = \gamma_c \left[H_{bc}l_1 + H_{cf}l_{2s} + \frac{H_{bc} + H_2 - h}{2} (l_{bc} - l_1) + \frac{1}{2} H_{cf}(l_{1s} - l_{2s}) \right] \quad (1)$$

- The relative lever arm x_{pc} (m) measured from the downstream bead can be calculated by the following relation:

$$x_{pc} = \frac{1}{2}l_1 + (l_{bc} + l_1) + \frac{1}{3} \left(5l_{1s} - \frac{7}{2}l_1 \right) + \frac{l_{bc} - l_1}{3} \frac{(H_{bc} - h) + 2H_2}{(H_{bc} - h) + H_2} \quad (2)$$

(b) The submersible threshold model (part 2) of the micro-dam has a rectangular shape, illustrated by the Figure 8 below:

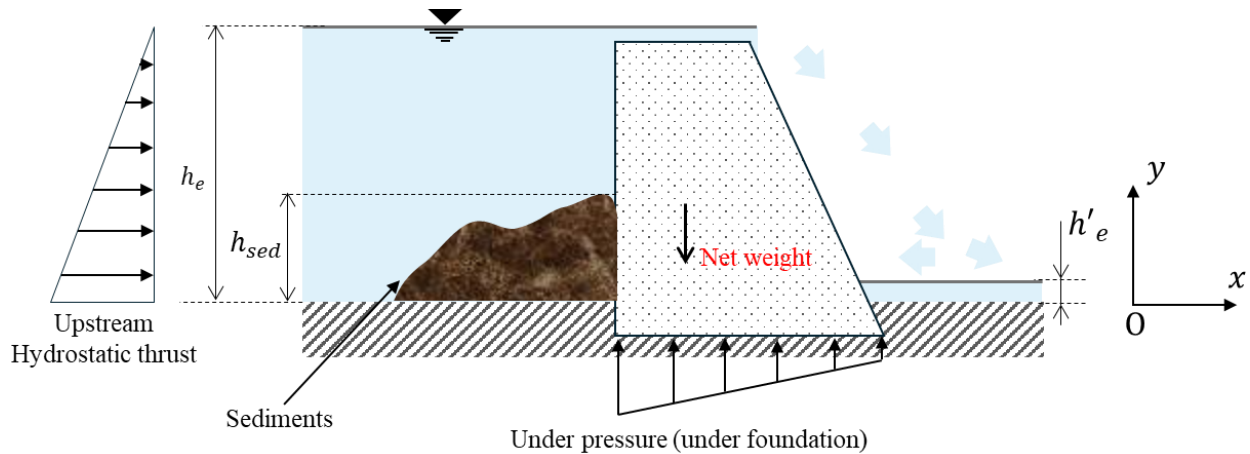


Figure 8 Conceptual model of the STHMD submersible threshold.

The calculation of the geometric parameters in this part allows establishing the following relationships with respect to Figure 6 and Figure 8 [9, 10, 31]:

- Weight at the submersible threshold W_s (kN):

$$W_s = \gamma_c H_s \left[l_{2s} + \frac{1}{2} (l_{1s} - l_{2s}) \right] \quad (3)$$

- The relative leverage x_s (m) measured from the downstream heel:

$$x_s = \frac{1}{3} \left(5l_{1s} - \frac{7}{2} l_{2s} \right) \quad (4)$$

(c) The model of the lateral buttresses (part 3) is illustrated in Figure 9, is a rectangular block. These lateral buttresses of the structure studied are not directly exposed to hydrostatic thrusts, as they are housed in the banks; they increase the equivalent base of the structure and contribute greatly to the stabilizing moment.

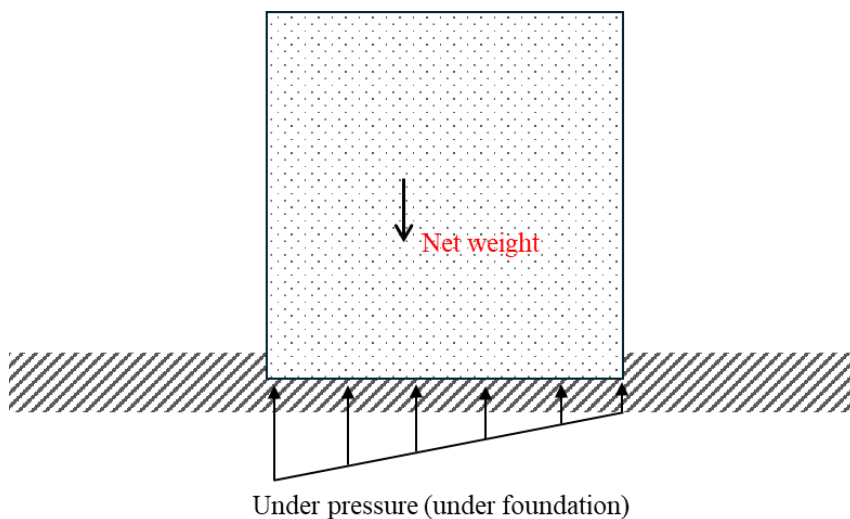


Figure 9 Lateral counterfort model of the STHMD.

From Figure 6 and Figure 9, it is easily shown that the geometric parameters related to the model can be determined by the relationships below [9, 10, 31]:

- Weight at the level of the buttresses W_{cf} (kN):

$$W_{cf} = 2\gamma_c H_{cf} l_{cf} \quad (5)$$

- The relative lever arm x_{cf} (m) measured from the downstream heel:

$$x_{cf} = \frac{1}{2} l_{cf} \quad (6)$$

These relationships allow the stabilizing moments of each component part of the micro-dam of the entire hydraulic structure to be directly determined.

2.3.2 Equation of Thrusts and Moments on the STHMD

Segmenting the work into three parts allows evaluation of the parameters of the separate structures; this approach then enables determination of the moments and hydrostatic thrust for the entire STHMD.

The Stabilizing Moment.

The stabilizing moment of the STHMD is essentially provided by the self-weight of the superstructure's elements. It is the first source of stability because the structure's weight resists external forces. Each block contributes proportionally to its density and its vertical-zonal lever arm relative to the downstream pivot. Volume sizing is therefore a key element to ensure sufficient leverage to counter increasing hydrostatic moments as the water level rises.

- The total weight of the micro-dam $W_{mb}^{(t)}$ (kN) per meter of length is deduced by summing the relative weights [31]:

$$W_{mb}^{(t)} = \sum_{i=1}^n W_{part}^{(n)} \quad (7)$$

Considering equations (1), (3), and (5), the total weight is deduced by:

$$W_{mb}^{(t)} = W_{pc}^{(1)} + W_s^{(2)} + W_{cf}^{(3)} \quad (8)$$

- The total stabilizing moment $M_s^{(t)}$ (kN·m) of the micro-dam can be given from the following relation:

$$M_s^{(t)} = \sum_{i=1}^n W_{part}^{(n)} x_{part}^{(n)} \quad (9)$$

The equation can be rewritten as follows, given that the structure consists of three parts:

$$M_s^{(t)} = W_{pc}^{(1)} x_{pc}^{(1)} + W_s^{(2)} x_s^{(2)} + W_{cf}^{(3)} x_{cf}^{(3)} \quad (10)$$

where: x_{pc} , x_s , and x_{cf} denote the horizontal lever arms of the central part, threshold, and buttresses, respectively, measured from the downstream heel of the structure.

The Destabilizing Moment.

