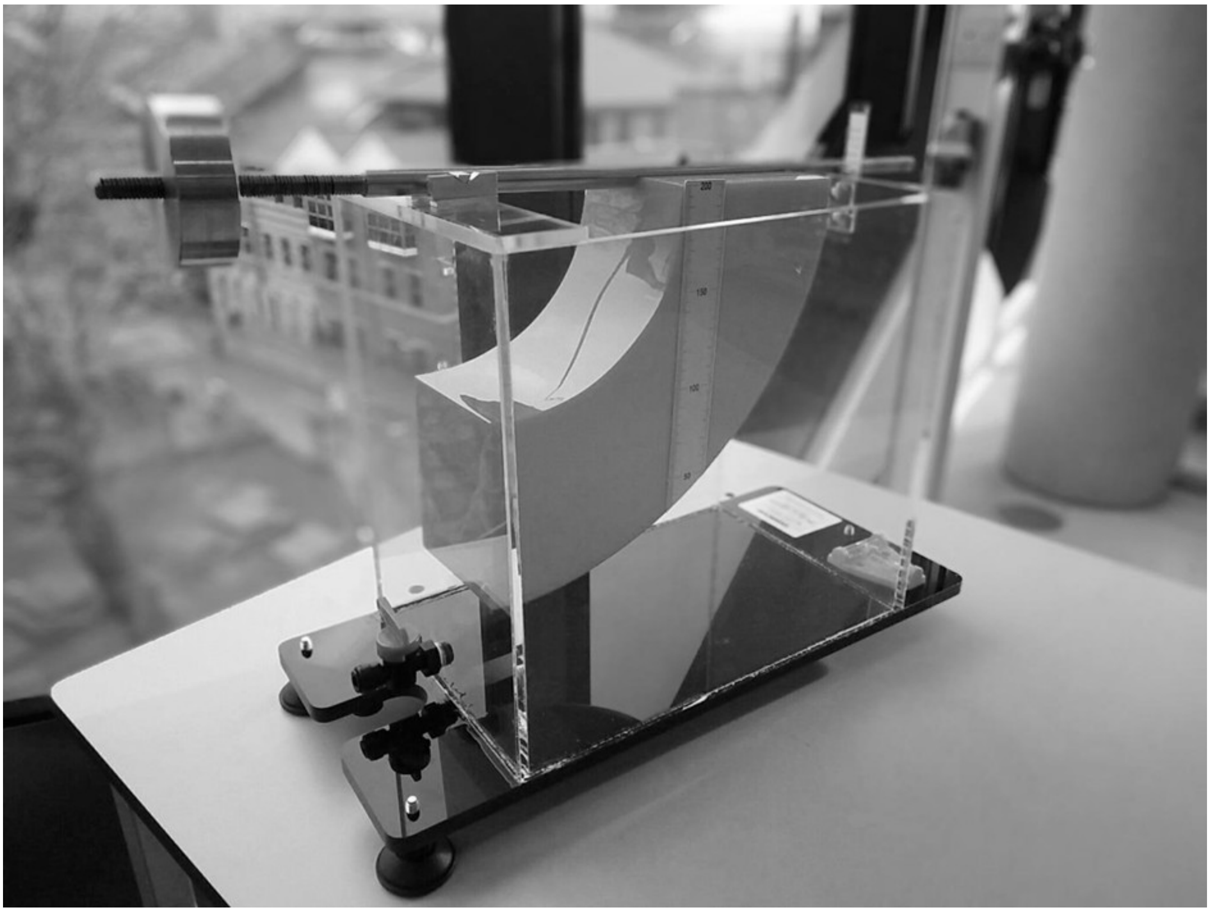
Forces on Submerged Surfaces

Andrew Garrard



LEARNING OUTCOMES

Prac-tical	Experimentally determine forces on a submerged surface
Integ-rate	Calculate the depth of the centre of pressure
Concept	Compare values obtained though theory and experimentation
Record	Maintain a professional experimental record

a.garrard@sheffield.ac.uk

Pre: -%, During -%, Post -%

Forces on a Submerged Surface:
Pre-experiment Activity

A pre-experimental activity must be completed before starting this experiment. Failure to complete these tasks may result in being refused entry into the laboratory.

