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STUDY ON THE STABILITY OF SEAWALL/ EMBANKMENT IN SULTAN KUDARAT AGAINST HISTORICAL LARGE TSUNAMI IN THE PHILIPPINES

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ABSTRACT

In this study, tsunami hazard assessment was conducted along the constructed seawall in Sultan Kudarat, Philippines, and its slope stability against the August 15, 1918, historical tsunami event was verified. The nesting grid system was used to simulate a nonlinear long wave tsunami. The maximum tsunami height at the front of the seawall was 7.79 m without seawall and 9.42 m with seawall conditions, whereas the maximum tsunami inundation at the front of the seawall is 5.93 m without seawall and 6.85 m with seawall conditions. Due to the constructed seawall, the inundation at the rear side was reduced by ~40%. In addition, the wave coefficient of hydrostatic pressure at the front and rear sides of the seawall was derived using CADMAS-SURF/3D, and three sections of the seawall were analyzed for slope stability. One section was typical with no loading condition. The pressures computed using the semi-empirical equations at the front bottom (p_1), front top (p_2), rear bottom (p_3), and rear top (p_4) of the seawall, in KPa, were 57.68, 41.32, 9.12, and 3.41 for section 1 and 71.70, 37.44, 33.10, and 22.77 for section 2, respectively. Slope stability analysis against sliding performed using the circular slip method by Fellenius/Petterson and simplified Bishop shows that an acceptable factor of safety of 2.55 and 2.84 for a typical section, 1.47 and 1.68 for section 1, and 1.33 and 1.55 for section 2. Hydraulic experiment was conducted for the future design of the required mass of armor units for additional stability. In future studies, other historical events such as August 17, 1976, may be considered. Tsunami inundation and the necessity of seawalls in other areas in Southern Mindanao may also be evaluated in the future. Other sections of the seawall, including other modes of failure, may also be considered to obtain a more disaster-resilient structure.

Keywords: Seawall, Tsunami Wave Forces, Slope Stability, Sultan Kudarat

1. INTRODUCTION

The WorldRiskReport of 2023 showed that the Philippines has the highest disaster risk index among 193 countries recognized by the United Nations worldwide. The report includes exposure of the region to different phenomena such as earthquakes, tsunamis, cyclones, coastal floods, riverine floods, drought, and sea-level rise. These risks are mainly due to its geological and geographical location along the Pacific Ring of Fire.

The Department of Public Works and Highways (DPWH), as the engineering and construction arm of the Philippine government, continuously strives to mitigate and minimize these

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risks and hazards by ensuring the safety of infrastructure facilities. As a result, the lives of the general public are secured.

Herein, tsunami hazard assessment was conducted along the constructed seawall in Sultan Kudarat, Philippines, and its slope stability against the August 15, 1918, historical tsunami event, was verified.

2. TSUNAMI SIMULATION AND INUNDATION

2.1. Data

To perform tsunami simulation and inundation, bathymetry data from the National Centers for Environmental Information–ETOPO Global Relief Model 2022 (https://www.ncei.noaa.gov/) with a resolution of 15-arc seconds were used.

To ensure good result of tsunami inundation, we merged the bathymetry data with the topography data from the National Mapping and Resource Information Authority (NAMRIA) of the Philippines while we considered the recorded tsunami height from the National Centers for Environmental Information – National Oceanic and Atmospheric Administration (NOAA) for model validation.

The seawall height and cross section are based on the "As-Built" Plan from the DPWH Sultan Kudarat 2nd District Engineering Office.

2.2. Methodology

To evaluate tsunami propagation and inundation depth within the project location, we used the tsunami simulation code developed by Goto and Ogawa (1997) incorporating the nesting grid system; this system allowed for the movement and shifting of water fluxes from larger to smaller regions. ETOPO 15-arc seconds was resampled with the different grid sizes, and the bathymetry data were merged with 10-m topography data from National Mapping and Resource Information (NAMRIA) of the Philippines for layers 3 and 4 to obtain a better resolution. The summary of parameters used for computing tsunami propagation and inundation is provided in Table 1.

Table 1. Summary of parameters used for computing tsunami simulation and inundation.