This parameter is mainly governed by the hydrostatic thrust exerted perpendicularly on the upstream vertical faces of the micro-dam. It is also sometimes called overturning. It is admitted that the lateral buttresses embedded in the banks do not receive the upstream thrust. The pivot point lies at the edge of the reference frame.

- The hydrostatic thrust or force applied to the upstream vertical walls of the STHMD is determined from the integration of the hydrostatic thrust on submerged surfaces; for a portion of the water column between depths y and water height H_e (m) it is shown that the total hydrostatic thrust $P_{dh}^{(t)}$ (kN) is given by the relationship below [11, 21, 32]:

$$P_{dh}^{(t)} = \frac{1}{2} \gamma_w (H_e^2 - y^2) \quad (11)$$

where: γ_w ($\text{kN}\cdot\text{m}^{-3}$) is the water density, y is the variation of loads along the vertical axis.

- Considering the depths y and water height H_e (m), it is also shown that the hydrostatic destabilizing moment $M_{dh}^{(t)}$ ($\text{kN}\cdot\text{m}$) is calculated by the following relationship:

$$M_{dh}^{(t)} = \frac{1}{6} \gamma_w (H_e - y)^2 (H_e - 2y) \quad (12)$$

The Destabilizing Moment of the Sediments.

Sedimentary deposits upstream modify the stress state on the upstream face of the micro-dam. Sediments are deposits transported by energy loss; they generally behave like saturated soil, exerting additional lateral pressure, often modelled from the Rankine theory. It contributes in a non-negligible way to the destabilizing moments integrated into glide and overthrow calculations.

- The sediment thrust $P_{d, sed}^{(t)}$ (kN) over a portion of y and sediment height H_{sed} (m) also called sedimentary force, relative to the STHMD, can be determined by the following relationship [19, 20]:

$$P_{d, sed}^{(t)} = \frac{1}{2} k_a (\gamma_{sed} - \gamma_w) (H_{sed}^2 - y^2) \quad (13)$$

where: k_a is the active thrust coefficient, γ_{sed} ($\text{kN}\cdot\text{m}^{-3}$) is the volumetric weight of sediments and H_{sed} (m) is the upstream height of sediments.

- As applied to the destabilizing moment of hydrostatic thrust at equation (12), the destabilizing moment of sediments is deduced by equation (13):

$$M_{d, sed}^{(t)} = \frac{1}{6} k_a (\gamma_{sed} - \gamma_w) (H_{sed} - y)^2 (H_{sed} - 2y) \quad (14)$$

The Moment of Lifting.

The pressure due to uplift under the footing is obtained by integrating the hydrostatic pressure acting on the immersed foundation surfaces. In the case of the structure studied, the downstream water level is assumed negligible compared to the upstream height, corresponding to a free regime

downstream of the submersible threshold. The uplift pressure distribution is then linear between the total upstream load and a zero pressure downstream.

- The total uplift pressure $P_{upl}^{(t)}$ (kN) of the STHMD is established as follows [11, 32]:

$$P_{upl}^{(t)} = \frac{1}{2} \gamma_{\omega} (l_{1s} - l_{cf} + l_{bc}) H_e \quad (15)$$

- The lifting moment $M_{upl}^{(t)}$ (kN·m) in relation to the pivot axis at the base of the downstream foot is given by the following relationship:

$$M_{upl}^{(t)} = \frac{1}{2} \gamma_{\omega} (l_{bc} + l_{1s} - l_{cf}) \left[\frac{1}{2} l_1 + \frac{5}{3} (l_{bc} - l_1) + \frac{4}{3} l_{1s} \right] H_e \quad (16)$$

2.3.3 Equilibrium Equation of Thrusts and Moments on the STHMD

The stability of the dam is evaluated on classical equilibrium equations governing sliding, overturning, and uplift. These equations provide a quantitative assessment of structural safety with respect to the principal failure mechanisms, in accordance with commonly accepted hydraulic engineering guidelines.

- The ratio of vertical stabilization forces $F_v^{(t)}$ (kN) and horizontal forces $F_h^{(t)}$ (kN) defines the sliding safety factor FS_{slt} as follows [16, 32, 33]:

$$FS_{slt} = \frac{\sum_{i=1}^n F_v^{(n)}}{\sum_{i=1}^n F_h^{(n)}} \tan(\delta) \quad (17)$$

The application of this relation to the studied model, using equations (7), (11), (13) and (15), allows establishing the safety coefficient at the following sliding [11, 12]:

$$FS_{slt} = \frac{(W_{mb}^{(t)} - P_{upl}^{(t)})}{P_{dh}^{(t)} + P_{d.sed}^{(t)}} \tan(\delta) \quad (18)$$

where: δ (°) is the foundation friction angle.

- The safety factor for reversal FS_{rev} is determined by the following relation [11, 12, 32]:

$$FS_{re} = \frac{\sum_{i=1}^n M_s^{(i)}}{\sum_{i=1}^n M_d^{(i)}} \quad (19)$$

This relationship highlights the ratio of stabilizing to destabilizing moments. By applying relation (19) to the model of the studied work, this coefficient is deduced by relation (20):

$$FS_{re} = \frac{M_{pc}^{(1)} + M_s^{(2)} + M_{cf}^{(3)}}{M_{dh}^{(t)} + M_{sed}^{(t)} + M_{upl}^{(t)}} \quad (20)$$

- The safety coefficient at lifting FS_{upl} makes it possible to verify that the applied vertical loads remain higher than the result of uplift pressure. It is determined by the ratio of the self-weight of the STHMD and the upthrusts from below the sole [27, 34]:

$$FS_{upl} = \frac{W_{mb}^{(t)}}{P_{upl}^{(t)}} \quad (21)$$

The set of these equations provides a robust diagnosis of the structure's behavior in the face of major hydraulic stresses and constitutes the basis of the usual stability criteria for massive concrete or masonry dams.

2.4 Three-Dimensional Design Workflow and Practical Recommendations

For preliminary design, select the main geometric parameters within the ranges investigated in this study to balance hydraulic performance, structural stability, and constructability. In particular, the dimensions reported in Table 3, Table 4, and Table 5 constitute a fully documented reference configuration for the studied hydraulic head range, which may serve as a starting point for comparable configurations, subject to site-specific verification. The corresponding cross-sectional dimensions should be adjusted according to the target upstream water level (H_e), with the investigated range of 0.20 m-2.00 m providing a preliminary reference for configurations under comparable hydraulic conditions. The design procedure consists of first defining the target upstream water-level range (H_e) from hydrological and energy-production requirements, followed by preliminary sizing of the cross-section based on hydraulic and constructability constraints. The resulting configuration is then checked for sliding, overturning, and uplift using the analytical formulation, and the corresponding safety factors are compared with the thresholds given in Table 2. Finally, critical and/or optimized configurations should be validated using the 3D FEM model presented in Section 2.5 before proceeding to detailed design. The final dimensions must nevertheless be confirmed through site-specific hydraulic, geotechnical, structural, and constructability assessments.

2.5 Three-Dimensional Numerical Modeling of the STHMD Using COMSOL Multiphysics

The three-dimensional numerical model of the STHMD was implemented in COMSOL Multiphysics using the Solid Mechanics interface to meaningfully assess the structural response beyond what the analytical rigid-body formulation already provides. Because the STHMD geometry is not prismatic along its length, the central block, the submersible threshold, and the lateral buttresses have distinct cross-sections, connected through non-planar geometric transitions. The structure was modeled as a homogeneous, isotropic, linear-elastic concrete material, consistent with the quasi-elastic behavior expected for a massive low-height gravity structure under service loading. The mechanical properties assigned to the concrete are summarized in Table 6. A linear-elastic constitutive model was adopted, as no yielding or cracking behavior was investigated in this preliminary structural assessment.

