# Lab 2 Center of Pressure

CTC-261

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# CONTENTS

# INTRODUCTION

This lab is used for hydraulics and fluid mechanics. The center of pressure is the exact point in which the total pressure causes an acting force through a point. These hydrostatic forces cause pressure loading of the liquid acting on a submerged surface. These forces are typically put onto the walls of dams. This pressure is applied at steeper angles and changes with the height of the water. It's important to know how these processes work so engineers can predict how to strengthen the design of structures affected by the hydrostatic force. The center of pressure experiment allows observation and computation of the hydrostatic force acting at the center of pressure on the vertical plane.

## EQUIPMENT LIST

In this lab a Center of Pressure Apparatus was used to observe the resultant force of water acting at the center of pressure. The thermometer used to determine the temperature of the water was a total immersion glass liquid Celsius thermometer. Standard millimeter and centimeter ruler was used to verify the dimensions of the Apparatus. A large 52ounce plastic container was used to add water to the quadrant tank.

# EXPERIMENTAL PROCEDURE

First, the setup of the experiment was completed. There was a clamp that secured the hopper to the back of the unit that was removed. The tank was preassembled for this experiment. The only steps for setup that were completed were ensuring the rolling surface and the edges moved smoothly along the surface. Then, ensuring that the hanger for the weights was aligned correctly. The weight of the hanger and the apparatus were adjusted to an equilibrium point before starting the lab. This took some time to complete due to the necessity of it being very accurate.

Next, the experiment was performed, this experiment took some time to complete. The first part of the procedure to complete the experiment started with applying weight to the hanger. The first trial used 20 grams of weight. When doing to trail after the addition of the weight added water was slowly added into the tank. This took great care and precision to ensure not to add too much water otherwise the weight would be out of balance. The back scale was carefully read to determine the h value of the experiment. The mass and water height data were then recorded for this section. The steps of each trial were repeated numerous times using a variety of different weights. The weight trials included 20, 50, 70, 100, 120, 150, 200, 250, 300, 350, and 400 grams of weight. The steps in the trails were done in the exact same process for all the various weights.

Finally, The equipment was and the station were thoroughly cleaned, to ensure nothing got lost or broken during the processes. The water contents from the tank were poured back into the reservoir that the water was collected from. The tank was then thoroughly dried, and the protective plate was reattached, and the tank was placed and affixed to the back plate. Everything was then put back into place from when the experiment was started.

## OBSERVED DATA

The data collected during the lab was done in accordance with the experimental procedure described above. The data collected is listed below in the following tables:

Center of Pressure Apparatus dimensions:

| Verified Equipment Dimensions | |
|---|---|
| Radius | (mm) |
| R1 (inner) | 100 |
| R2 (outer) | 200 |
| R3 (moment arm) | 203 |
| | |
| Width of Vertical Rectangular Plane | 75 |

Water temperature data of the water used in the center of Pressure Apparatus:

| Water Properties | |
|---|---|
| Water Temp ( C ) | 21.0 |
| Specific Weight of Water ($N/m^3$) | 9788 |

Height of water data in the Center of Pressure Apparatus to level the tank with the hanging mass applied:

| Experimental Data | | | |
|---|---|---|---|
| Tilt (Degrees) | M (gm) | h (mm) | Submerged (yes or No) |
| 0 | 20 | 180 | No |
| 0 | 50 | 166 | No |
| 0 | 70 | 160 | No |
| 0 | 100 | 148 | No |
| 0 | 120 | 142 | No |
| 0 | 150 | 134 | No |
| 0 | 200 | 122 | No |
| 0 | 250 | 112 | No |
| 0 | 300 | 102 | Yes |
| 0 | 350 | 92 | Yes |
| 0 | 400 | 84 | Yes |

