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STRESS DISTRIBUTION ANALYSIS ON THE SPILLWAY STRUCTURE

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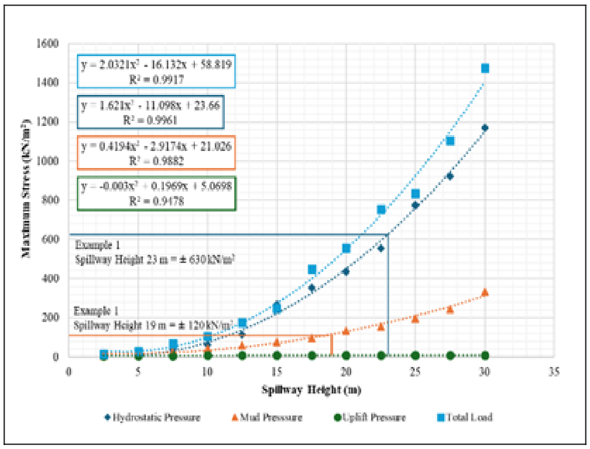
Graphical abstract



Abstract

The stress distribution varies between different areas. This is caused by several main factors such as spillway height and the magnitude of the forces. The research objective is to analyze stress distribution on the spillway structure due to the acting forces and to generate graphs that can be used as a quick way to obtain its structural stress values. The method employs 12 models of ogee-crested spillways with varying heights. The loads acting include hydrostatic pressure, mud, uplift, and self-weight. Stress distribution is calculated using SAP2000 software. The stress results are illustrated against spillway height. Trendlines and polynomial equations are fitted to the graphs and tested with interpolation and extrapolation. Graph validation is performed against previous studies, showing reasonably good accuracy. In conclusion, stress distribution on the spillway structure due to hydrostatic pressure, mud, uplift, and self-weight varies in each area. This study successfully obtains graphs that can be used as a quick method to obtain its structural stress values.

Keywords: Spillway, SAP2000, Stress Distribution Graph, Acting Loads

1.0 INTRODUCTION

The spillway structures in Indonesia play a crucial role in irrigation and the provision of drinking water [1]. The spillway body experiences pressure from its own weight and external forces, namely hydrostatic, mud, and uplift forces [2,3,4]. Pressure exceeding the structural strength limit can lead to damage [5], as it induces stress distribution within the spillway body [6,7], potentially causing structural deterioration.

This stress distribution varies between different areas [8,9,10] due to several key factors such as spillway height and the magnitude of the forces at play [11,12,13]. Hence, it is essential to analyze the stress distribution within the spillway structure.

While previous research might have addressed stress distribution in spillway structures, this study employs models with varied dimensions and forces, presenting novel findings. The research aims to analyze stress distribution within spillway structures caused by acting forces and to generate graphs for quick determination of structural stress values. These findings are validated against previous research to assess the accuracy of the stress distribution.

2.0 RESEARCH METHODOLOGY

2.1 Research Object

In this research, the object is a spillway structure utilizing the ogee crest type with variations in height, namely 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, and 30 meters. This study will consider hydrostatic pressure, mud pressure, uplift pressure, and self-weight load.

2.2 Research Instrument

This study utilized the assistance of SAP2000 v25.0.0 software - License #3010*1AF5T7BN4SWZRA9 to conduct structural analysis of a spillway. The output generated by SAP2000 includes stress values resulting from the loads acting on the structure [14,15,16].

2.3 Spillway Hydraulics

The ogee weir model used is shown in Figure 1. To design the ogee weir, equations from the US. Army Corps of Engineers are used. These equations can be seen in equation 1 [17]. Equation 1 requires the values of K and n, which can be found in Table 1 [18].

$$\frac{Y}{hd} = \frac{1}{K}\left[\frac{X}{hd}\right]^n \qquad (1)$$

where:
X = X-coordinate of the structure.
Y = Y-coordinate of the structure.
hd = planned flood height.

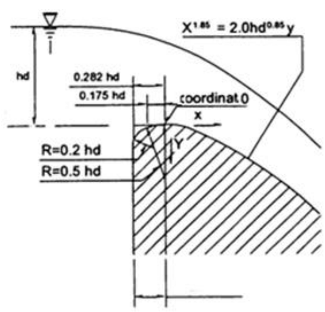


Figure 1 Type of Crest Ogee
Source: Open-channel hydraulics [18]

Table 1 Values of K and n

Downstream Surface Slope	K	N
Vertical	2.000	1.850
3:1	1.936	1.836
3:2	1.939	1.810
1:1	1.873	1.776

2.4 Hydrostatic Pressure

Hydrostatic pressure is the pressure that arises within a fluid (liquid or gas) as a result of the height of the fluid column accumulated above a point in the fluid. This pressure is caused by gravity affecting the mass of fluid above a particular point. The equation used to calculate hydrostatic pressure can be seen in equation 2 [20].

$$P = \rho \cdot g \cdot h \qquad (2)$$

where:
P = hydrostatic pressure (in pascals, Pa).
ρ = density of the fluid (kg/m³).
g = gravitational acceleration (9.81 m/s²).
h = the height of the fluid column above the point where the pressure is being measured (m).