Table 6 Material properties and hydraulic parameters.

Variables	Symbol	Unit	Values
Maximum sediment height	H_{sed}	m	0.5
Bulk density of concrete	γ_c	kN/m ³	24
Volume weight of water	γ_w	kN/m ³	10
Sediment volume weight	γ_{sed}	kN/m ³	16
Active thrust coefficient	k_a	-	0.45
Density of concrete	ρ	kN/m ³	2400
Friction angle	δ	(°)	36.8
Young's module	E	GPa	25
Poisson's ratio	ν	-	0.20

The computational domain was discretized using quadratic tetrahedral solid elements. The foundation-structure interface was modeled as a fully bonded (tied) contact, consistent with the rigid-foundation hypothesis adopted in the analytical model, under which no relative sliding, interface adhesion, or cohesion is mobilized. The boundary conditions applied to the model are as shown in Figure 10.

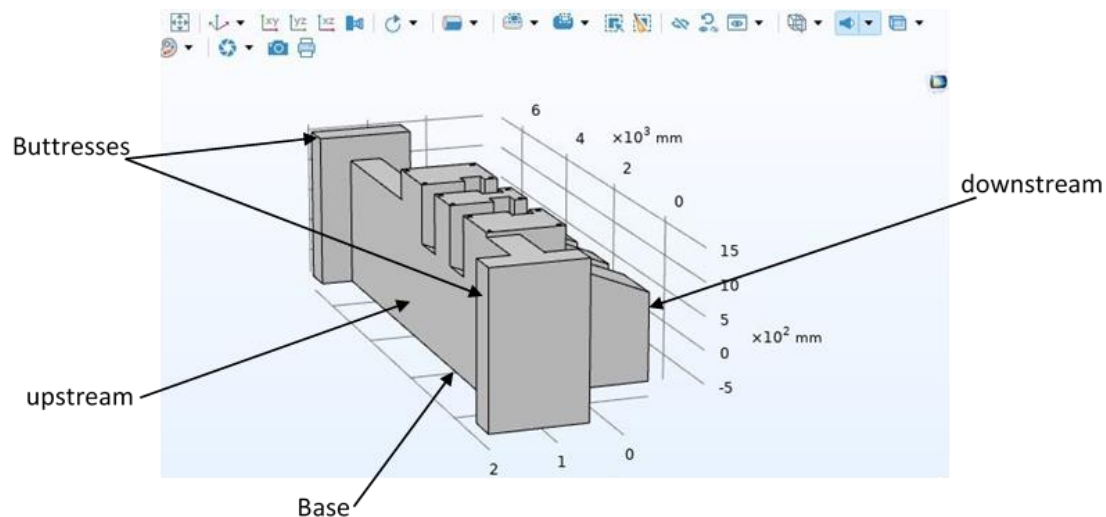


Figure 10 Three-dimensional numerical domain of the STHMD in COMSOL Multiphysics showing boundary conditions.

The base and buttresses of the structure were assigned a fixed constraint, with all translational and rotational degrees of freedom set to zero; the buttresses were fully embedded in the surrounding ground and therefore not directly subjected to hydrostatic or sediment thrust. At the base interface, the uplift sub-pressure thrust and its associated destabilizing moment were applied, following the piezometric distribution defined in the analytical model. On the upstream face of the structure, the hydrostatic thrust and its corresponding overturning moment were applied as a triangular pressure distribution proportional to the upstream water height H_e , along with the equivalent sediment thrust and its associated moment, applied over the corresponding submerged sediment height H_{sed} , consistent with the analytical formulation. The downstream face and lateral bank interfaces were left free of external hydraulic loading, in accordance with the negligible

downstream thrust hypothesis. The analytical formulation presented in Section 2.3 evaluates the global equilibrium of the structure under the rigid-body assumption, verifying the safety factors against sliding, overturning, and uplift. By construction, this approach cannot capture the internal stress and strain distribution within the structure, nor can it detect localized stress concentrations at geometric discontinuities, such as the transitions between the central block, the threshold, and the buttresses. This section presents a three-dimensional finite element model to complement the analytical assessment.

3. Results and Discussion

The stability of the hydraulic structure was studied using a dual approach: analytical analysis and numerical simulations based on established equations. The simulations are carried out using the real geometry of the structure and the applied pressure fields, considering the entire length (hydrostatic thrust, sediments, and uplift pressure), thereby allowing visualization of the distribution of constraints and identification of critical areas.

3.1 Simulation and Analytical Analysis of the Stability of the STHMD

The analytical analysis of the model studied is based on the physical data of the system presented in the different tables (Table 3, Table 4, Table 5 and Table 6), and some additional physical data (hydraulic parameters, material properties) are included in Table 6.

The analytical results from different calculations of the equilibrium equations are presented in Table 7, specifying the parameters and stability criteria of the STHMD per unit length, with $y = 0$ on the vertical plane.

Table 7 Weights, moments, and safety coefficients after analytical calculations.

Weight and different thrusts					Stabilizing and destabilizing moments				Stability security coefficients		
H_e (m)	$W^{(t)}_{mb}$ (kN)	$P^{(t)}_{dh}$ (kN)	$P^{(t)}_{sed}$ (kN)	$P^{(t)}_{upl}$ (kN)	$M^{(t)}_s$ (kN·m)	$M^{(t)}_{dh}$ (kN·m)	$M^{(t)}_{sed}$ (kN·m)	$M^{(t)}_{upl}$ (kN·m)	FS_{sl}	FS_{rev}	FS_{upl}
0.20	381.93	0.20	0.00	3.50	2110.15	0.01	0.00	12.02	1395.50	175.41	109.10
0.40	381.93	0.80	0.01	7.00	2110.15	0.11	0.00	24.03	345.66	87.41	54.56
0.60	381.93	1.80	0.03	10.50	2110.15	0.36	0.00	36.05	152.19	57.95	36.37
0.80	381.93	3.20	0.05	14.00	2110.15	0.85	0.00	48.07	84.80	43.13	27.28
1.00	381.93	5.00	0.08	17.50	2110.15	1.67	0.01	60.08	53.76	34.17	21.82
1.20	381.93	7.20	0.12	21.00	2110.15	2.88	0.01	72.10	36.97	28.14	18.19
1.40	381.93	9.80	0.17	24.50	2110.15	4.57	0.02	84.12	26.90	23.79	15.59
1.60	381.93	12.80	0.22	28.00	2110.15	6.83	0.03	96.13	20.39	20.49	13.64
1.80	381.93	16.20	0.27	31.50	2110.15	9.72	0.04	108.15	15.95	17.90	12.12
2.00	381.93	20.00	0.34	35.00	2110.15	13.33	0.06	120.17	12.79	15.80	10.91

The analysis of these results generally makes it possible to assess the overall stability of the half-dam studied. The data in Table 6 allow for establishing the profiles of the security experts. The analytical simulation gives the following different results in Figure 11.