## SAMPLE CALCULATIONS

**Millimeters to Meters Conversion, Height of Water in Tank from The Top:**

$$h = 122mm * \frac{1m}{1000mm} = 0.122m$$

**Grams to Kg Conversion:**

$$Kg = 200g * \frac{1kg}{1000g} = 0.20kg$$

**Moment in (N*M) from Applied Mass on Hanger:**

$$Moment = mass\ on\ hanger(kg) * moment\ arm\ of\ mass(R3) * acceleration\ due\ to\ gravity\ \left(\frac{m}{s^2}\right)$$

$$Moment = 0.20kg * 0.203m * \frac{9.81m}{s^2} = 0.3983N * M$$

**Depth of Water in The Tank:**

$$dw = outer\ radius\ (R2) - height\ of\ the\ water\ from\ the\ top\ (h)$$

$$dw = 0.20m - 0.122m = 0.078m$$

**Area of Partially Submerged Vertical Rectangular Plane Calculation:**

$$Area = 0.075m * 0.078m = 0.00585m^2$$

**h-bar, Distance from The Water's Surface to The Centroid of The Rectangular Plane:**

$$h - bar = \frac{1}{2} * depth\ of\ water$$

$$h - bar = 0.5 * 0.078m = 0.039m$$

**Moment of Inertia About the Centroid Calculation:**

$$Ix' = \frac{b * h^3}{12}$$

$$Ix' = \frac{0.075m * (0.078m)^3}{12} = 2.966 * 10^{-6}m^4$$

**Theoretical Resultant Force in (N), Force Water Applies to The Vertical Rectangular Planar Surface:**

$$F = \gamma * h - bar * Area$$

$$F = \frac{9788N}{m^3} * 0.039m * 0.00585m^2 = 2.23N$$

**Center of Pressure from The Water's Surface:**

$$Ycp = h - bar + \frac{I - bar}{h - bar * Area}$$

$$Ycp = 0.039m + \frac{2.966 * 10^{-7}m^4}{0.039m * 0.00585m^2} = 0.052m$$

**Theoretical Moment Arm:**

$$Tma = Ycp + height\ of\ water\ (h)$$

$$Tma = 0.052m + 0.122m = 0.174m$$

**Experimental Resultant Force Using Experimental Moment Arm:**

$$F = \frac{moment(N * M)}{Tma}$$

$$F = \frac{0.3983N * M}{(0.174m)} = 2.29N$$

**% Difference in Resultant Force**

$$\%\ difference = \frac{experimental\ force - theoretical\ force}{theoretical\ force}$$

$$\%\ difference = \frac{2.29N - 2.23N}{2.23N} * 100 = 2.7\%$$

**Area of Fully Submerged Vertical Rectangular Plane Calculation:**

$$Area = 0.75m * height\ of\ vertical\ plane$$

$$Area = 0.75m * 0.1m = 0.0075m^2$$

**h-bar, Fully Submerged Distance from The Water's Surface to The Centroid of The Rectangular Plane:**

$$h - bar = (inner\ radius - water\ height\ (h)) + (\frac{1}{2} * height\ of\ vertical\ plane)$$

$$h - bar = (0.1m - .092m) + \left(\frac{1}{2} * 0.1m\right) = 0.058m$$

hanging mass. Some rounding error was introduced into the Excel calculations since the intermediate and final calculations were rounded leading to slightly greater error percentages. The hand calculations were rounded at the end leading to slightly lower error results.

## CONCLUSION

The theoretical resultant force applied to the vertical rectangular plane at the centroid of the plane was observed during the experiment. Force is the product of the specific weight of the water at a certain temperature, the depth of the water, and the area of the plane the water is in contact with. The force theoretically acts at the center of pressure which is slightly below the centroid of the vertical plane the water is in contact with.