2.5 Mud Pressure

Mud pressure is the pressure generated by the layer of mud or sediment at the upstream spillway. The magnitude of this pressure depends on the depth of the mud, the coefficient of friction, and the weight of the mud itself. Mud pressure is calculated using equation 3 [19].

$$Ps = \frac{\tau_s h^2}{2}\frac{1-\sin\theta}{1+\sin\theta} \qquad (3)$$

where:
Ps = Force located at 2/3 depth from the top of the mud working horizontally (kN)
τs = Weight of mud (kN)
h = Depth of mud (m)
Θ = Angle of friction

2.6 Uplift Pressure

Uplift pressure is the upward force affecting structural integrity due to groundwater flow. This phenomenon can occur in various structures, including spillways. As a result of this stress, there is a decrease in the effective weight of the structure above it. Uplift pressure can be calculated using Equation 4 [21].

$$Px = Hx - (Lx / L) \times \Delta H \qquad (4)$$

where:
Px = Uplift pressure at point X (t/m^2)
Lx = Distance of seepage path at point x (m)
L = Total length of seepage path (m)
ΔH = Difference in energy head (m)
Hx = Energy head at upstream spillway (m)

2.7 Self Weight (Dead Load)

Self-load is the weight of the structure itself, which is constant and fixed [19]. This load is categorized as dead load, which can be calculated by multiplying the volume of the structure by the density of the material.

2.8 Load Combinations

The loading combinations used in this study refer to SNI 1727-2020 Article 2.3 [23]. The combinations used in this study are as follows:

1. F
2. Ha
3. Hb
4. F + Ha + Hb
5. 1,4D
6. 1,4D + F
7. 1,4D + Ha
8. 1,4D + Hb
9. 1,4D + F + Ha + Hb

where:
D = Dead load
F = Hydrostatic pressure
Ha = Mud pressure
Hb = Uplift pressure

In loading combinations using hydrostatic and mud pressure, calculations are only made for the maximum depth.

2.9 Model and Data Analysis

The data analysis conducted in this study is as follows:

1. Calculating spillway dimensions to obtain the profile of the spillway body up to its stilling basin.
2. Computing hydrostatic pressure using Equation 2.
3. Determining mud pressure using Equation 3.
4. Evaluating uplift pressure for each model using Equation 4.
5. Developing spillway models using SAP2000 Software and inputting all previously calculated loads.
6. Recording maximum and minimum stresses for each loading combination and spillway model.
7. Creating graphs illustrating the relationship between spillway height and stress for each loading combination.
8. Generating trendlines and polynomial equations for each spillway height-stress graph.
9. Grouping graphs into four categories: maximum and minimum stress distributions with and without self-weight.
10. Testing graphs using mathematical calculations and trendline drawing to quantify differences.
11. Conducting extrapolation testing to assess graph usability limits.
12. Validating graphs by comparing stress distribution results with previous research findings.

Please refer to Figure 2 for the flowchart of the research process, illustrating the analysis from the beginning to the end.

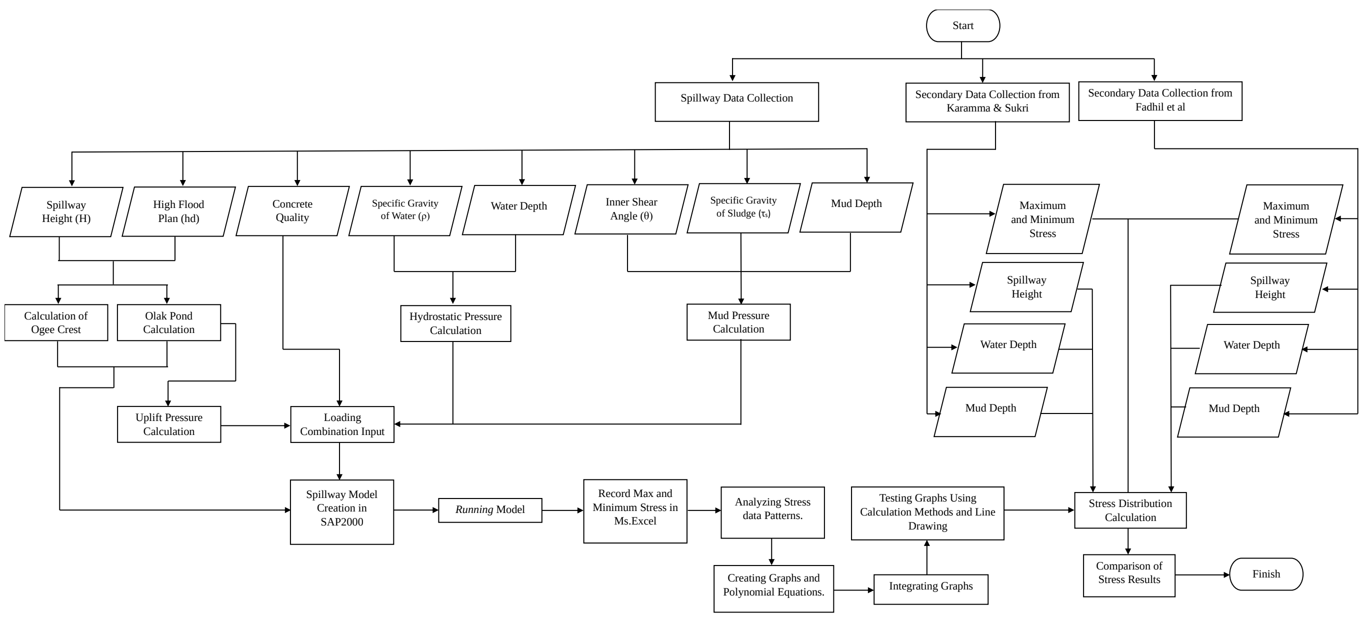


Figure 2 Research Flow Chart

3.0 RESULTS AND DISCUSSION

3.1 Spillway Model

In performing calculations for the model in this study, the following data are used:

1. Spillway height (H)(m) : 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, dan 30
2. Planned flood height (hd)(m) : 3 (Medium flood height [20])
3. Density of water (ρ)(kg/m^3) : 1000
4. Gravity (g)(m/s^2) : 9.81
5. Concrete grade (kg/cm^2) : 350 (K350) = f'c 29.05 MPa
6. Density of concrete (γ)(kN/m^3) : 24
7. Modulus of elasticity (E) : 26252.77
8. Density of mud (τs)(kN/m^3) : 5.88
9. Internal friction angle (θ) : 20^0

3.1.1 Crest Calculation

The calculation and design of a spillway structure are based on Open-channel hydraulics [18]. The depiction of the spillway is shown in Figure 3. The shape of the spillway depicted is based on the coordinates resulting from the calculation. These calculations yield the value of y, which represents the height of the spillway, and x represents the thickness of the spillway, thus facilitating the process of depicting the spillway in SAP2000.

