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Morphological Changes of Dredged Slopes Under Wave Action in Shallow Water

Kasmawati[1,a*], Muhammad Arsyad Thaha[2,b], Mukhsan Putra Hatta[2,c]

[1]Department of Civil Engineering, Hasanuddin University,
Jalan Poros Malino Km-6, Gowa 92171, INDONESIA

[2]Department of Civil Engineering, Hasanuddin University,
Jalan Poros Malino Km-6, Gowa 92171, INDONESIA

**Corresponding author; kasmawati.stmt08@gmail.com*

Email: [a]kasmawati.stmt08@gmail.com, [b]arsyad999@gmail.com, [c]mukhsan.hatta@unhas.ac.id

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Abstract: Dredging in shallow water modifies seabed geometry and may reduce the stability of artificial underwater slopes when they are exposed to wave action. This study evaluates morphological changes of dredged slopes using laboratory flume data consisting of 729 observations and 81 test combinations. The experiments considered three sediment groups (D16, D50, and D100), three water depths (13, 21, and 23 cm), three wave-period settings (T = 4, 5, and 6), and three exposure times (5, 10, and 15 min). The analysis focused on changes in bed elevation (ΔZ) and slope angle (Δθ) after wave loading. The results show that all test combinations experienced downward morphological change, with ΔZ ranging from -9.8 to -0.8 cm and an average of -6.75 cm. The slope angle also decreased, with Δθ ranging from -9.0° to -2.0° and an average of -5.91°. The strongest average bed lowering occurred after 15 min of wave exposure, indicating that repeated wave action progressively reshaped the dredged slope. The findings confirm that wave-induced loading is an important driver of post-dredging slope deformation and should be incorporated in shallow-water dredging design and monitoring.

Keywords: dredged slope, morphological change, wave action, shallow water, laboratory flume

1. Introduction

Maintenance dredging and capital dredging are widely used to provide navigation channels, port basins, turning areas, and other shallow-water maritime facilities. Although dredging is essential for navigation and coastal infrastructure development, it changes the natural seabed profile and often produces artificial slopes that differ from the original seabed in geometry, density, and stress condition. These changes can make the new dredged slope more sensitive to external hydraulic loads.

In shallow water, surface waves interact strongly with the seabed because wave-induced pressure fluctuations can reach the bed and act repeatedly on the sediment surface. When the seabed has been cut into a steep or newly formed slope, this cyclic forcing can trigger erosion near the toe, redistribution of sediment along the face, reduction of slope angle, and progressive lowering of the bed surface. The combination of altered geometry and wave action is therefore an important problem in dredging engineering.

Previous studies on wave-seabed interaction indicate that wave loading can increase pore-water pressure and reduce effective stress in saturated sediments. From a geotechnical perspective, the reduction of effective stress weakens the resisting shear force of the soil, while from a morphodynamic perspective the same process may appear as bed deformation, slumping, and sediment displacement. For dredged slopes, both mechanisms are relevant because hydraulic forcing and sediment response occur simultaneously.

Despite the importance of this process, many dredged-slope evaluations still rely on static geometry or general stability criteria. Laboratory-scale investigation is useful because it allows the combined influence of wave condition, water depth, sediment group, and exposure time to be observed under controlled conditions. The present study uses recently collected laboratory flume data to examine how wave action changes the morphology of dredged slopes in shallow water.

Corresponding author: kasmawati.stmt08@gmail.com
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The objective of this paper is to analyze morphological change under wave loading by quantifying bed elevation change (ΔZ) and slope-angle change (Δθ). The analysis is intended to support the design and monitoring of dredged slopes in shallow-water environments where repeated wave loading may accelerate slope deformation.

2. Materials and methods

2.1 Experimental facility

The laboratory data were obtained from tests conducted in a wave flume. The flume consisted of a steel frame with glass walls and was approximately 15 m long, 0.30 m wide, and 0.45 m high. A wave absorber was placed at the downstream end to reduce reflected waves. The model slope was formed inside the flume using sediment material, and wave loading was applied to observe morphological deformation of the dredged slope.

The experimental condition represented a dredged slope in shallow water. Before each run, the sediment bed was re-formed to the target slope geometry. The water depth was then adjusted to the specified condition, and regular waves were generated. Changes in vertical position and slope angle were recorded after exposure to wave action.

2.2 Experimental variables and data structure

The dataset consisted of 729 observations. These observations represented 81 test combinations formed from three sediment groups, three water depths, three wave-period settings, and three exposure times. Each test combination included repeated wave-height readings. The main variables used in this paper are listed in Table 1.