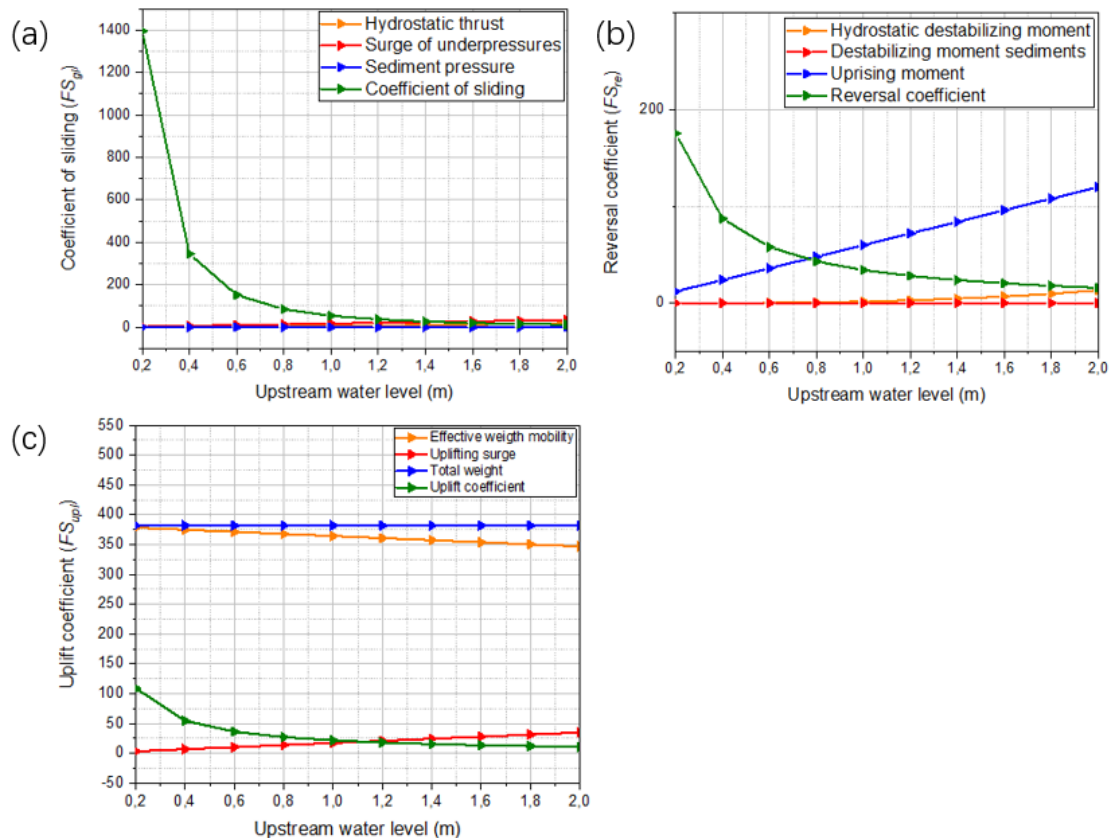


Figure 11 Stability coefficients of the STHMD: (a) sliding, (b) overturning and (c) uplift.

The analysis of the safety coefficients obtained for the STHMD, studied per meter of length, shows a very satisfactory overall behavior for all considered failure modes. The coefficients all have values well above the usual recommended thresholds (Table 1). This is consistent with the fact that the analytical safety factor formulation adopted in Equations 15, 18, and 21 directly follows the equilibrium-based verification approach recommended by ICOLD and USBR guidelines [17, 21] for gravity-type hydraulic structures, adapted to the specific geometry of the STHMD; the present results can therefore be regarded as methodologically consistent with, rather than independently validated against, established gravity-dam design practice. Nevertheless, the observed increases in these coefficients are consistent with the increase in hydrostatic forces and uplift pressures acting on the structure. The sliding stability coefficient ranges from 1395 to 12 (Table 7), indicating that the studied micro-dam is not subject to sliding. This reflects a very favorable relationship between the stabilizing forces (the structure's self-weight) and the destabilizing horizontal forces. The dam's geometry provides horizontal stability even at the maximum flooding considered, as the coefficient remains well above the minimum threshold. The overturning safety coefficient is also very comfortable values, ranging from 175 to 15.8. Its decrease with increasing H_e reflects the growing destabilizing moment generated by the hydrostatic and sediment thrusts about the toe of the structure, while the stabilizing moment provided by the self-weight remains fixed by the structure's geometry; as with the sliding mode, this moment ratio remains highly favorable throughout the

studied H_e range, and overturning is very unlikely given the structure's wide base and low center of gravity. The structure has a consequent stabilizing lever arm. The safety coefficient for uplift, oscillating between 109 and 10.9, remains well above the regulatory threshold, typically 1.2-1.5 (Table 2). Its decrease with increasing H_e results from the linear growth of the sub-pressure distribution beneath the foundation with the upstream water; since this uplift force scales linearly with H_e , while the destabilizing hydrostatic thrust scales with H_e^2 , the uplift safety factor decreases more gradually than the sliding and overturning factors across the studied range. For conventional concrete gravity dams operating under heads of 15-40 m, sliding and overturning safety factors typically range from 1.52-3.45 and 2.13-4.6 under standard analytical equilibrium methods [19, 32]. These markedly higher values obtained here directly reflect the scale difference; below $H_e = 0.5$ m, destabilizing hydrostatic thrust remains proportionally negligible, allowing the self-weight of STHMD to provide an overwhelming stabilizing margin. The high safety margins, especially at low H_e , mainly reflect the ultra-low head regime; destabilizing thrusts scale with H_e^2 while the STHMD self-weight is fixed by geometry, so the force rises sharply as H_e decreases. This, combined with the conservative friction, explains the higher values than those for conventional gravity dams. Existing FEM-based stability studies of concrete gravity dams have primarily focused on large-scale structures under seismic or dynamic loading, including reliability assessments [35] and the influence of long-term concrete degradation on seismic performance [36]. These works, while methodologically related in their combined analytical and FEM approach, address a fundamentally different loading regime and structural scale than the present study.

The observed decay reflects the increase in vertical thrust (uplift pressure) proportional to the upstream water level. However, the final values remain well above the critical limits, confirming that the self-weight of the structure is sufficient to counter the hydrostatic thrust, the sediment thrust, and the uplift pressure.

3.1.1 Sensitivity of the Sliding Safety Factor to the Foundation Friction Angle

A sensitivity analysis of the sliding safety factor to the foundation friction angle δ was performed by direct rescaling of Eq. (18) for values from 20°, 25°, 30°, 36.8° and 40°, following the upstream water height, given in Table 8.

Table 8 Sensitivity of the sliding safety factor to the foundation friction angle δ .

Friction angle δ (°)					
H_e (m)	$\delta = 20^\circ$	$\delta = 25^\circ$	$\delta = 30^\circ$	$\delta = 36.8^\circ$	$\delta = 40^\circ$
0.20	678.95	869.85	1077.00	1395.50	1565.26
0.40	168.17	215.46	266.77	345.66	387.71
0.60	74.04	94.86	117.45	152.19	170.70
0.80	41.26	52.86	65.45	84.80	95.12
1.00	26.16	33.51	41.49	53.76	60.30
1.20	18.00	23.04	28.53	36.97	41.47
1.40	13.09	16.77	20.76	26.90	30.17
1.60	9.92	12.71	15.74	20.39	22.87
1.80	7.76	9.94	12.31	15.95	17.89
2.00	6.22	7.97	9.87	12.79	14.35

As shown in Table 8, the sliding safety factor decreases proportionally with $\tan(\delta)$, as expressed in equation 18. Across the entire range of upstream water levels studied ($H_e = 0.20$ - 2.00 m), the sliding factor remains well above the regulatory threshold (Table 1) for every friction angle value tested, including the most conservative case considered ($\delta = 20^\circ$, representative of a loose granular soil interface rather than the concrete-rock contact assumed for this structure). At the governing condition, the highest water level studied, $H_e = 2.00$ m, where the safety margin is smallest, the sliding factor decreases from 12.79 at the nominal value ($\delta = 36.8^\circ$) to 6.22 at $\delta = 20^\circ$, a reduction of approximately 51%, yet still more than three times above the regulatory threshold as shown in Figure 12.