3.1.2 Olak Pond Calculation

Calculation of the olak pond results in the length of the olak pond (Lj), the height of the end sill (a), and the width of the end sill (2a) [18]. The calculation results are shown in Table 2. In the table, differences in dimensions are observed. Refer to Figure 4 for an illustration of the olak pond. The figure depicts the depiction of the olak pond based on the calculation data in

Table 2. The depiction is then integrated with the spillway structure to obtain a perfect spillway structure.

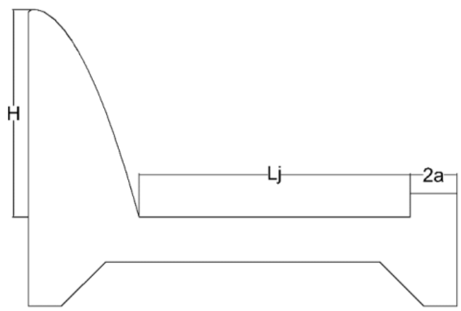


Figure 4 Spillway and Olak Pond

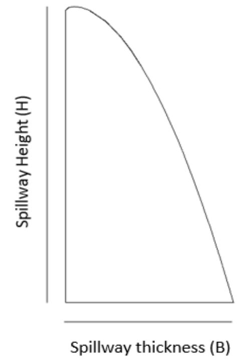


Figure 3 Spillway Crest

Table 2 Calculation of The Olak Pond

Item	Dimension (m)											
	2,5 m	5 m	7,5 m	10 m	12,5 m	15 m	17,5 m	20 m	22,5 m	25 m	27,5 m	30 m
Lj	3.3	6.5	9.8	13.1	16.3	19.6	22.9	26.1	29.4	32.7	35.9	39.2
a	0.3	0.6	0.9	1.1	1.4	1.7	2	2.3	2.6	2.8	3.1	3.4
2a	0.6	1.2	1.8	2.2	2.8	3.4	4	4.6	5.2	5.6	6.2	6.8

3.2 Load

3.2.1 Hydrostatic Pressure

The hydrostatic pressure is calculated only at the maximum water depth, which is the height of the spillway (H). This pressure takes the form of a triangular load acting at the upstream of the spillway. It is calculated using equation 2. The calculation results are shown in Table 3. It can be observed that the hydrostatic pressure increases with the water depth.

Table 3 Hydrostatic Pressure

Spillway Height and Water Depth (m)	Hydrostatic Pressure (kN/m²)
2.5	24.525
5	49.05
7.5	73.575
10	98.1
12.5	122.625
15	147.15
17.5	171.675
20	196.2
22.5	220.725
25	245.25
27.5	269.775
30	294.3

3.2.2 Mud Pressure

Mud originates from river sediment transport [22]. Mud pressure is calculated only at the maximum mud depth, which is the height of the spillway (H). This pressure takes the form of a triangular load acting at the upstream spillway. This pressure is calculated using Equation 3. The calculation results are shown in Table 4. It can be observed that mud pressure increases with increasing mud depth.

Table 4 Mud Pressure

Spillway Height and Mud Depth (m)	Mud Pressure (kN/m²)
2.5	9.00909
5	36.03636
7.5	81.08181
10	144.1454
12.5	225.2272
15	324.3272
17.5	441.4454
20	576.5817
22.5	729.7363
25	900.909
27.5	1090.1
30	1297.309

3.2.3 Uplift Pressure

The uplift pressure on the spillway is calculated using equation 4. When calculating the uplift pressure, calculation points are determined as shown in Figure 5. In the figure, calculation points and the illustration of the resulting pressure are known. The calculation results of uplift pressure for each spillway model are shown in Table 5. It can be seen that the uplift pressure values gradually decrease from upstream to downstream of the spillway.

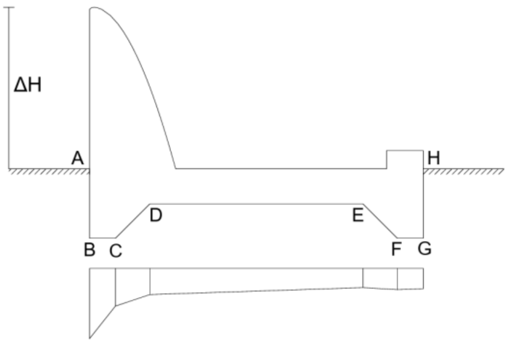


Figure 5 Points of Uplift Pressure Calculation

3.2.4 Self Weight

The spillway and overflow structures are designed to handle excess water flow. The stress analysis of these structures is crucial for ensuring their stability and safety. In this study, the self-weight is automatically calculated using SAP2000 software, eliminating the need for manual self-weight calculations.