Table 1 - Main experimental variables used in the analysis

Variable	Symbol/Unit	Values or description
Sediment group	D	D16, D50, and D100
Water depth	h (cm)	13, 21, and 23
Wave-period setting	T	4, 5, and 6
Exposure time	t (min)	5, 10, and 15
Wave height	H (cm)	1.0-5.9, based on observed readings
Bed elevation change	ΔZ (cm)	Z after wave loading minus initial no-wave Z
Slope-angle change	Δθ (degree)	Angle after wave loading minus initial no-wave angle

2.3 Morphological indicators

Morphological change was evaluated using two main indicators. The first indicator was the change in bed elevation, ΔZ, and the second was the change in slope angle, Δθ. Negative values indicate that the slope became lower or flatter after wave loading. A relative wave-height ratio, Hr, was also considered to describe the intensity of wave loading relative to the water depth.

$$\Delta z = Z_{wave} - Z_0 \quad (1)$$

$$\Delta\theta = \theta_{wave} - \theta_0 \quad (2)$$

$$H_r = \frac{H}{h} \quad (3)$$

2.4 Data processing

The recorded spreadsheet was first structured by sediment group, wave-period setting, water depth, and exposure time. For each of the 81 combinations, the repeated wave-height readings were summarized as average, minimum, and maximum values. The corresponding ΔZ and Δθ values were then computed using the no-wave reference condition. Descriptive statistics, group averages, graphical comparisons, and simple regression diagnostics were used to interpret the morphological response.

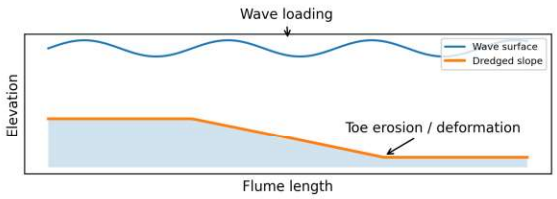

Fig. 1 - Conceptual interaction between wave loading and dredged-slope morphology

3. Results

3.1 Overall morphological response

The overall data show that wave action produced consistent morphological lowering of the dredged slope. Across all 729 observations, the measured wave height ranged from 1.0 to 5.9 cm, with an average of 3.37 cm. The computed elevation change ranged from -9.8 to -0.8 cm, with an average value of -6.75 cm. The slope-angle change ranged from -9.0° to -2.0°, with an average value of -5.91°.

These values indicate that the slope surface was not only displaced vertically but also became flatter under repeated wave action. This response is consistent with the physical expectation that waves mobilize sediment near the exposed slope face and transport material away from the initial profile.

Table 2 - Summary of morphological response by sediment group

Sediment	n	Mean H (cm)	Mean ΔZ (cm)	Mean Δθ (°)
D16	27	3.62	-6.81	-4.57
D50	27	3.20	-7.03	-6.63
D100	27	3.29	-6.40	-6.54

3.2 Effect of sediment group

The sediment groups showed different morphological responses. The D50 group produced the largest average elevation reduction, followed by D16 and D100. In terms of angular change, the D50 and D100 groups showed stronger flattening than D16. This suggests that the slope response was not controlled by sediment size alone; it was also influenced by the interaction between sediment group, water depth, wave height, and exposure duration.

For the D16 group, the average ΔZ was -6.81 cm and the average Δθ was -4.57°. For the D50 group, the average ΔZ reached -7.03 cm and the average Δθ reached -6.63°. For the D100 group, the average ΔZ was -6.40 cm and the average Δθ was -6.54°. The difference between the elevation and angular responses indicates

that a slope may experience strong vertical lowering without necessarily showing the strongest angular reduction.

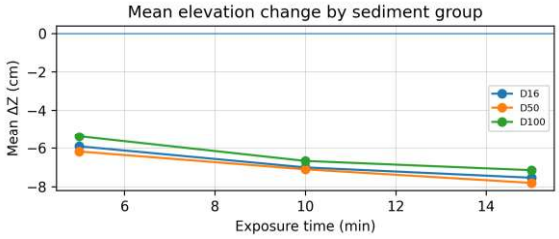

Fig. 2 - Mean bed elevation change as a function of exposure time and sediment group.

3.3 Effect of exposure time

Exposure time had a clear influence on the magnitude of morphological change. The average ΔZ changed from -5.83 cm at 5 min to -6.92 cm at 10 min and -7.49 cm at 15 min. Similarly, the average Δθ changed from -5.17° at 5 min to -6.06° at 10 min and -6.52° at 15 min. These results show that deformation became progressively larger as the slope was subjected to longer wave loading.