The hanging mass on the left side of the apparatus (203mm) from the center zero-degree line produced a moment force. The force pulled the vertical rectangular plane out of parallel with the zero-degree line creating an angle between the two. The water in the quadrant tank opposite the hanging mass was used to bring the vertical rectangular plane to the zero-degree line. The water produced a force perpendicular to the plane which overcame the force exerted by the hanging mass bringing the tank back to level. The water's theoretical moment arm was the product of the height of the water in the tank plus the center of pressure distance. The force of the water acting at the center of pressure applied to its moment arm resulted in a moment force which overcame the force exerted by the hanging mass. The partially submerged vertical plane experienced a greater difference between the experimental resultant force and the theoretical resultant force of the water. The experimental resultant force indicated the water was exerting a greater force than the theoretical resultant force. The force the water exerted on the fully submerged vertical plane was nearly equal to the experimental resultant force.

The results of the experiment indicate the water exerted a force perpendicular to the vertical rectangular plane acting at the center of pressure. Since the water in the tank at a certain depth exerted a moment force which opposed and overcame the force of the hanging mass. The experimental resultant force of the water did appear to exert a force similar to the force of the applied mass to cause the vertical plane to return to the zero-degree line. The experimental resultant force acting at the center of pressure indicated the actual force exerted perpendicular to the vertical plane was greater than the theoretical calculated force of the water. Therefore, the experimental resultant force acting at the center of pressure does not lead to an explicit conclusion of the water's theoretical resultant force.

**Moment of Inertia Fully Submerged About the Centroid Calculation:**

$$Ix' = \frac{(b) * (hp)^3}{12}$$

$$Ix' = \frac{0.075m * (0.1m)^3}{12} = 6.25 * 10^{-6}m^4$$

## CALCULATED DATA & RESULTS

Below is the reduced data providing the theoretical resultant force of the water and the experimental force of the water acting on the vertical rectangular plane. See attached Hand calculations in (Appendix A) verifying the Excel spreadsheet used to calculate the resultant force.

| B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Submerged? | Hanger Mass (gm) | h (mm) | h (m) | Moment (N-m) | Depth (m) from plane bottom | Area of Vertical Rect Plane (m2) | h-bar (m) | Moment of Inertia about Centroid) | Theoretical Resultant Force (N) | Centerof Pressure from Water Surface | Theoretical Moment Arm Distance | Experimental Resultant force using Moment (Col E) | % difference |
| part sub | 20 | 180 | 0.18 | 0.0398 | 0.02 | 0.0015 | 0.01 | 5.00E-08 | 0.15 | 0.013 | 0.193 | 0.21 | 40 |
| part sub | 50 | 166 | 0.166 | 0.0996 | 0.034 | 0.0026 | 0.017 | 2.46E-07 | 0.42 | 0.023 | 0.189 | 0.53 | 24 |
| part sub | 70 | 160 | 0.16 | 0.1394 | 0.04 | 0.0030 | 0.02 | 4.00E-07 | 0.59 | 0.027 | 0.187 | 0.75 | 27 |
| part sub | 100 | 148 | 0.148 | 0.1991 | 0.052 | 0.0039 | 0.026 | 8.79E-07 | 0.99 | 0.035 | 0.183 | 1.09 | 10 |
| part sub | 120 | 142 | 0.142 | 0.2390 | 0.058 | 0.0044 | 0.029 | 1.22E-06 | 1.23 | 0.039 | 0.181 | 1.32 | 7 |
| part sub | 150 | 134 | 0.134 | 0.2987 | 0.066 | 0.0050 | 0.033 | 1.80E-06 | 1.60 | 0.044 | 0.178 | 1.68 | 5 |
| part sub | 200 | 122 | 0.122 | 0.3983 | 0.078 | 0.0059 | 0.039 | 2.97E-06 | 2.23 | 0.052 | 0.174 | 2.29 | 3 |
| part sub | 250 | 112 | 0.112 | 0.4979 | 0.088 | 0.0066 | 0.044 | 4.26E-06 | 2.84 | 0.059 | 0.171 | 2.92 | 3 |
| full sub | 300 | 102 | 0.102 | 0.5974 | 0.098 | 0.0075 | 0.048 | 6.25E-06 | 3.52 | 0.065 | 0.167 | 3.57 | 1 |
| full sub | 350 | 92 | 0.092 | 0.6970 | 0.108 | 0.0075 | 0.058 | 6.25E-06 | 4.26 | 0.072 | 0.164 | 4.24 | 0 |
| full sub | 400 | 84 | 0.084 | 0.7966 | 0.116 | 0.0075 | 0.066 | 6.25E-06 | 4.85 | 0.079 | 0.163 | 4.90 | 1 |