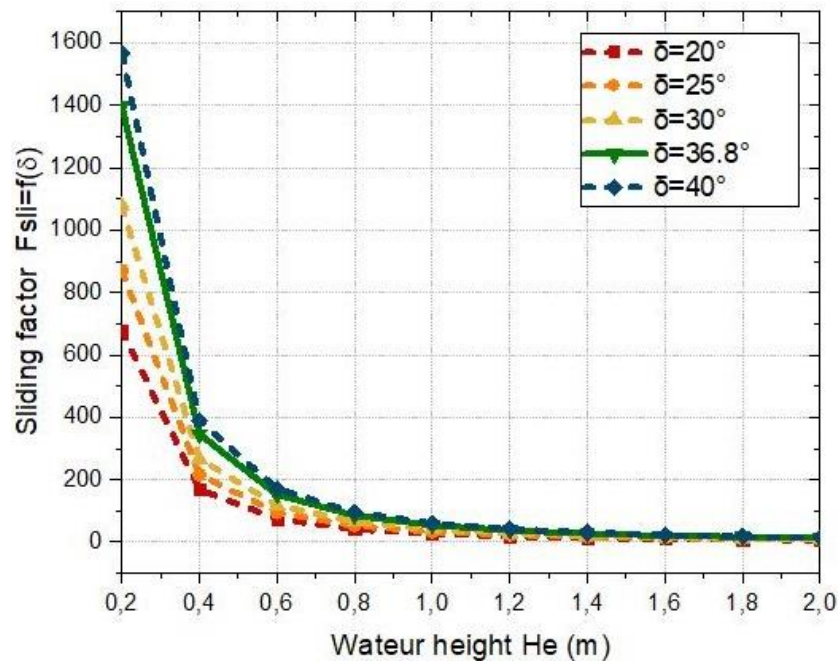


Figure 12 Sensitivity of the sliding safety factor to the foundation friction angle δ .

3.2 Numerical Simulation Using the Finite Element Method in COMSOL Multiphysics

The numerical validation of the STHMD stability was performed in COMSOL Multiphysics using the Solid Mechanics interface. The final 3D model from the SolidWorks design was imported (Figure 13), retaining only the relevant hydraulic and structural volumes.

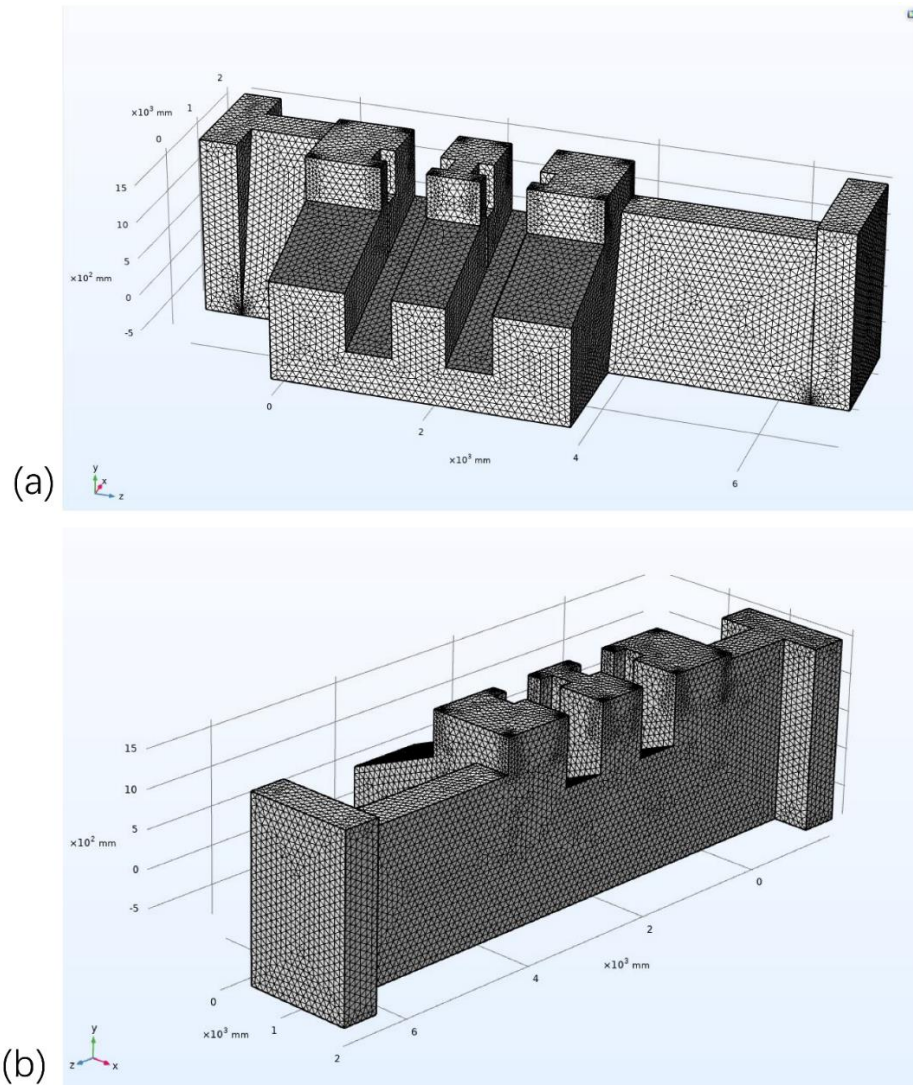


Figure 13 Extremely fine mesh of the STHMD: (a) downstream view, (b) Upstream view.

Prior to the production simulations, a mesh independence study was carried out to ensure that the reported displacement and volumetric strain results were not sensitive to discretization density. Successive mesh refinements were tested, from a coarse to the final refined configuration, using the maximum displacement at $H_e = 2$ m as the convergence indicator; the relative variation between the two finest mesh levels was below 2%, confirming a mesh-independent solution. Local refinement was applied at the upstream face, the threshold stops, the foundation-structure contact zone, and the flow recirculation region, where stress and pressure gradients are expected to be more pronounced. The final mesh resolved 838,083 degrees of freedom. A stationary (time-independent) study was performed independently for each of the ten upstream water levels H_e (0.20 m to 2.00 m), using COMSOL's PARDISO direct solver, with convergence assessed on the relative residual of the displacement field, tolerance of 10^{-3} ; all simulations converged without divergence or oscillatory behavior. On a workstation equipped with an Intel Core i7 processor (2.80 GHz, 16 GB RAM), the complete set of simulations required about 1 h 33 min of computation time. For each configuration, we first applied the structure's self-weight as a body load, then incrementally applied the corresponding hydrostatic, sediment, and uplift pressures associated with the target H_e .

The simulations carried out allow us to obtain the displacement curves, with isosurface representation and a loading representation of the hydrostatic thrust and volume deformation graphs in section for different values of H_e from 0.20 m, 0.40 m, 0.60 m, 0.80 m, 1 m, 1.20 m, 1.40 m, 1.60 m, 1.80 m and 2 m, where hydrostatic thrust is considered important.