3.3 Computer Modeling

3.3.1 Model Creation

The steps in creating a spillway model in SAP2000 are as follows [1]:

1. Create a new worksheet by clicking File > New Model.
2. Determine the spillway material by clicking Define > Materials > Add New Material.
3. Create load patterns by clicking Define > Load Patterns.
4. Create load cases by clicking Define > Load Cases.
5. Create load combinations by clicking Define > Load Combination.
6. Create joint pattern by Define > Joint Pattern.
7. Create a grid or reference lines by Define > Coordinate System/Grid > Modify/Show System.
8. Draw the spillway using the Draw Poly Area tools.
9. Extrude the area into a 3D shape by clicking Edit > Extrude > Extrude Area to Solid.
10. Provide supports to the spillway by clicking Assign > Joint > Restraints.

Table 5 Uplift Pressure

Item	Uplift Pressure (kN/m^2)											
	2,5 m	**5 m**	**7,5 m**	**10 m**	**12,5 m**	**15 m**	**17,5 m**	**20 m**	**22,5 m**	**25 m**	**27,5 m**	**30 m**
A	24.52	49.03	73.57	98.07	122.625	147.1	171.675	196.13	220.725	245.17	269.775	294.2
B	29.82	60.83	89.47	120.37	149.12	179.82	208.77	239.19	268.42	298.48	328.07	357.77
C	29.17	59.68	87.52	117.93	145.87	176.06	204.21	234.19	262.56	292.06	320.91	349.96
D	20.26	42.48	60.78	83.25	101.30	123.2	141.82	162.99	182.34	202.63	222.86	243.04
E	14.89	27.57	44.67	56.85	74.46	86.94	104.25	117.2	134.03	147.61	163.82	178.65
F	16.44	31.38	49.32	64.20	82.22	97.12	115.10	130.14	147.99	163.25	180.87	197.25
G	15.79	30.24	47.37	61.75	78.96	93.36	110.54	125.06	142.13	156.83	173.71	189.44
H	0	0	0	0	0	0	0	0	0	0	0	0

3.3.2 Load Data Input

The spillway model is designed in a 3D form, enabling the utilization of surface pressure loading. To input the surface pressure loading, pre-defined joint patterns are employed to form the pressure distribution. The joint patterns for hydrostatic pressure are denoted as F, mud pressure as H, and uplift pressure as U. An example of the input results in SAP2000 can be seen in Figures 6 to 8. These figures illustrate the representation of hydrostatic, mud, and uplift pressures after being inputted into the constructed model.

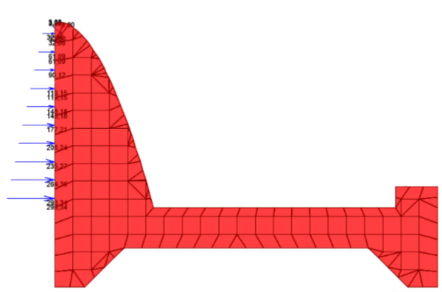


Figure 6 Hydrostatic Pressure

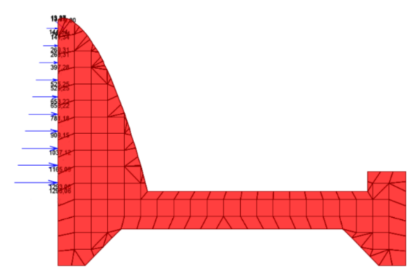


Figure 7 Mud Pressure

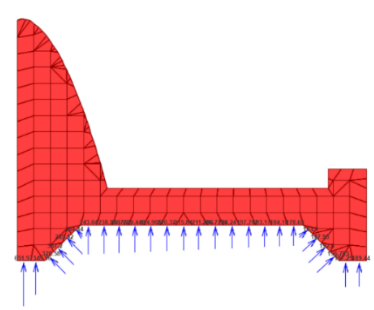


Figure 8 Uplift Pressure

3.3.3 Model Calculation Result

The model has been inputted with loads and has entered the running stage. An example of the maximum and minimum stress results from all models can be seen in Tables 6 and 7. It is known that all stresses increase as the dam height increases, thus a method can be sought to create a stress distribution graph on the spillway structure that is easy and accurate to use.

The method employed is to create a graph showing the relationship between spillway height and stress. Based on this graph, trendlines and polynomial equations (y) are established for each loading combination. An example graph can be seen in Figure 9. This figure illustrates the relationship between spillway height and maximum stress due to hydrostatic pressure. It is observed that the maximum stress continues to increase with the increase in spillway height, as well as with other loading combinations. The overall results of the graphs for each loading combination are grouped into four categories, as presented in Figures 10 to 13. These figures represent the output generated from the analysis of stress distribution on the spillway structure. Within these graphs, polynomial equations and annotations are provided to determine stress distribution through mathematical calculations or line drawings.

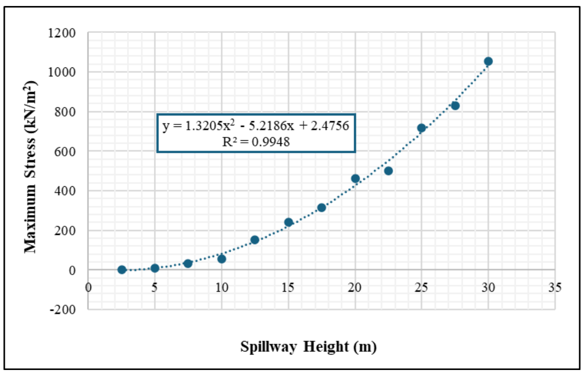


Figure 9 Sample of Maximum Stress

3.4 Chart Analysis

The stress distribution graph on the spillway structure body yields four graphs. Graph 1 in Figure 11 represents the maximum stress without self-weight, graph 2 in Figure 12 represents the minimum stress without self-weight, graph 3 in Figure 13 represents the maximum stress with self-weight, and graph 4 in Figure 14 represents the minimum stress with self-weight. These findings are tested using two methods, namely mathematical calculations and graph plotting.