The correlation between exposure time and ΔZ was -0.38. Because ΔZ is negative, this negative correlation indicates that longer exposure was associated with greater bed lowering. This observation is important for dredging practice because short-term stability immediately after excavation may not represent the long-term morphology under repeated wave action.

Table 3 - Average response by exposure time

Time (min)	n	Mean H (cm)	Mean ΔZ (cm)	Mean Δθ (°)
5	27	3.51	-5.83	-5.17
10	27	3.37	-6.92	-6.06
15	27	3.23	-7.49	-6.52

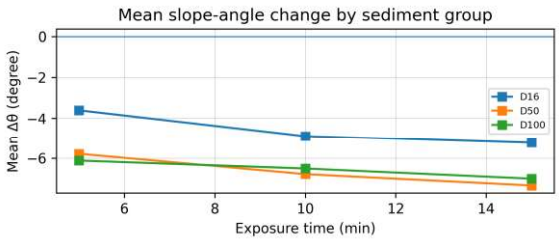

Fig. 3 - Mean slope-angle change as a function of exposure time and sediment group.

3.4 Effect of water depth and wave height

Water depth also affected the observed response. The mean elevation change was -6.31 cm at 13 cm water depth, -7.24 cm at 21 cm, and -6.69 cm at 23 cm. The intermediate water depth produced the strongest average lowering in this dataset. This pattern indicates that the morphological response depends on the balance between wave transformation, wave-bed interaction, and the initial geometry of the dredged slope.

The average wave height was weakly to moderately related to elevation change, with a correlation coefficient of -0.25. This result means that higher waves generally tended to produce greater bed lowering, although the response was not purely linear. Scatter in the relationship can be attributed to differences in water depth, sediment group, wave-period setting, and exposure time.

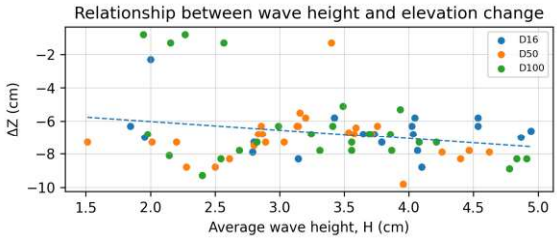

Fig. 4 - Relationship between average wave height and bed elevation change.

Table 4 - Average response by water depth

Water depth (cm)	n	Mean H (cm)	Mean ΔZ (cm)	Mean Δθ (°)
13	27	2.77	-6.31	-5.76
21	27	3.52	-7.24	-5.89
23	27	3.82	-6.69	-6.09

4. Discussion

The results demonstrate that wave action is a significant driver of dredged-slope morphology in shallow water. The consistent negative values of ΔZ and Δθ indicate that the slope was lowered and flattened after wave exposure. This response can be explained by repeated wave-induced shear stress along the bed, sediment entrainment from the slope face, and local erosion near the toe of the dredged profile.

The effect of wave loading was not uniform for every test combination. Some combinations showed relatively limited bed lowering, while others produced severe elevation reduction. The strongest lowering occurred for D50 at T = 6, h = 21 cm, and 15 min exposure, where ΔZ reached -9.8 cm and Δθ reached -9.0°. This condition suggests that certain combinations of sediment characteristics, water depth, and exposure time can amplify slope deformation.

The dominant role of exposure time is also important. Repeated wave action allows small deformations to accumulate, causing progressive adjustment of the slope profile. In practical dredging work, this implies that the slope may continue to deform after excavation even if it initially appears stable. For this reason, field monitoring should not be limited to the immediate post-dredging condition but should include observation after wave events or during seasonal energetic conditions.

The relationship between average wave height and morphological change was not perfectly linear. This is reasonable because wave effect on a dredged slope depends not only on H but also on relative water depth, wave period, sediment response, and exposure duration. Thus, design recommendations based only on a single wave-height threshold may be insufficient. A more robust assessment should consider the combined action of wave height, wave period, water depth, and sediment properties.

From a design perspective, the findings support the use of more conservative dredged-slope geometry in shallow water. Possible mitigation measures include reducing slope steepness, providing

toe protection, limiting excavation depth in exposed zones, and scheduling dredging outside energetic wave periods. The results also suggest the need for repeated profile surveys to detect post-dredging morphological adjustment.

4.1 Mechanism of slope-profile adjustment

The observed reduction in bed elevation is interpreted as the combined result of sediment detachment from the slope face, downslope movement of loosened grains, and redistribution near the toe of the model. When incident waves reach the dredged slope, the oscillatory motion near the bed imposes repeated shear stress. This process disturbs the initially formed slope surface and promotes movement of sediment particles toward a lower-energy configuration.