The numerical simulation results show that the studied structure exhibits extremely small displacements, confirming its good mechanical behavior under the main destabilizing forces. The maximum displacement, obtained for the maximum water height ($H_e = 2$ m), is 0.0139 mm (Figure 14), which is negligible relative to the structure's overall dimensions. The amplitudes of displacement, between 1.36×10^{-3} mm and 12.5×10^{-3} mm, while Figure 15 presents the corresponding three-dimensional isosurfaces of displacement amplitude, showing that displacement increases progressively from the base of the structure, where it is minimal, consistent with the fixed foundation boundary condition, toward the crest of the central block, confirming the expected structural response of a base-fixed gravity structure under hydrostatic loading. This confirms the absence of mechanical singularities likely to generate local failure [26, 34]. The zones of highest stress are located at the base of the structure. Under these prescribed hydrostatic and uplift loading, the resulting stress field within the structure remains concentrated near the base, consistent with the location of the maximum applied pressure, without generating stress amplification at the base-buttress or base-central-block transitions, confirming that the structure's response remains governed by the applied load distribution rather than by localized geometric stress concentration effects. The volume deformation at maximum water height ranges between -8×10^{-6} and 6×10^{-6} , reflecting a quasi-elastic behavior of the concrete, with no abnormal concentration of dilation or internal compression (Figure 16). This amplitude also confirms that the structure functions in the elastic linear domain for all the hydraulic conditions studied. The distribution of hydrostatic thrust and uplift pressures perfectly illustrates that the efforts are greater at the base and weaker at the top ($H_e = 2$ m) (Figure 17). The numerical results corroborate the analytical calculations; the safety coefficients are consistent with the small upstream-to-downstream displacements and low volume deformations. The STHMD therefore has satisfactory mechanical stability for the hydraulic conditions studied, validating its size for river installation as part of a micro-hydroelectric application. The results, confirming the mechanical stability of the structure under the considered stresses, highlight the potential of this design for rapid, economically viable deployment in micro-hydropower projects. The structural simplicity, combined with satisfactory stability, represents a major advantage for electrifying isolated rural areas, where budgetary and logistical constraints often limit the use of conventional hydraulic structures. Beyond applying established gravity-dam verification methods, this study yields two structure-specific outcomes. First, the relative dominance of the failure modes is shown to depend on H_e : unlike conventional gravity dams, where sliding is typically most critical, uplift becomes the least conservative mode as H_e increases within the studied range, due to its linear (rather than quadratic) dependence on water level. Second, because all safety factors are satisfied by more than an order of magnitude once H_e falls below approximately 1 m, we propose that stability verification be treated as a necessary but non-governing check in this range for this class of structure, with sizing instead controlled by hydraulic and constructability requirements; the standard 1.5-2.0 safety thresholds become progressively more discriminating as H_e approaches the upper end of the ultra-low-head range considered here.

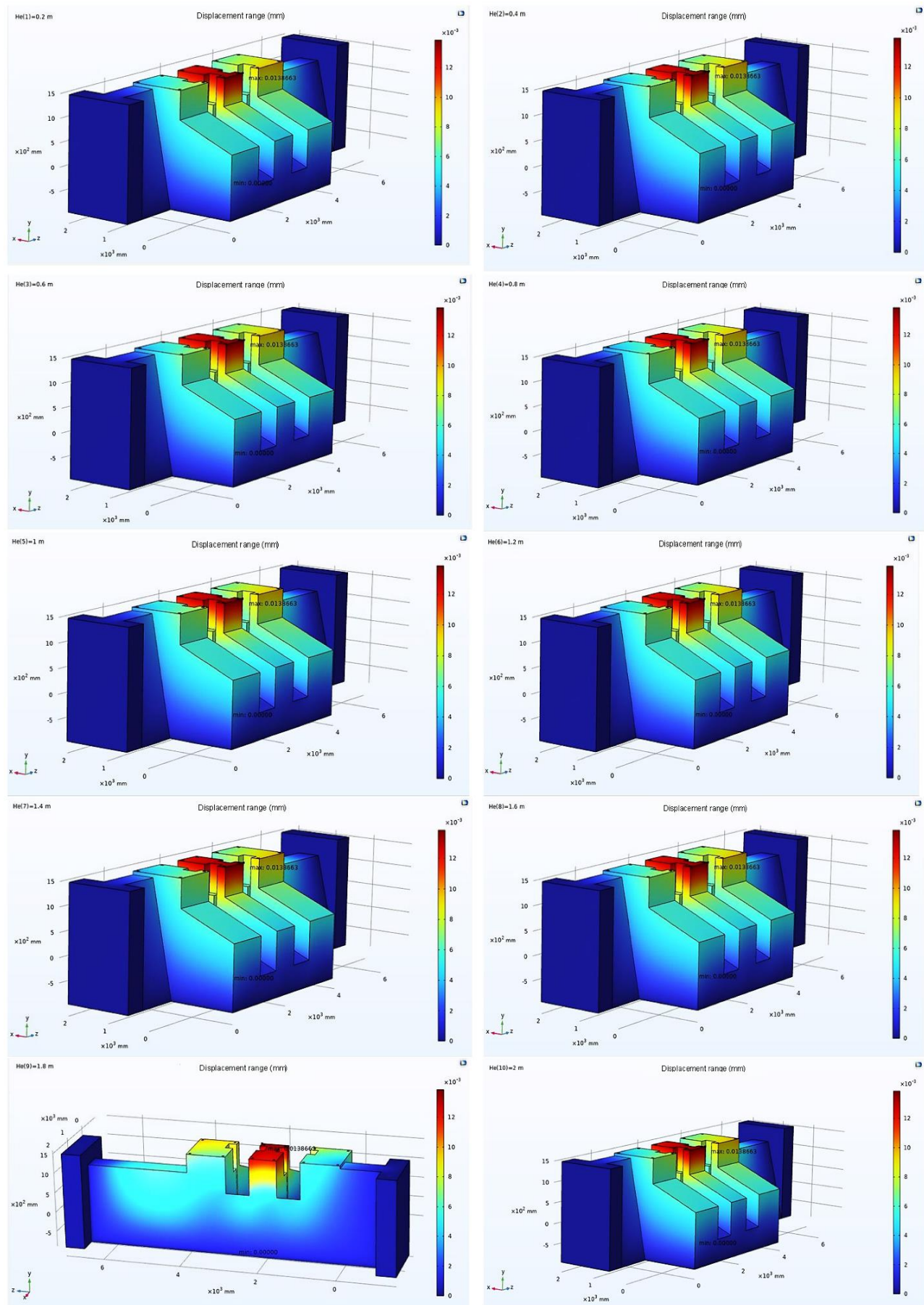


Figure 14 Displacement constraint amplitude (mm) of the STHMD.