The usage involves determining the spillway height and the acting forces. For example, determining the maximum stress distribution on a spillway with a height of 23 meters due to hydrostatic pressure. Graph 1 in Figure 11 is used because we want to determine the maximum stress without self-weight. The first step is to read the graph description to determine which graph is used to find the stress due to hydrostatic pressure. Stress distribution can be determined in two ways: by directly drawing lines or using the polynomial equation provided, which is $y = 1.621x^2 - 11.098x + 23.66$.

To draw the line, refer to Example 1 in Figure 11. It can be seen that the stress is approximately 630 kN/m². The calculation using the polynomial equation is as follows:

Given:

H = 23 m

$$
\begin{aligned}
y &= 1.621x^2 - 11.098x + 23.66 \\
&= 1.621 \times 23^2 - 11.098 \times 23 + 23.66 \\
&= 625.9150 \text{ kN/m}^2
\end{aligned}
$$

Next example, what is the distribution of maximum stress that occurs on a spillway with a height of 19 m due to mud pressure. How to draw the line see Example 2 in Figure 11. It appears that the stress that occurs is approximately 120 kN/m². The calculation of the polynomial equation is as follows:

Given:

H = 19 m

$$
\begin{aligned}
y &= 0.4194x^2 - 2.9174x + 21.026 \\
&= 0.4194 \times 19^2 - 2.9174 \times 19 + 21.026 \\
&= 116.9988 \text{ kN/m}^2
\end{aligned}
$$

Based on both examples, it is known that the stress distribution obtained through the method of drawing lines with calculations using polynomial equations yields relatively similar values. After conducting testing 100 times, it was found that the difference is above and below 5%.

To determine the limits of graph usage, extrapolation testing was performed. An additional model was created with heights of 35 and 40 meters to obtain the maximum and minimum stresses. Stress distribution calculations were made using graphs for heights of 35 and 40 meters. The calculation results were compared with the original stress data to determine the deviations that occurred. See Figure 10. This is an example of a graph comparing the original stress values with the extrapolated results of stress distribution graph due to hydrostatic pressure. The blue graph represents the original stress values, while the orange one represents the extrapolated results. It can be observed that both graphs show deviations starting when the dam height exceeds 30 m. At a spillway height of 35 m, the average deviation is around a dozen percent, while at a dam height of 40 m, the deviation reaches around fifty percent. This means that the stress distribution graph is recommended for use not exceeding a spillway height of 35 m because the higher the deviation, the more it will affect its structural safety factor.

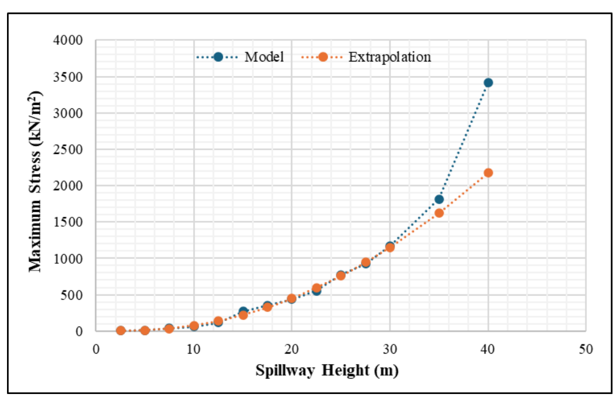


Figure 10 The comparison of original stress with extrapolation

To validate the accuracy of the stress distribution graph obtained, a comparison of the stress calculation results with previous studies was conducted. Two previous studies used for comparison are Karamma & Sukri [1] and Fadhil et al. [14]. The comparison results are shown in Tables 8 and 9. Study [1] obtained stress due to hydrostatic pressure of 308.1565 kN/m^2 & -462.901 kN/m^2 and due to mud pressure of 77.2866 kN/m^2 & -123.4383 kN/m^2. Study [14] obtained stress due to hydrostatic pressure of 140.6251 kN/m^2 & -53.2161 kN/m^2 and mud pressure of 100.4658 kN/m^2 and -38.0188 kN/m^2. Based on the calculation results, it is known that the comparison in Table 8 yields correction factors ranging from 0.7 to 2.8, and in Table 9 yields correction factors ranging from 0.3 to 3.9. Values less than 1 indicate that the calculation is smaller than the research results, and vice versa. The significant difference in Table 9 is suspected because the study only calculated the spillway crest section, while this study calculated the entire spillway including the olak pond, similar to what was done by Karamma & Sukri [1].

Table 6 Maximum Stresses

Combination	Maximum Stress (kN/m^2)											
	2,5 m	5 m	7,5 m	10 m	12,5 m	15 m	17,5 m	20 m	22,5 m	25 m	27,5 m	30 m
F	3.453	10.587	35.963	61.339	114.7915	268.244	352.0715	435.899	555.0575	774.216	922.5355	1170.855
Ha	7.214	14.408	28.076	41.744	59.0385	76.333	95.317	134.301	155.3865	196.472	245.0705	333.669
Hb	5.479	5.88	6.1595	7.139	7.3585	7.418	7.5755	7.653	7.7985	7.844	8.335	8.526
F+Ha+Hb	15.421	27.896	67.148	106.4	177.273	248.146	451.0725	553.999	754.349	834.699	1104.648	1474.597
1,4D	30.213	42.237	60.6405	79.044	125.48	171.916	224.176	276.436	351.4455	426.455	493.2975	560.14
1,4D+F	17.234	26.509	38.149	89.789	152.058	274.327	367.589	420.851	583.9	706.949	904.1905	1201.432
1,4D+Ha	15.245	26.503	38.2015	49.9	62.3815	74.863	88.3295	101.796	115.008	128.22	146.233	164.246
1,4D+Hb	25.271	41.905	57.694	73.483	118.8015	164.12	215.543	266.966	340.5675	414.169	480.368	546.567
1,4D+F+Ha+Hb	27.214	56.461	78.003	149.54	268.004	316.462	462.707	638.952	753.192	967.432	1253.133	1558.833