1 Aims and objectives

To compare the experimentally measured and theoretically derived forces acting on a submerged surface.

2 Background

The force experienced by a surface submerged in water is the area of the surface multiplied by the pressure of the water at the point of the surface's centre of area (or centroid), as shown in equation 1,

$$F = \rho g A \bar{x} \qquad \textbf{[1]}$$

Where F is the force on the surface, ρ is the fluid density g is the gravitational constant (9.81 m.s^{-2}), A is the area of the submerged surface and $\bar{x}$ is the distance of the centroid below the surface. The point at which the force acts, the *"centre of pressure"*, is given by equation 2,

$$\bar{h} = \bar{x} + \frac{I_G}{A\bar{x}} \qquad \textbf{[2]}$$

Where $\bar{h}$ is the depth below the surface of the centre of pressure and I_G is the 2nd moment of area about the centroid of the submerged surface.

Figure 1 shows the end face of a ¼ toroid, of cross sectional dimensions *b* by *d*, submerged and partially submerged under the water:

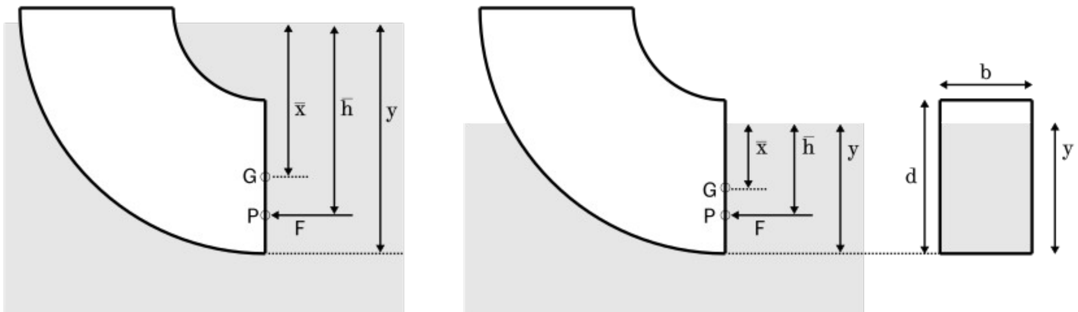


Figure 2: Nomenclature used to describe the dimension of the surface of a ¼ toroid left) when fully submerged, centre) when partially submerged and right) end face when partially submerged

The nomenclature used in figure 2 is as follows:

- G is the centre of area (centroid).
- P is the centre of pressure.
- $\bar{x}$ is the depth of the centroid (G) below the surface.
- $\bar{h}$ is the depth of the centre of pressure (P) where the force is acting below the surface.
- y is the depth below surface of the bottom of the ¼ toroid.
- b and d are the dimensions of the cross section of the end face of the ¼ toroid.

When the end face of the ¼ toroid is fully submerged the totality of the area of the end face is covered with water, and equation 3 applies:

$$\bar{x}=y-\frac{d}{2} \qquad A=bd \qquad I_G=\frac{bd^3}{12} \qquad \textbf{[3]}$$

When the end face of the ¼ toroid is partially submerged only a portion of the area of the end face is covered with water, and equation 4 applies:

$$\bar{x}=\frac{y}{2} \qquad A=by \qquad I_G=\frac{by^3}{12} \qquad \textbf{[4]}$$

3 Planning and preparation

3.1 Equipment

During the experiment a Cussons p6237 Centre of Pressure Apparatus. The equipment consists of a ¼ quarter toroid, with nominal dimensions of internal radius 100 mm, outside radius 200 mm and 75 mm wide. It is contained inside a clear Perspex tank that can be filled with water to various levels. The depth of the water can be measured using a scale attached to the side of the toroid and is mounted on a balance arm so that so that its rectangular end face is vertical and the two curved surfaces are concentric with the line of action of the knife edge pivots. The balance arm has a balance pan, which can be loaded with weights, at one end and an adjustable counterbalance at the other, as shown in figure 2.