Layer	Longitude (m)*		Latitude (m)*		Grid size (nx/ny)	Spatial grid size (m)	Equation of Simulation
01	477898	790338	539696	785618	231/182	1350	Non-linear
02	523715	756665	585099	754015	518/375	450	Non-linear
03a	595722	632994	718013	745709	248/185	150	Non-linear
03b	732139	751291	650099	631684	128/123	150	Non-linear
03	577916	677416	628466	718031	663/597	150	Non-linear
04	621572	643855	674556	696603	446/441	50	Non-linear

*Based on Universal Transverse Mercator (UTM) Zone 51N.

The initial earthquake source parameters were validated using geometric mean (K) and standard deviation (κ) of the observed and computed tsunami heights. The validated/revised earthquake source parameters are presented in Table 2.

Table 2. Revised/validated earthquake source parameters for the August 15, 1918 event.

Event	Magnitude	Corner Location of the fault		Length (km)	Width (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip Amount (m)	Depth (m)
		Longitude	Latitude							
1918	8.32	124.90	5.25	148.1	60	305	36	69	10.58	0

2.3. Results and Discussion

The maximum tsunami height at the front of the seawall was 7.79 m without seawall and 9.42 m with seawall conditions (Figure 1), whereas the maximum tsunami inundation at the front of the seawall was 5.93 m without seawall and 6.85 m with seawall conditions. The tsunami height and inundation at the front side of the seawall increased due to the presence of a seawall in the area.

Although the tsunami overflowed the seawall, we observed that the presence of the seawall mitigated the impact of the tsunami by reducing the inundation depth by about 40% in the areas at the rear side of the seawall (Figure 2).

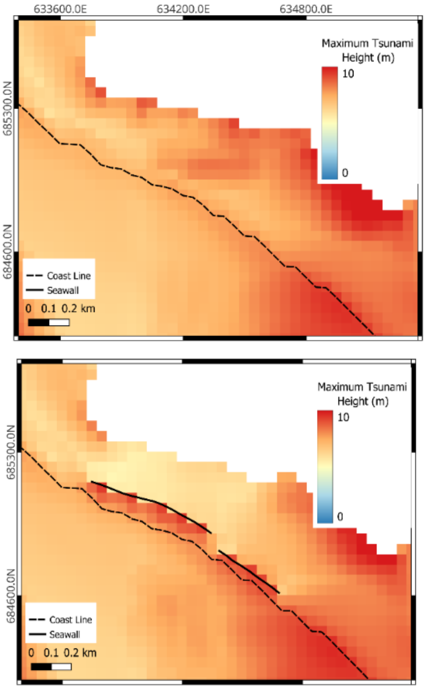

Figure 1. Maximum tsunami height without (top) and with (bottom) seawall conditions. The figures are magnified view near the seawall from layer 04.

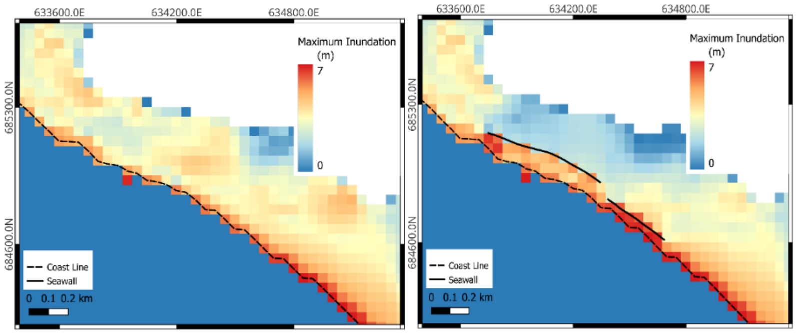

Figure 2. Maximum tsunami inundation without (left) and with (right) seawall conditions. The figures are magnified view near the seawall from layer 04.

3. NUMERICAL WAVE TANK, TSUNAMI WAVE FORCES AND SLOPE STABILITY ANALYSIS

3.1. Data

The seawall height, cross section, and the nearest available subsurface soil exploration data are from the DPWH Sultan Kudarat 2nd District Engineering Office.

3.2. Methodology

We used Japan's free numerical analysis code software/numerical wave tank known as CADMAS-SURF/3D, which is based on the volume of fluid (VOF) method (Coastal Development Technology Research Center, 2001). Grid spacing was set in three regions, provided in Table 3.

Table 3. Summary of grid spacing for numerical wave tank.