Table 7 Minimum Stresses

Combination	Minimum Stress (kN/m^2)											
	2,5 m	5 m	7,5 m	10 m	12,5 m	15 m	17,5 m	20 m	22,5 m	25 m	27,5 m	30 m
F	-12.41	-36.75	-137.79	-238.8	-509.769	-980.71	-1630.78	-1880.8	-2552.41	-3423.9	-4306.5	-5189.03
Ha	-24.35	-50.02	-106.27	-162.5	-258.372	-354.21	-463.088	-571.96	-752.493	-933.02	-1123.14	-1313.26
Hb	-7.742	-7.88	-8.2335	-8.587	-8.6335	-8.78	-9.375	-9.87	-10.878	-12.286	-12.9295	-13.573
F+Ha+Hb	-28.31	-86.75	-246.87	-407	-774.86	-1142.7	-1705	-2267.2	-3318.28	-4369.2	-5085.88	-13.573
1,4D	-48.13	-56.10	-82.997	-109.8	-135.784	-161.68	-188.366	-215.04	-241.158	-267.26	-292.337	-317.407
1,4D+F	-27.24	-53.21	-307.90	-562.5	-785.695	-908.79	-1510.42	-1812.0	-2704.78	-3134.5	-4130.49	-5193.47
1,4D+Ha	-41.45	-52.16	-74.191	-96.21	-139.509	-182.80	-246.844	-310.88	-408.727	-506.56	-647.137	-787.707
1,4D+Hb	-36.13	-54.96	-80.764	-106.5	-132.341	-158.11	-184.681	-211.24	-237.252	-263.25	-288.245	-313.233
1,4D+F+Ha+Hb	-29.25	-80.46	-205.61	-530.7	-950.786	-1370.8	-1880.08	-2289.3	-2966.09	-3942.8	-5266.5	-6590.18

Table 8 Comparison of Karamma & Sukri Research Results with Calculation

Force	Value	Karamma & Sukri Research (kN/m^2)	Calculation Result (kN/m^2)	Correction Factor
1	2	3	4	4/3
Hydrostatic Pressure	Maximum	308.1565	221.915	0.7
	Minimum	-462.901	-952.4325	2.1
Mud Pressure	Maximum	77.2866	71.63	0.9
	Minimum	-123.4383	-346.612	2.8

Table 9 Comparison of Fadhil et al Research Results with Calculation

Force	Value	Fadhil et al Research (kN/m^2)	Calculation Result (kN/m^2)	Correction Factor
1	2	3	4	4/3
Hydrostatic Pressure	Maximum	140.6251	55.079	0.4
	Minimum	-53.2161	-209.3301	3.9
Mud Pressure	Maximum	100.4658	28.7408	0.3
	Minimum	-38.0188	-137.2066	3.6