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## ERROR ANALYSIS

Some error may have been introduced into the experimental resultant force when trimming the tank to the zero-degree line. The vertical zero-degree line was visually sighted through the Perspex tank until the vertical rectangular plane was parallel with the line. The vertical plane may not have been perfectly at the zero-degree line. Sighting the zero-degree line through the Perspex tank containing water may have compounded this issue during the experiment. The water on the partially submerged plane exhibited a larger experimental resultant force which may be the result of error. During the experiment some water spattered on the walls of the tank without reaching the bottom. This would cause a greater water height reading lessening the water depth in the quadrant tank and reducing the theoretical resultant force. The large errors at the beginning of the experiment may have been caused by the base plate being slightly out of level. The tank may have needed to be rocked slightly to overcome opposing forces on the tank and allow it to settle. The hypothesis of this difference is the plate being slightly out of level and or the moment required initiate movement of the mass of the tank in conjunction with the

## RECOMMENDATION

The experiment could be more accurately performed by using a small beaker reducing the water splashing on the side walls of the tank affecting the depth of the water in the tank.

## REFERENCES

Baran S. Jayne, PE, Fluid Statics Lecture Slides (17-26)

Baran S. Jayne, PE, The Center of Pressure Experiment, (https://mylearning.suny.edu/d2l/lms/dropbox/user/folder_submit_files.d2l?db=2339599&grpid=0&isprv=0&bp=0&ou=1261266)

Baran S. Jayne, PE, Center of Pressure Reinvent, (https://mylearning.suny.edu/d2l/le/content/1261266/viewContent/32696864/View)

# APPENDIX A: HAND CALCULATIONS

Calculations performed to verify the Excel Formulas.

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Center of Pressure – Fluid Statics – Vertical Rectangular Plane Surface.

Center of Pressure Excel Sheet Check.

Data Collected

$R_1$ (inner radius-m) = $\boxed{0.10\text{ m}}$

$R_2$ (outer radius-m) = $\boxed{0.20\text{ m}}$

$R_3$ (moment arm-m) = $\boxed{0.203\text{ m}}$

B (width-m) = $\boxed{0.075\text{ m}}$

$\gamma$ (N/m³) = $\boxed{9788}$ for <u>21.0 C</u>° water temperature

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<u>Partially submerged 20g mass</u>

$\boxed{20g}$ hanger mass $\rightarrow (20g/1000) = \boxed{0.02\text{ Kg}}$

h (m) = $\boxed{0.18}$

Depth of water = $(0.2 - 0.18) = \boxed{0.02\text{ m}}$

Moment from mass = $0.02\text{ Kg} \cdot 9.81 \frac{m}{s^2} \cdot 0.203\text{ m} = \boxed{0.0398\text{ N}\cdot\text{m}}$

Area of vertical rectangular plane = $(0.02\text{ m} \cdot 0.075\text{ m}) = \boxed{0.0015\text{ m}^2}$

h-bar (m) = $(0.02\text{ m}/2) = \boxed{0.01\text{ m}}$

Moment of inertia about the centroid = $\bar{I}_x = \frac{0.075 \cdot (0.02)^3}{12} = \boxed{5.0\times10^{-8}}$