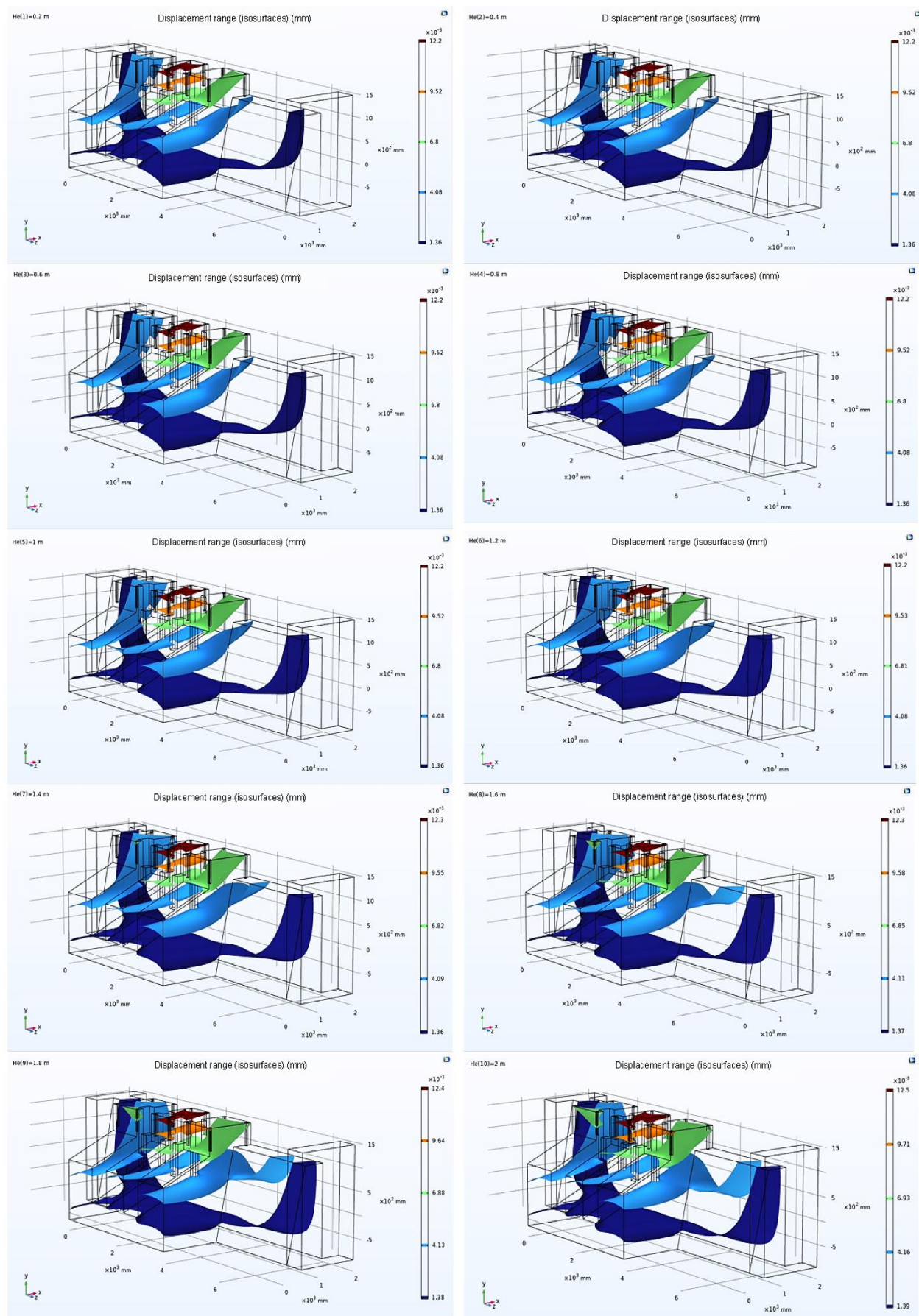


Figure 15 Displacement range of the STHMD displacement constraint amplitude (mm).

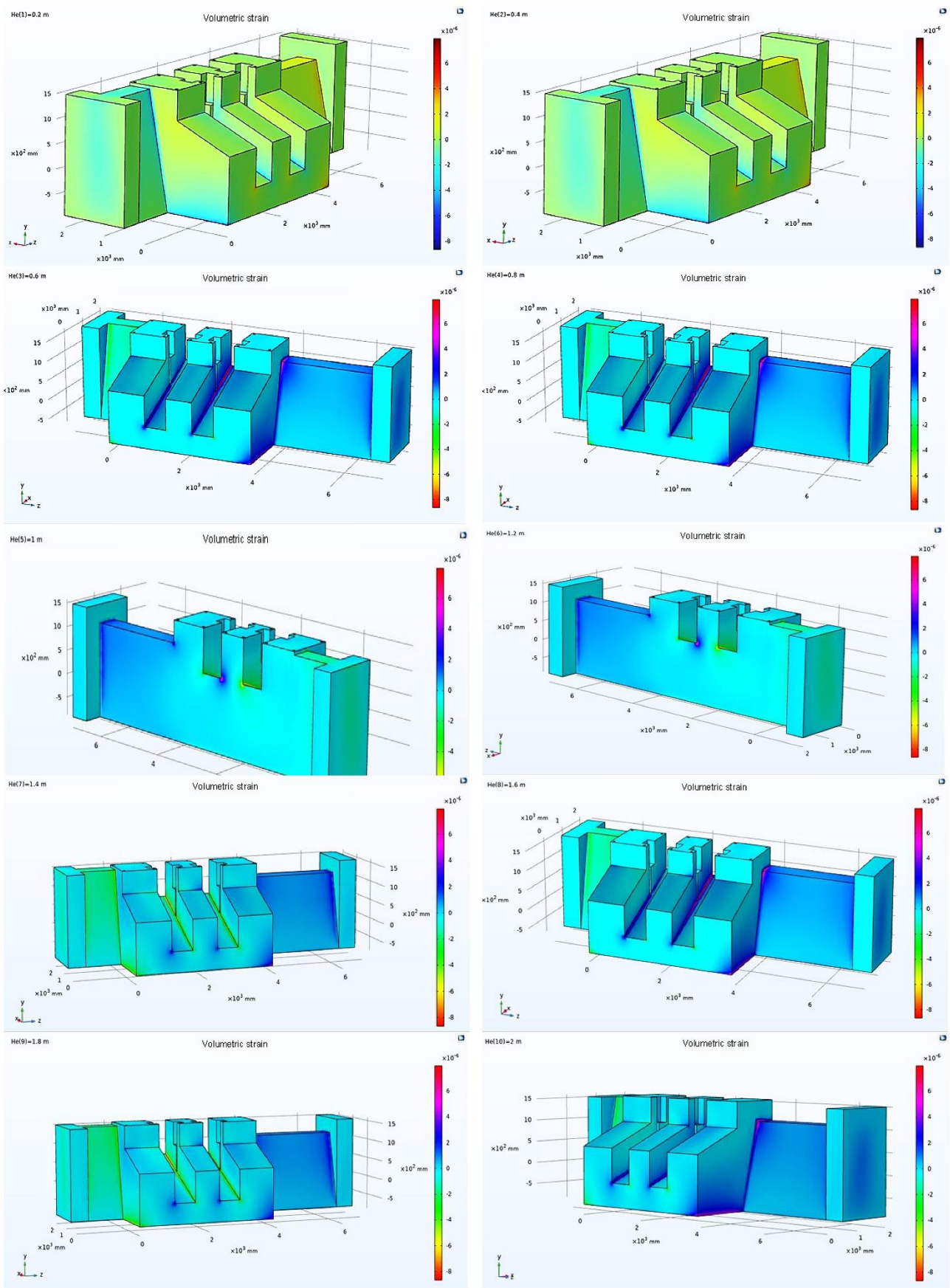


Figure 16 Representation of the volume deformations of the STHMD.