3.2 Outline

The general aim of this experiment is to determine the hydrostatic force acting on the horizontal face of the ¼ toroid. The equipment is first balanced (using the adjustable counterbalance) without any water in the tank. When this is the case, the clockwise and anticlockwise moment about the fulcrum must be equal and opposite. When water is added to the tank, a force is imparted on the horizontal end face of the ¼ torrid. If the rig is set up as in figure 2, this will create an additional clockwise moment on the lever arm about the fulcrum. If masses are placed on the balance pan, the rig is set up as in figure 2, this will create an additional anticlockwise moment about the fulcrum.

In this experiment, mass will be added to the balance pan and water added to the tank until the balanced beam becomes level. The results must be that that additional moment created by adding the masses to the balance pan are equal and opposite to the moment created by the hydrostatic force on the ¼ toroid end face. Given that the moment created by the masses is know, this allows the hydrostatic force and positon to be determined and compared with theory.

3.3 Procedure

1. Make a note in the experimental record of the appropriate dimension of the ¼ toroid.
2. If it has been removed for step 1, replace the ¼ toroid into the tank ensuring the knife edge is in the locating slots.
3. Adjust the counterbalance weight until the beam level indictors shows the balance arm is horizontal.
   Do not adjust the counterbalance to level the balance arm after this point, or this will lose the datum setting.
4. Hang the balance pan and all the masses on the end of the balance arm.
5. Fill the tank with water until the until the balance arm tips. Fine adjustment can be made by overfilling and using the tap to slowly drain the tank.
6. Record the mass hanging on the balance arm (including the mass of the pan itself) and the height of the water surface (above the bottom edge of the ¼ toroid) using the scale.
7. Remove one or more masses and adjust the water level until the balance arm is horizontal again using the method in step **4**. Record the values in step **5**.
8. Repeat step **6** as many times as necessary.

3.4 Health and Safety

In addition to the Building and Fluids Engineering General Health and Safety Rules, care should be taken when handling masses. Ensure you are wearing sturdy footwear and that masses are kept above the hydraulic bench to avoid them falling on the floor.

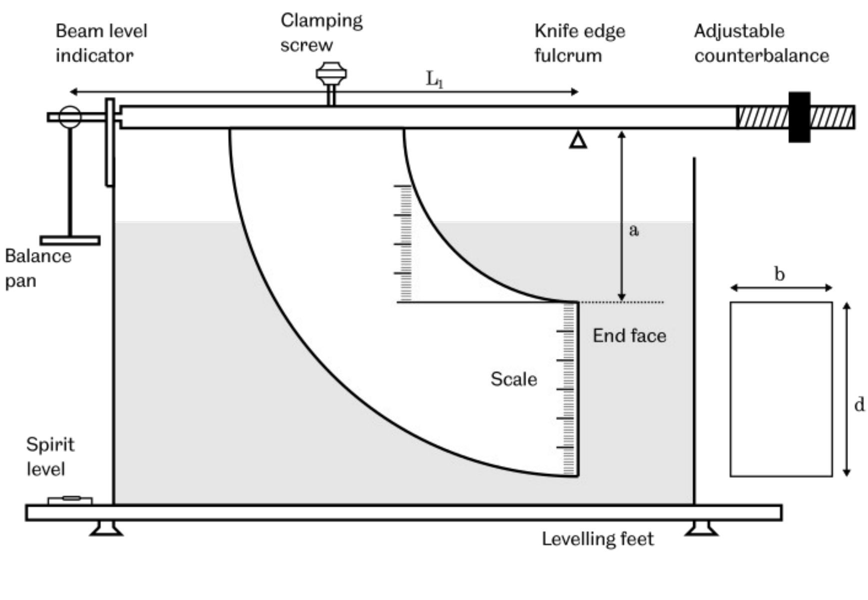


Figure 2: Schematic diagram of the equipment used in the experiment.