Theoretical resultant force (N) = $F = 9788\text{ N/m}^3 \cdot 0.01\text{ m} \cdot 0.0015\text{ m}^2 = \boxed{0.15\text{ N}}$

CP from water surface = $\bar{h} + \frac{\bar{I}}{\bar{h}\cdot A}$

$= 0.01\text{ m} + \frac{5.0\times10^{-8}}{0.01\text{ m}\cdot 0.0015\text{ m}^2} = \boxed{0.013\bar{3}\text{ m}}$

Theoretical moment arm = $(\underset{\overset{\uparrow}{h}}{0.18\text{ m}} + \underset{\overset{\uparrow}{CP}}{0.013}) = \boxed{0.193\text{ m}}$

Partially submerged 100 g

hanger mass $= (100g/1000g) = \boxed{0.1 Kg}$

$h (cm) = \boxed{0.148 m}$

Depth of water $= (0.2 - 0.148) = \boxed{0.052 m}$

Moment from mass $= 0.1 Kg \cdot 9.81 m/s^2 \cdot 0.207 m = \boxed{0.1991 N \cdot m}$

Area of vertical rectangular plane $= (0.075 m \cdot 0.052 m) = \boxed{0.0039 m^2}$

$\bar{h} = (0.052 m/2) = \boxed{0.026 m}$

Moment of inertia about the centroid $\bar{I} = \dfrac{0.075 \cdot (0.052)^3}{12} = \boxed{8.79 \times 10^{-7} m^4}$

Theoretical resultant force $= F = 9788 N/m^3 \cdot 0.026 m \cdot 0.0039 m^2 = \boxed{0.993 N}$

Center of pressure from water surface $= y_{cp} = 0.026 m + \dfrac{8.79 \times 10^{-7} m^4}{(0.026 m)(0.0039 m^2)} = \boxed{0.035 m}$

Theoretical moment arm $= (\underset{\substack{\uparrow \\ h}}{0.148} + \underset{\substack{\uparrow \\ cp}}{0.035}) = \boxed{0.183 m}$

Partially submerged 250g

hanger mass $= (250g/1000) = \boxed{0.25Kg}$

$h(\text{cv}) = \boxed{0.112m}$

Depth of water $= (0.2m - 0.112m) = \boxed{0.088m}$

Moment from mass $= 0.25Kg \cdot 0.203m \cdot 9.81m/s^2 = \boxed{0.4979 N \cdot m}$

Area of vertical Rect plane $= (0.075m \cdot 0.088m) = \boxed{0.0066m^2}$

$\bar{h} = (0.088m/2) = \boxed{0.044m}$

Moment of Inertia about the centroid $= \bar{I} = \dfrac{0.075m(0.088m)^3}{12} = \boxed{4.26 \times 10^{-6} m^4}$

Theoretical resultant force (N) $= F = 9788 N/m^3 \cdot 0.044m \cdot 0.0066m^2 = \boxed{2.84N}$

CP from water surface $\quad y_{CP} = 0.044m + \dfrac{4.26 \times 10^{-6} m^4}{0.044m \cdot 0.0066m} = \boxed{0.059m}$

Theoretical moment arm distance $= (0.112m + 0.059m) = \boxed{0.171m}$

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Fully submerged 350g

hanger mass $= (350g/1000) = \boxed{0.350 kg}$

h (m) $= \boxed{0.092 m}$

depth of water $= (0.2m \; 0.092 m) = \boxed{0.108 m}$

moment from mass $= 0.350 kg \cdot 0.203 m \cdot 9.81 m/s^2 = \boxed{0.697 N \cdot m}$

Area of vertical Ref plane $= (0.075 m \cdot (0.2m - 0.1m)) = \boxed{0.0075 m^2}$

$\bar{h} = (0.1m - 0.092m) + (0.05m) = \boxed{0.058m}$

moment of inertia about centroid $= I_x = \frac{0.075m \cdot (0.1m)^3}{12} = \boxed{6.25 \times 10^{-6} m^4}$