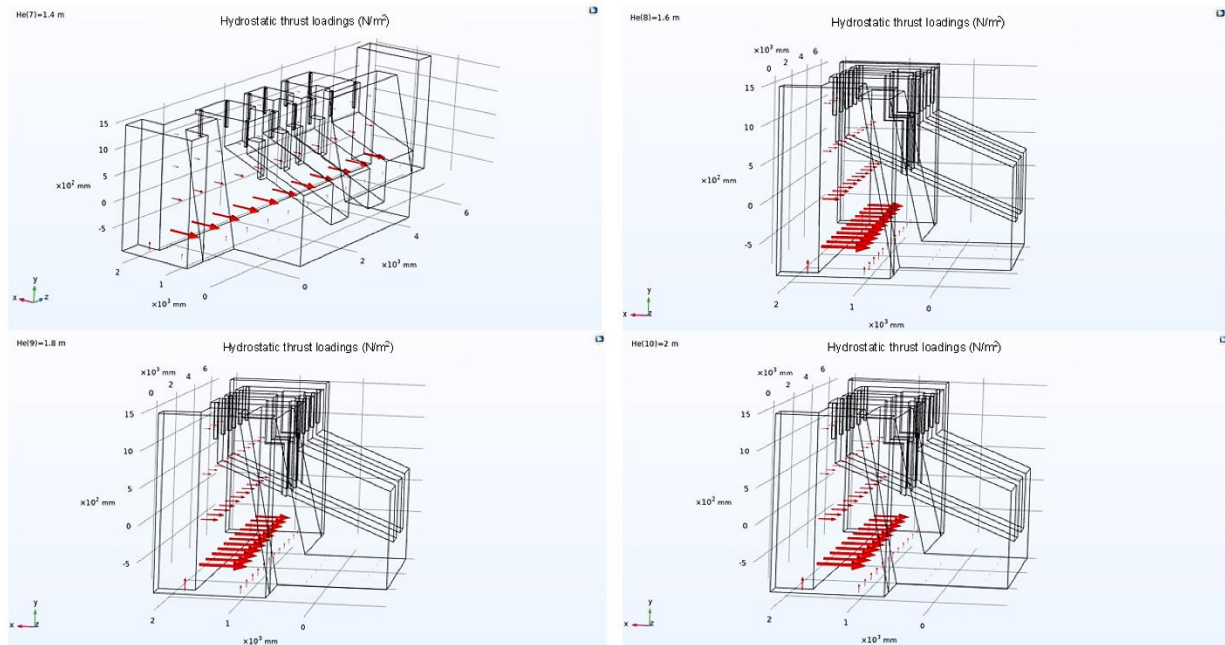


Figure 17 Distribution of hydrostatic pressure loads and uplift pressure (N/m^2).

3.3 Applicability Limits

The proposed framework is applicable to compact, low-slenderness gravity type structures operating under hydrostatic heads below approximately 2 m, at the preliminary design stage, and founded on competent, low-compressibility ground. It relies on standard simplifying assumptions as seen in section 3.1, homogeneous material, negligible thermal effects, and absence of local stress concentration in the global equilibrium formulation consistent with practice at this design stage. It does not currently account for scour and long-term reverberant erosion at the foundation interface, seismic loading, or detailed soil-structure interaction, which should be addressed through complementary geotechnical, hydraulic morphological, and seismic hazard studies prior to final design and construction. The numerical model does not include fluid-structure interaction or soil-structure interaction: hydraulic loads are applied as static-equivalent pressure distributions, and the foundation is modeled as a fixed, non-deformable support, consistent with the rigid-foundation assumption adopted in the analytical formulation. Consequently, the model does not capture flow-induced dynamic loading, pore-pressure redistribution within the foundation under transient hydraulic conditions, or foundation deformability effects on the structure's stress and displacement fields. Extending the sensitivity analysis to sediment height, uplift distribution, and concrete density, as well as a fully probabilistic treatment, will be a priority for future work, pending site-specific geotechnical and hydro-sedimentary data.

4. Conclusions

This study developed and applied a structural stability modeling framework for STHMD operating under ultra-low hydraulic head conditions (<0.5 m). The approach combined analytical equilibrium calculations with three-dimensional finite-element simulations in COMSOL Multiphysics to assess the main mechanical failure modes: sliding, overturning, and uplift. Analytical results indicated high safety factors, confirming the intrinsic stability of the structure, while numerical simulations

revealed minimal maximum displacements (0.0139 mm) and negligible volumetric strains, further validating the structural rigidity of STHMD under representative hydraulic loading conditions. The main contribution of this work is an integrated analytical-numerical modeling framework, which provides a reproducible methodology for evaluating the mechanical stability of compact STHMD in low-gradient rivers. The consistently high safety margins observed across the studied range of H_e suggest that the current geometry, primarily sized from hydraulic and constructability considerations, is not stability-critical for this site. This opens a potential avenue for geometric optimization. This framework highlights the key roles of hydrostatic thrust, sediment pressure, uplift forces, and foundation interactions in governing structural response at micro-scale, offering insight beyond conventional large-dam criteria. This study proposes a preliminary analytical-numerical stability assessment methodology for submersible threshold micro-dams under ultra-low hydraulic head conditions, illustrated through a design-stage case study on the Douni River. While the results indicate substantial stability margins under the adopted assumptions, generalization of the framework to other sites or configurations will require field validation, dedicated geotechnical investigation, and sensitivity analysis. Future research could extend this modeling approach by incorporating drainage effects, dynamic sediment transport, or long-term phenomena such as fatigue, erosion, and siltation to further refine the stability assessment. Additionally, coupling the stability model with hydraulic and energy performance simulations could enable a more comprehensive design methodology for ultra-low-head micro-hydropower systems. Overall, this study provides a robust foundation for the mechanical design and stability assessment of STHMD, contributing to the safe and reliable deployment of compact hydraulic structures under ultra-low hydraulic head conditions. Beyond its structural contribution, the STHMD supports sustainable water resource management in rural, off-grid settings: unlike impounding dams, it allows a continuous base flow to pass over the threshold rather than permanently storing the river's discharge, while enabling low-carbon micro-hydropower generation for rural electrification along the Douni River.

Notation

The following symbols and units are used in this paper:

γ_c	Unit weight of concrete	kN/m ³
γ_w	Unit weight of water	kN/m ³
γ_{sed}	Unit weight of sediments	kN/m ³
H_e	Upstream water level (hydraulic head)	m
H_{sed}	Upstream height of sediment deposits	m
y	Vertical position along the water/sediment column (integration variable)	m
k_a	Active earth-thrust coefficient (Rankine)	-
δ	Foundation friction angle	(°)
W_{pc}	Self-weight of the central part (part 1)	kN
x_{pc}	Lever arm of the central part, from the downstream heel	m
W_s	Self-weight of the submersible threshold (part 2)	kN
x_s	Lever arm of the threshold, from the downstream heel	m
W_{cf}	Self-weight of the lateral buttresses (part 3)	kN
x_{cf}	Lever arm of the buttresses, from the downstream heel	m

$W_{mb}^{(t)}$	Total self-weight of the micro-dam	kN
$M_s^{(t)}$	Total stabilizing moment	kN·m
$P_{dh}^{(t)}$	Total hydrostatic thrust	kN
$M_{dh}^{(t)}$	Destabilizing moment due to hydrostatic thrust	kN·m
$P_{d, sed}^{(t)}$	Total sediment thrust	kN
$M_{d, sed}^{(t)}$	Destabilizing moment due to sediment thrust	kN·m
$P_{upl}^{(t)}$	Total uplift thrust	kN
$M_{upl}^{(t)}$	Destabilizing (uplift) moment	kN·m
$F_v^{(t)}$	Sum of vertical stabilizing forces	kN
$F_h^{(t)}$	Sum of horizontal destabilizing forces	kN
FS_{sli}	Sliding safety factor	-
FS_{ovr}	Overturning safety factor	-
FS_{upl}	Uplift safety factor	-

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Author Contributions

Conceptualization, P. Koua-Mbani. and M. Liassa Nkoy; Methodology, M. Liassa Nkoy.; Software, P. Koua-Mbani.; supervision, F. Moukanda Mbango and M. Liassa Nkoy; Writing-original draft preparation, P. Koua-Mbani.; validation F. Moukanda Mbango. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, Grammarly was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the authors. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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