Location	Xmin (m)	Xmax (m)	Zmin (m)	Zmax (m)	Grid spacing in x (m)	Grid spacing in z (m)	Number of grids (nx/nz)
Offshore boundary of the channel	-30	-5	2.2	12	0.10	0.05	250/196
Around the embankment	-5	15	2.2	12	0.05	0.05	401/196
Near shore boundary of the channel	15	50	2.2	12	0.10	0.05	348/196

The tsunami wave forces during overflowing were calculated using the water levels at the front and rear sides of the wall (Technical Standards and Commentaries for Port and Harbour Facilities in Japan, 2020), and to consider ground motion, we used the pseudo-static method for seismic forces as per DPWH Design Guidelines Criteria and Specifications 2015.

We applied circular slip surface to determine the stability of slopes and embankment assuming that the soil body above the slip surface was subdivided into blocks. We applied the method of slices proposed by Fellenius (1936) and Bishop (1955). The verification according to the factor of safety can be determined by Eq. (1):

$$\frac{M_p}{M_a} > FS \qquad (1)$$

where M_a is the sliding moment, M_p is the resisting moment and FS is the factor of safety. In DPWH, we set FS of 1.50 for permanent condition and 1.10 for earthquake consideration. Figure 3 shows the diagram of forces and circular slip surface.

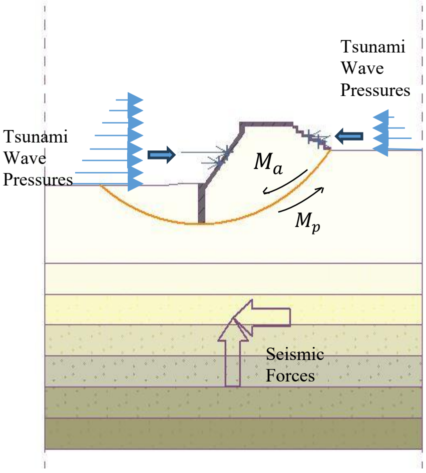

Figure 3. Schematic of the slope stability analysis.

3.3. Results and Discussion

We assumed six cases for the numerical wave tank, and for all cases, the measured pressure at the front side of the wall was almost the same as the static pressure. However, for the rear side of the wall, the static pressure was considerably larger than the measured pressure.

We considered three sections of the seawall to calculate tsunami wave forces and perform slope stability analysis. The first one is the typical section of the seawall, in permanent condition (no loads), while the other two sections with inundation depths based on the simulation results.

We considered a_f, the wave pressure coefficient at the front side of 1.04 while we set a_r, the wave pressure coefficient at the rear side of 0.38 at Section 1 based on inundation depths and water level difference between the front and rear sides of the wall and 0.75 for Section 2 for safe value of design. The factor of safety for all sections as shown in Table 4 are acceptable using Fellenius/Petterson and simplified Bishop method.

Table 4. Summary of slope stability results.

Section	Inundation depth (m)		a_f	a_r	Tsunami Wave Pressure (KPa)				Factor of Safety		Remarks
	Front Side	Rear Side			p_1	p_2	p_3	p_4	Fellenius/ Petterson	Simplified Bishop	

Typical	N/A	N/A	N/A	N/A	0	0	0	0	2.55	2.84	Acceptable
Section 1	5.46	2.37	1.04	0.38	57.68	41.32	9.13	3.41	1.47	1.68	Acceptable
Section 2	6.79	4.35	1.04	0.75	71.70	37.44	33.10	22.77	1.33	1.55	Acceptable

4. HYDRAULIC EXPERIMENT

4.1. Methodology

We performed a hydraulic experiment at the Ports and Airports Research Institute of Japan using the 1/16 model of the seawall/embankment. We placed two current meters (one in front and another on the rear side of the seawall) and two water gauges (one in front and another on the top of the seawall) to measure the flow velocity and height, respectively. Figure 4 shows the experimental setup.