Theoretical Resultant force $= F = 9788 N/m^3 \cdot 0.058m \cdot 0.0075m^2 = \boxed{4.26 N}$

CP from water surface $Y_{CP} = 0.058m + \frac{6.25 \times 10^{-6} m^4}{0.058m \cdot 0.0075m^2} = \boxed{0.072 m}$

Theoretical Moment arm distance $= (0.092m + 0.072m) = \boxed{0.164m}$

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EXPerimental resultant Force and % difference

Partially Submerged 20g

$$\text{EXP resultant Force} = \frac{0.0378\,N\cdot m}{0.147\,M} = \boxed{0.209N}$$

$$\%\text{ difference} = \frac{(0.206N - 0.15N)}{0.15N}\cdot 100 = \boxed{37.5\%}$$

partially submerged 100g

$$\text{EXP resultant force} = \frac{0.1991\,N\cdot m}{0.183\,m} = \boxed{1.09N}$$

$$\%\text{ difference} = \frac{(1.09N - 0.997N)}{0.997N}\cdot 100 = \boxed{9.4\%}$$

Partially Submerged 250g

$$\text{EXP resultant force} = \frac{0.4979\,Nm}{0.171\,m} = \boxed{2.91N}$$

$$\%\text{ difference} = \frac{(2.91 - 2.84N)}{2.84N}\cdot 100 = \boxed{2.5\%}$$

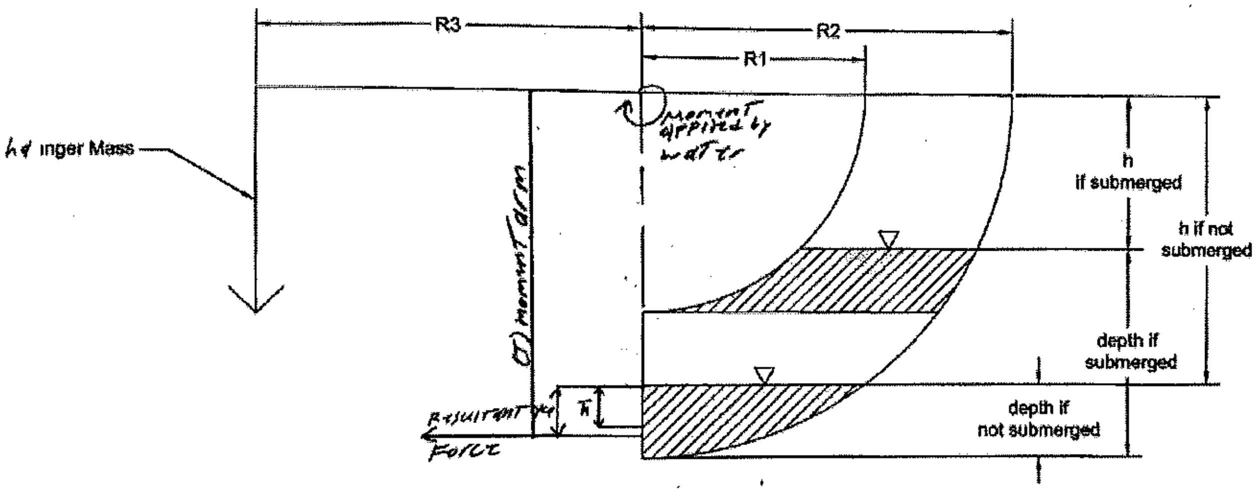
Fully Submerged 350g

$$\text{EXP resultant force} = \frac{0.697\,N\cdot m}{0.164\,m} = \boxed{4.25N}$$

$$\%\text{ difference} = \frac{(4.25 - 4.26)}{4.26}\cdot 100 = \boxed{-0.2\%}$$

# APPENDIX B: DIAGRAMS

Partially submerged



Fully submerged