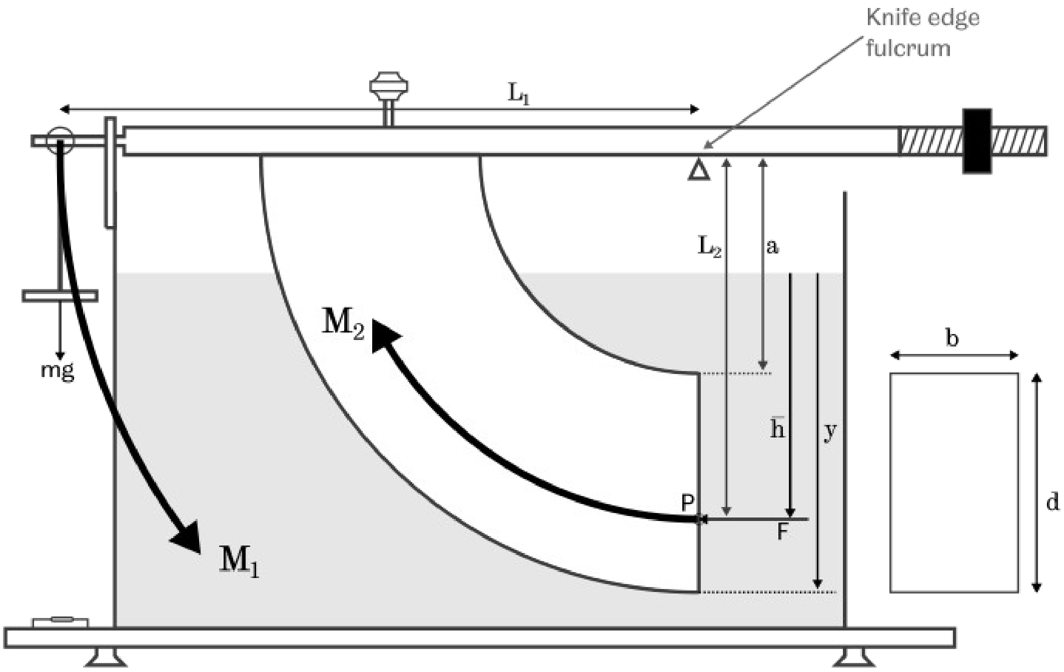
Forces on Submerged Surfaces: Experimental Record

Complete your experimental record on a pad or in a laboratory notebook during the activity. Don't forget to note the date you conducted the work. Your experimental record should contain the following sections.

1. Aims and Objectives
2. Names of collaborators for the experiment
3. Equipment
4. Procedure
5. Results – this will be a table of mass on the hanger and depth of water, noting when the end face is fully or partially submerged. Don't forget to record observations and uncertainty.
6. Discussion and conclusions:

In a discussion and concolusion section of your experimeanl record you should compare the theoretical and experimental depth of the centre of pressure($\bar{h}$). In order to do this, moments will be taken about the knife edge fulcrum. When the beam is level, the anticlockwise moment (M_1), will be the weight on the balance pan (mg¿ multiplied by the distance from the knife edge (L_1). This will equal the clockwise moment (M_2), given by multiplying the force from the water on the end face (given by equation 1 in the pre-experimental activity) and the distance between the knife edge and the centre of pressure (L_2).

L_2 is equivalent to a+d-y+$\bar{h}$. As a and d are known gemometric parameters and y is measrued in the experiment. Thefore this can be used to determine the experimentally recorded value of $\bar{h}$. This can be comapred to the theoreitcyaaly determiend value of $\bar{h}$, given by equation 2.



Construct a table similalr to this following in your experimental record to compare the Experimental $\bar{h}$ and Theoretical $\bar{h}$.

Expt	$\bar{x}$ *(eq. 3 or 4)*	A *(eq. 3 or 4)*	I_G *(eq. 3 or 4)*	F *(eq. 1)*	**M_1** *(mgL)*	**L_2** *(mgL/F)*	**Experiment** $\bar{h}$ *(L_2-(a+d-y))*	**Theory** $\bar{h}$ *(eq. 2)*
1								
2								
3								
...								

Forces on Submerged Surfaces: Post Experimental Activity

Answer the following questions:

1. How well does the measured position of the centre of pressure agree with theory? Can the experiment be improved to get better accuracy?
2. Is the moment measured due to the hydrostatic force on the rectangular face alone? Give reasons for this.
3. If a valve controlling the flow from a reserviour into a conduit was built as a rectangular plate pivoted about a horizontal axis though its centroid,

how would the moment required to open it change as the depth of water in the reservoir increased?