The flattening of the slope angle is a direct manifestation of this adjustment. In a newly dredged slope, the face is relatively steep and the sediment particles are not yet fully rearranged under hydraulic loading. As wave action continues, unstable particles are displaced, and the profile tends to move toward a milder slope. Therefore, the measured negative $\Delta\theta$ should not be interpreted only as a geometrical change, but also as evidence of mechanical adjustment of the sediment mass.

The magnitude of ΔZ and $\Delta\theta$ also suggests that deformation was not limited to superficial ripple development. Several test combinations produced elevation losses greater than 8 cm, indicating substantial profile modification relative to the laboratory model scale. Such a response is important because small-scale profile change in the laboratory may represent larger bathymetric adjustment in field-scale dredged channels or basins when the same physical mechanism acts repeatedly.

4.2 Role of sediment group

The difference among D16, D50, and D100 indicates that grain characteristics influence how the slope responds to wave loading. Finer or more mobile fractions may be more easily entrained from the slope face, whereas coarser fractions may require higher wave-induced shear stress before being displaced. However, the present data also show that the relationship is not a simple monotonic function of sediment group. The D50 group produced the largest mean elevation reduction, while D100 produced angular changes comparable to D50.

This behaviour can be explained by the interaction between grain mobility and slope geometry. If the grains are too mobile, sediment may be redistributed rapidly but not necessarily produce the greatest angular collapse. Conversely, coarser material may resist initial motion but, once mobilized, can produce a more pronounced structural adjustment of the slope face. Therefore, sediment group should be evaluated together with water depth, wave period, and exposure time.

4.3 Role of water depth and relative wave intensity

Water depth affects the transmission of wave-induced pressure and near-bed orbital motion. At smaller water depth, wave motion is more strongly coupled with the bed, but available water volume and wave form may constrain the generated wave condition. At larger water depth, the wave can develop differently and may transfer energy over a wider section of the slope. The strongest average ΔZ in this dataset occurred at 21 cm water depth, showing that the most severe deformation did not necessarily occur at the shallowest or deepest condition.

The relative wave-height ratio, H/h, is useful because it represents the intensity of wave loading relative to the available water depth. Nevertheless, the data show that this ratio alone cannot explain all morphological variation. Some combinations with moderate H/h still produced large lowering when exposure time was long. This confirms that dredged-slope response is cumulative and multivariable.

4.4 Critical test conditions

The most severe recorded case occurred for D50 at T = 6, h = 21 cm, and 15 min exposure, where ΔZ reached -9.8 cm and $\Delta\theta$ reached -9.0°. This condition represents a critical combination in which the slope experienced both strong vertical degradation and significant flattening. Other severe cases occurred for D100 at T = 5 with 13 cm and 21 cm water depths under 15 min exposure, where ΔZ values reached -9.3 cm and -8.9 cm, respectively.

These critical cases demonstrate that longer exposure time can magnify the effect of wave loading even when the average wave height is not always the highest in the dataset. For field application, this means that design checks should not only consider extreme wave height, but also the duration and repetition of wave events. A dredged slope subjected to a long sequence of moderate waves may undergo considerable deformation, especially if the sediment is easily mobilized.

The least severe responses occurred mainly in several D100 cases with h = 13 cm and short exposure time. In those cases, ΔZ was close to -0.8 to -1.3 cm. This suggests that certain combinations of sediment group, water depth, and loading duration can provide relatively better morphological resistance. However, even these cases still showed negative ΔZ, meaning that deformation was not fully prevented.

4.5 Implications for dredging practice

The laboratory findings have several implications for dredging projects in shallow water. First, the design of dredged slopes should include an allowance for post-dredging profile adjustment. If the design slope is based only on the excavation geometry, the actual profile after wave exposure may differ from the intended section. This can affect navigational clearance, slope stability, and maintenance dredging requirements.

Second, the toe of the dredged slope should receive particular attention because wave-induced sediment movement tends to concentrate deformation near the lower part of the profile. In field conditions, toe erosion can increase the driving force acting on the upper slope and may trigger progressive failure. Toe protection or a milder transition zone may therefore be useful in locations exposed to repeated waves.

Third, monitoring should be scheduled after significant wave events. The results show that deformation increases with exposure duration; therefore, surveys conducted only immediately after dredging may underestimate future morphological change. Repeated bathymetric surveys, pore-pressure monitoring, or visual inspection in physical models can improve the reliability of post-dredging assessment.