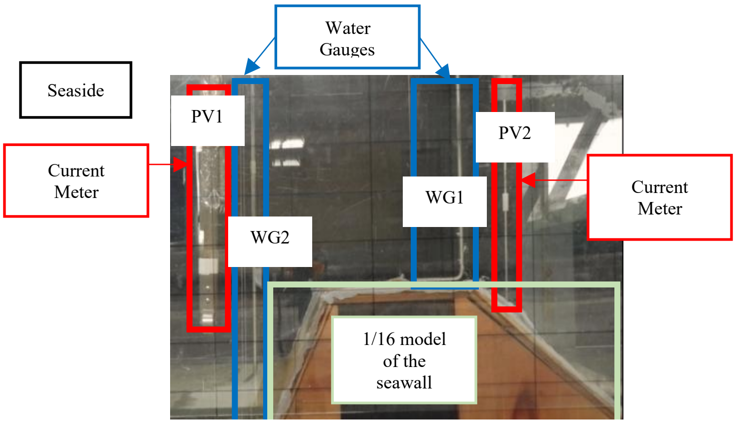

Figure 4. Setup for the hydraulic experiment.

4.2. Results and Discussion

For all six cases of hydraulic experiments, both the front and rear sides of the wall experienced flow velocity. The experimental result may be useful for determining the required mass of armor units in the future design of the seawalls by applying the Isbash formula, which was expressed by Coastal Engineering Research Center in Eq. (2):

$$M = \frac{\pi \rho_r U^6}{48 g^3 y^6 (S_r - 1)^3 (\cos\theta - \sin\theta)^3} \qquad (2)$$

where M is the required mass of the armor units, ρ_r is the density of the armor units, U is the flow velocity near the armor units, g is the gravitational acceleration, y is the Isbash number, S_r is the specific gravity of the armor units and θ is the angle of the slope.

The maximum tsunami height and velocity, together with the required mass of armor units at the rear side (with y=0.86 for exposure block and ρ_r=2.3 tons/m^3) for all cases, are shown in Table 5. The rear side is considered as a slope without steps in the calculation of the required mass.

Table 5. Maximum tsunami height, velocity and required mass of armour units for all cases of hydraulic experiment.

Case No.	Tank Level (cm)	Maximum Tsunami Height from NGL (m)		Maximum Velocity (m/sec)		Required Mass of Armor Units (tons)
		WG2	WG1	PV1	PV2	Rear
1	40	4.89	6.77	4.65	3.46	2.93
2	45	3.63	6.36	7.97	4.67	17.80
3	50	3.83	5.84	5.38	4.51	14.39
4	55	4.64	4.21	6.87	3.79	5.10

5	60.2	4.14	5.59	6.53	4.07	7.71
6	overtopping	4.45	4.13	4.66	4.98	25.60

5. CONCLUSIONS

In this study, we performed a non-linear long wave tsunami simulation to assess the effect of the existing seawall in Sultan Kudarat, Philippines, on the tsunami height and inundation considering the August 15, 1918, historical event with a moment magnitude of 8.3 based on NOAA. Based on the result of tsunami simulation and inundation modeling, the maximum tsunami height at the front of the seawall was 7.79 m without seawall and 9.42 m with seawall conditions, whereas the maximum tsunami inundation at the front of the seawall was 5.93 m without seawall and 6.85 m with seawall conditions. The presence of the seawall increased the tsunami height and inundation at the front side. In contrast, although tsunami overflowed over the seawall, the inundation at the areas at the back of the seawall was reduced by ~40%.

We also derived the wave coefficient of hydrostatic pressure at the front and rear sides of the seawall (a_f and a_r) using different boundary conditions, such as inflow boundary height and velocity. The measured pressure at the front of the seawall for all six cases is almost equal to static pressure. Hence, the value of a_f for all the cases are close to 1.00. However, a_r are sensitive and strongly depend on the rear side depth and water level difference between the front and rear sides of the wall.

We analyzed three sections of the seawall, one with typical section and no loads condition. The pressures/forces on the other two sections were based on the results of inundation depths from tsunami simulations and derived value of wave coefficient of hydrostatic pressure. Based on the results of slope stability analysis against sliding using the circular slip method of Fellenius/Petterson and simplified Bishop, all sections were acceptable. Moreover, the Fellenius/Petterson method of circular slip yielded a smaller value of the factor of safety, indicating a safety side design.

We also conducted hydraulic experiments to determine the height and velocities acting on the front and rear sides of the seawall using different set conditions. The results of this experiment may be useful in the future design of the seawall by applying the Isbash formula.

In general, seawalls play a crucial role in disaster management since they act as barriers for coastal facilities against natural disasters such as tsunamis and storm surges. Their presence increases the resilience of coastal areas, which makes them an element of comprehensive disaster risk reduction strategies. The results of this study can be integrated with other protective measures, such as early warning systems, to establish a multilayered defense against coastal hazards.

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