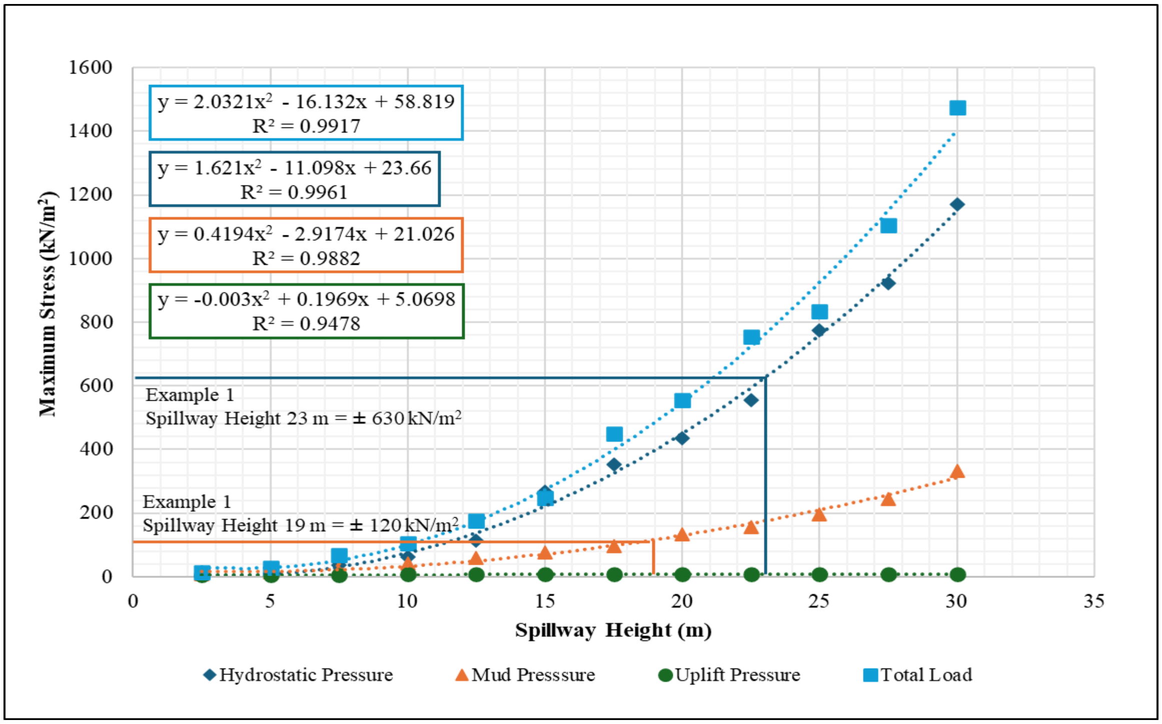


Figure 11 Graph Distribution of Maximum Spillway Stress

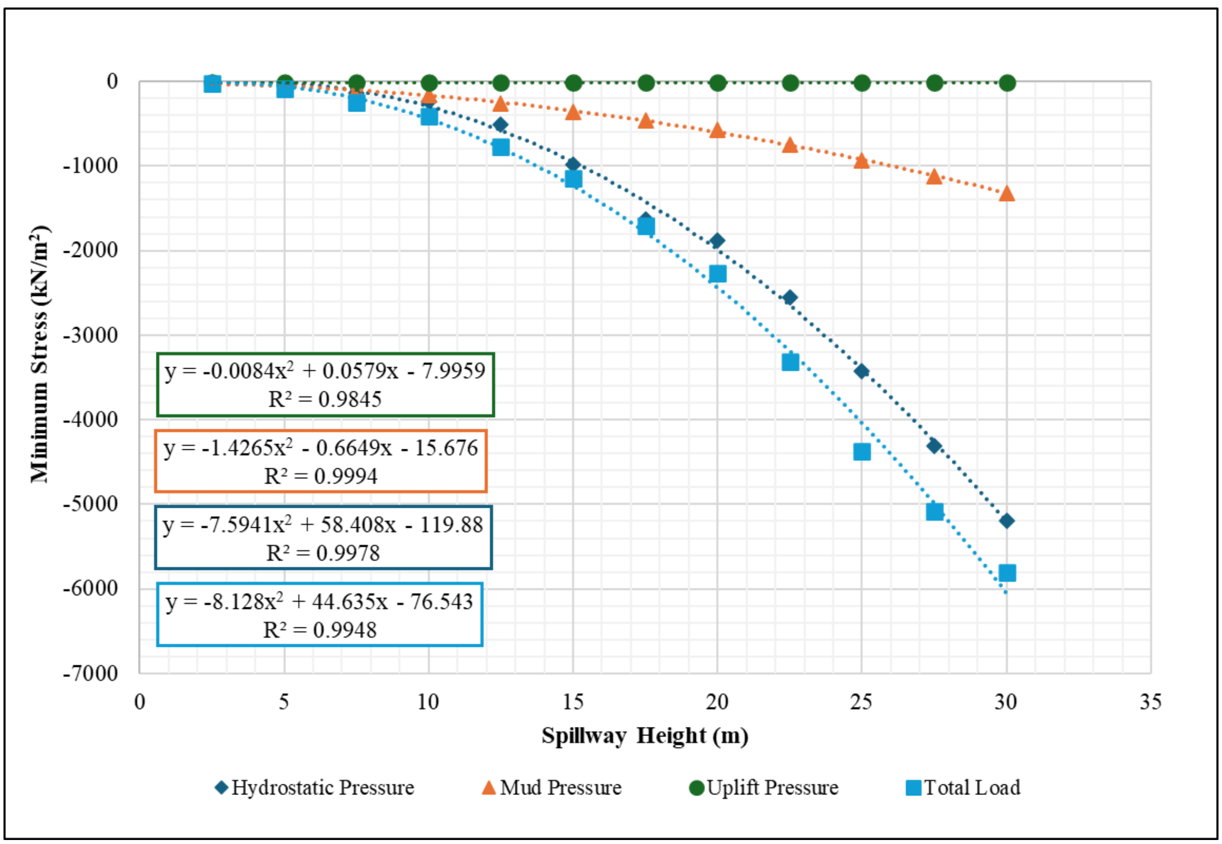


Figure 12 Graph Distribution of Minimum Spillway Stress

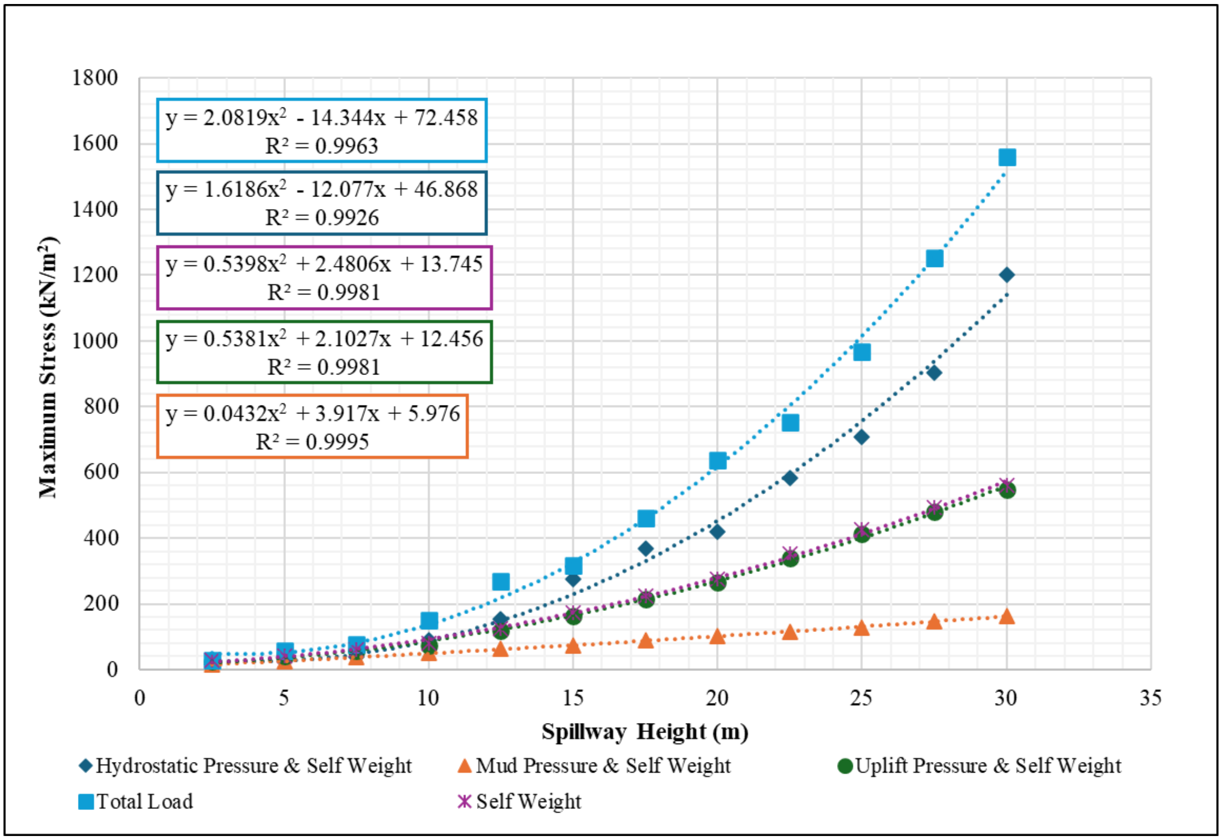


Figure 13 Graphic Distribution of Maximum Spillway Stress with Dead Load Combination

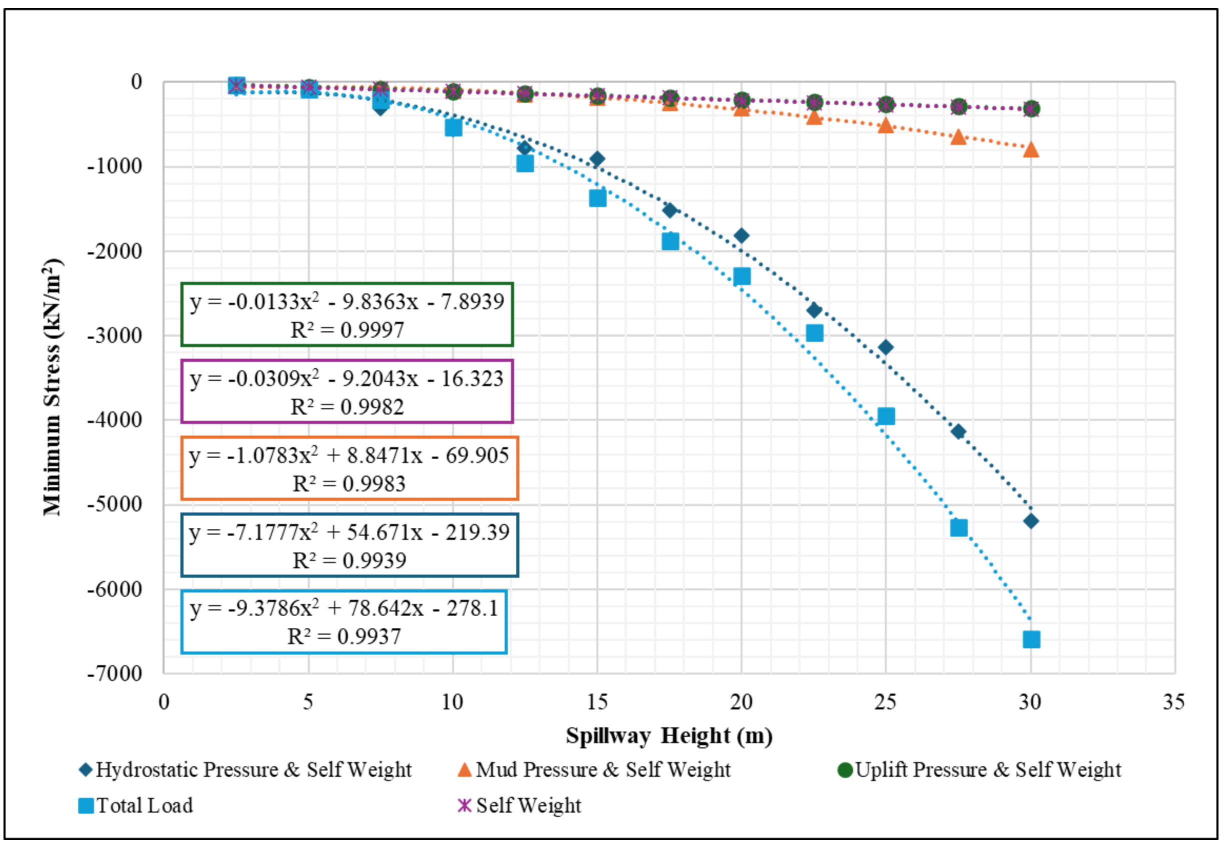


Figure 14 Graphic Distribution of Minimum Spillway Stress with Dead Load Combination

4.0 CONCLUSIONS

The conclusion is the distribution of stress that occurs on spillway structures due to hydrostatic pressure, mud, uplift, and self-weight varies in each area. This research successfully obtained a graph that can be used as a quick way to obtain the structural stress values. For example, if we want to determine the maximum stress on a spillway with a height of 10 m due to hydrostatic pressure, we can use the graph in Figure 10 and obtain a value of 74.78 kN/m^2. This graph can be a useful tool in structural planning to facilitate estimation of stress distribution on spillway structures. This conclusion demonstrates the significant contribution of the research to the development of knowledge about spillway structures.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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