4.6 Limitations and future research

This study is based on laboratory-scale data and therefore the results should be interpreted in terms of relative response and physical tendency rather than direct field-scale prediction. Scale effects, boundary effects of the flume, sediment preparation method, and the simplified wave condition may influence the absolute magnitude of the measured deformation. Nevertheless, laboratory data remain valuable because they isolate important mechanisms under controlled conditions.

Future work should include direct measurements of pore-water pressure, velocity near the bed, and detailed time-series bathymetry during each run. Numerical modelling could also be used to extend the laboratory observations to larger field-scale geometries. In addition, repeated tests for each condition would allow uncertainty to be quantified more rigorously and would

improve the statistical interpretation of the morphodynamic response.

Further research should also compare regular and irregular wave conditions. Natural wave climates consist of varying heights and periods rather than a single regular wave train. Testing irregular waves would provide a more realistic assessment of how dredged slopes adjust under coastal and port environments. Such work would improve practical guidelines for safe and efficient dredging in shallow water.

4.7 Statistical interpretation of the dataset

A simple linear diagnostic model was used to evaluate whether the measured variables could explain the direction and magnitude of morphological change. For ΔZ, the explanatory variables included average wave height, sediment group, wave-period setting, water depth, and exposure time. The resulting coefficient of determination was $R^2 = 0.24$. This moderate value indicates that the tested variables captured part of the morphological tendency, but a large proportion of the variability was still controlled by interaction effects and local slope response.

For $\Delta\theta$, the same set of explanatory variables produced $R^2 = 0.41$. This value is higher than the corresponding value for ΔZ, suggesting that slope-angle change was more consistently related to the selected experimental variables than vertical elevation change. This is reasonable because angular change represents an integrated shape adjustment, whereas ΔZ at a given point may be more sensitive to local erosion and deposition.

The regression result should not be used as a predictive design equation without further calibration. Its purpose in this paper is diagnostic: it shows that the response of dredged slopes is not governed by one parameter alone. A reliable empirical model would require a larger dataset, additional replicate tests, and variables such as near-bed velocity, pore pressure, sediment density, and detailed grain-size distribution.

The statistical results also confirm the importance of exposure time. In both descriptive statistics and regression diagnostics, longer exposure increased the magnitude of deformation. This supports the interpretation that wave action produces cumulative morphological change, not only instantaneous reshaping. Therefore, time-dependent monitoring and maintenance are necessary components of dredged-slope management.

4.8 Comparison with the general wave-seabed interaction concept

The observed deformation agrees with the general concept of wave-seabed interaction. When waves propagate over a shallow seabed, oscillatory pressure and near-bed motion impose cyclic loading on the sediment. In saturated material, this cyclic loading may increase excess pore pressure and reduce effective stress. At the same time, the oscillatory flow can move sediment particles along the slope surface. These two processes combine to produce mechanical weakening and morphodynamic adjustment.

The present study contributes to this concept by focusing on the morphology of a dredged slope rather than a horizontal seabed. A dredged slope has a discontinuity in bed geometry and a preferential direction for sediment movement. Once grains are mobilized, gravity assists downslope displacement and toe accumulation. Thus, dredged slopes can show stronger geometric adjustment than flat beds under similar wave exposure.

The results are also consistent with the engineering observation that newly dredged slopes often require an adjustment period before reaching a more stable profile. In the laboratory data, the initial no-wave reference was not maintained after wave loading. Instead, the slope profile shifted toward lower elevation and smaller angle. This suggests that wave exposure should be regarded as a post-construction conditioning process that may alter the final operational geometry.

5. Conclusion

This study analyzed morphological changes of dredged slopes under wave action in shallow water using 729 laboratory observations and 81 test combinations. The main conclusions are as follows:

1) Wave action caused consistent lowering and flattening of the dredged slope. The bed elevation change ranged from -9.8 to -0.8 cm, while the slope-angle change ranged from -9.0° to -2.0°.
2) Exposure time was a major factor controlling progressive deformation. The average ΔZ increased in magnitude from -5.83 cm at 5 min to -7.49 cm at 15 min.
3) Sediment response was condition-dependent. D50 produced the largest average elevation reduction, while D50 and D100 produced stronger average angular reduction than D16.
4) The effect of wave height was important but not purely linear. Morphological change was controlled by the combined effects of wave height, water depth, wave-period setting, sediment group, and exposure time.
5) Dredged-slope design in shallow water should explicitly include wave-induced morphology and should be supported by post-dredging monitoring, especially in areas exposed to repeated or energetic wave action.

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